Cross section and coupling measurements with the ATLAS detector for the 125 GeV Higgs Boson in the fermion decay channels

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Kristian Gregersen (University College London)

on behalf of the ATLAS Collaboration

Introduction

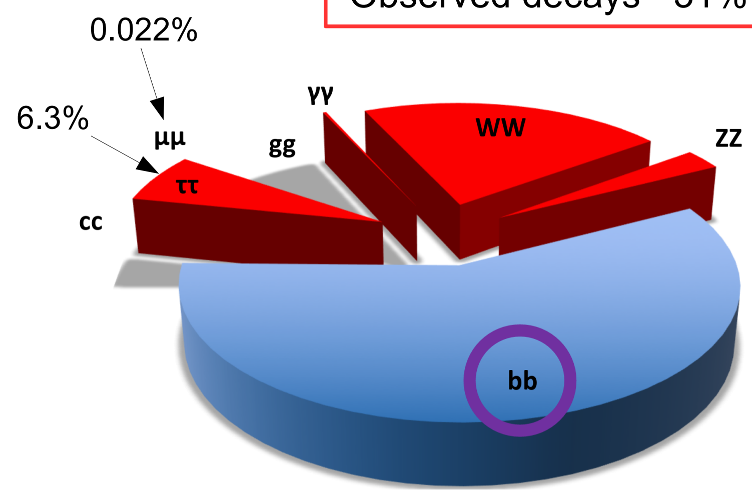
Decay modes of the Higgs boson

- ***Observed in* bosonic *decay channels***
  - $H \to ZZ^* \to 4l$
  - $H \to \gamma\gamma$
  - $H \to WW \to l\nu l\nu$
- ***Essential to determine* fermionic *decay modes***
  - Do they follow Standard model predictions?
- ***Searches for fermionic decays are* challenging**
  - $H \to bb$: Large backgrounds
  - $H \to \tau\tau$: Tau ID and trigger
  - $H \to \mu\mu$: Clean final state, but very small rate
- ***Combined Run 1 ATLAS+CMS results***
  - JHEP08 (2016) 045

Decay channel	Measured signif. (σ)	Expected signif. (σ)
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

SM Higgs (125 GeV) branching fractions:

Observed decays ~31%

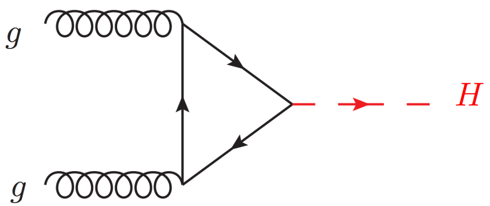


Dominant decay ~58%

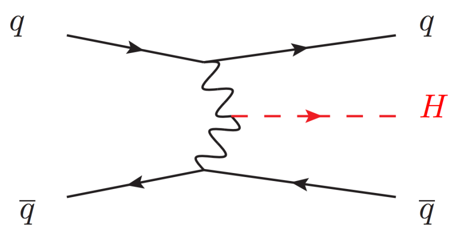
Introduction

Production of the Higgs boson

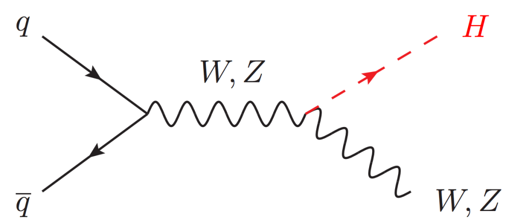
- **Gluon fusion *(ggH)***
  - Largest production cross section
  - Best suited for leptonic decay modes
  - ***σ = 48.6 pb***



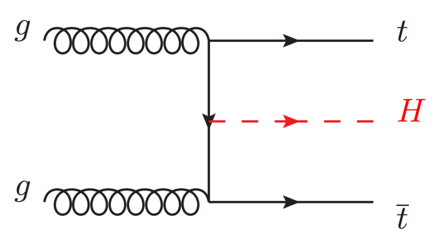
- **Vector boson fusion *(VBF)***
  - 2 forward jets gives unique handle for background reduction
  - Considered in all searches for fermionic decay modes
  - ***σ = 3.78 pb***



- **Associated production with W/Z boson *(VH)***
  - Leptonic decays of W/Z for triggering & background reduction
  - Considered in searches for ττ, bb decay modes
  - ***σ = 1.37 / 0.88 pb (W / Z)***



- **Associated production with tt *(ttH)***
  - Leptonic decays of top(s) for triggering & background reduction
  - Considered in searches for ττ, bb decay modes
  - ***σ = 0.59 pb***



Results for this talk

- **H** $\rightarrow \mu\mu$
  - 13 TeV
  - 36 fb^{-1}
  - Phys. Rev. Lett. 119 (2017) 051802
- **H** $\rightarrow \tau\tau$
  - 7,8 TeV
  - 4.5+20.3 fb^{-1}
  - JHEP 04 (2015) 117
- **H → bb**
  - VH
    - 13 TeV
    - 36.1 fb^{-1}
    - Submitted to JHEP, arXiv: 1708.03299
  - VBF + γ
    - 13 TeV
    - 12.6 fb^{-1}
    - ATLAS-CONF-2016-063
  - ttH
    - 13 TeV
    - 13.2 fb^{-1}
    - ATLAS-CONF-2016-080

Measurement expressed in terms of signal strength μ:

$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

for SM Higgs @ 125 GeV

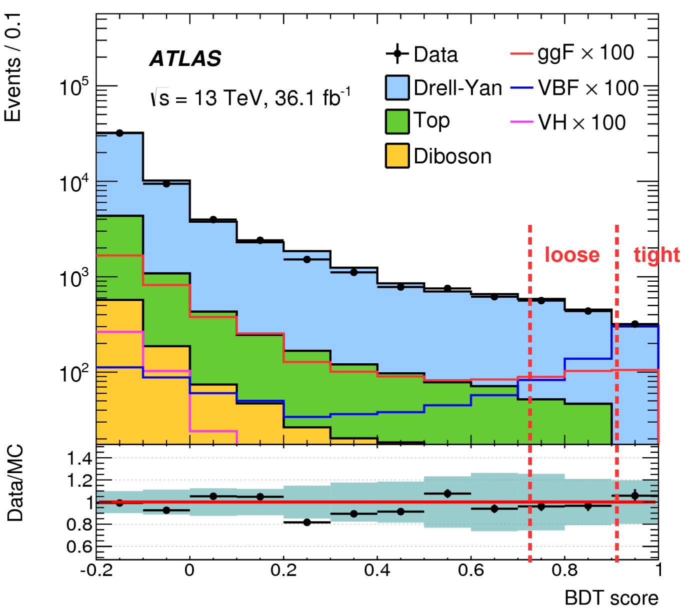
Phys. Rev. Lett. 119 (2017) 051802

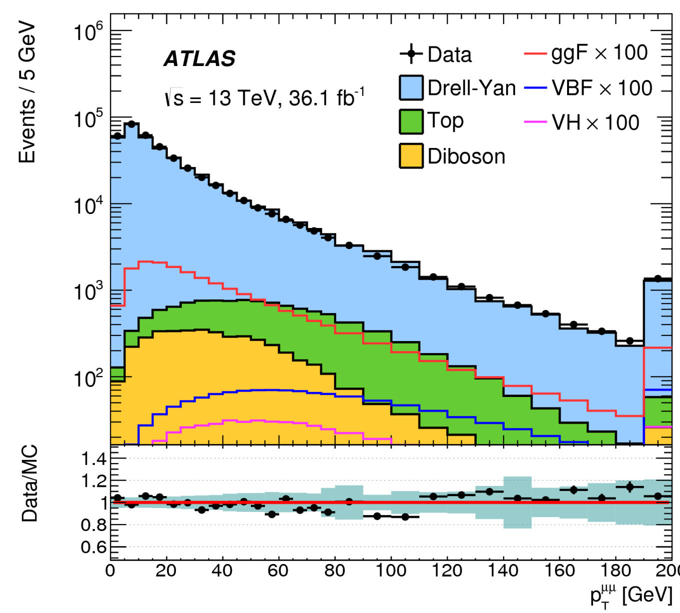
Event selection

- **VBF**
  - At least 2 jets
  - BDT to select VBF-like events (**New in Run-2**)
    - "tight" (BDT-score > 0.9)
    - "loose" (0.7 < BDT-score < 0.9)
- **ggF**
  - Not selected as VBF
  - Events categorised according to di-muon p_T and eta

	≥2 jets BDTscore ≥ 0.9	≥2 jets 0.7 < BDTscore < 0.9
<2 jets or BDTscore < 0.7	Central Muons, $p_T^{\mu\mu}$<15 GeV	Non-central Muons, $p_T^{\mu\mu}$<15 GeV
<2 jets or BDTscore < 0.7	Central Muons, 15<$p_T^{\mu\mu}$<50 GeV	Non-central Muons, 15<$p_T^{\mu\mu}$<50 GeV
<2 jets or BDTscore < 0.7	Central Muons, $p_T^{\mu\mu}$>50 GeV	Non-central Muons, $p_T^{\mu\mu}$>50 GeV

"Central"=Both muons have |η|<1

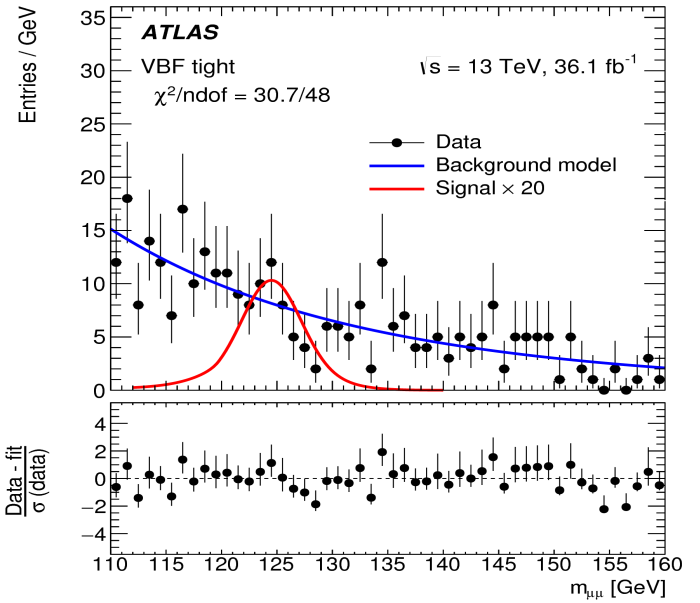




Phys. Rev. Lett. 119 (2017) 051802

Results

- **Binned maximum likelihood *fit to observed m(μμ)***
  - Using the sum of signal and background (“S+B model”)
- **Signal model**
  - Sum of Gaussian and Crystal Ball functions
- **Background model**
  - Breit-Wigner convoluted with a Gaussian, added to an exponential divided by a cubic function
  - The Breit-Wigner models the tail the Z → μμ background
- **Simultaneous *fit to m(μμ) for all categories***
  - μ = -0.1 ± 1.5
  - upper limit : μ < 3.0 (exp. 3.1) @ 95% CL
- **Combined with Run 1**
  - μ = -0.1 ± 1.4
  - upper limit : μ < 2.8 (exp. 2.9) @ 95% CL
- **Results limited by data statistics**



Event yields within 90% mass window

	S	B	$S/\sqrt{B}$	FWHM	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_T^{\mu\mu}$	32	38000	0.16	7.0 GeV	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_T^{\mu\mu}$	66	31000	0.37	7.1 GeV	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3 GeV	3160
Non-central high $p_T^{\mu\mu}$	40	13000	0.35	7.7 GeV	12829
VBF loose	3.4	260	0.21	7.6 GeV	274
VBF tight	3.4	78	0.38	7.5 GeV	79

JHEP 04 (2015) 117

Event selection and Results

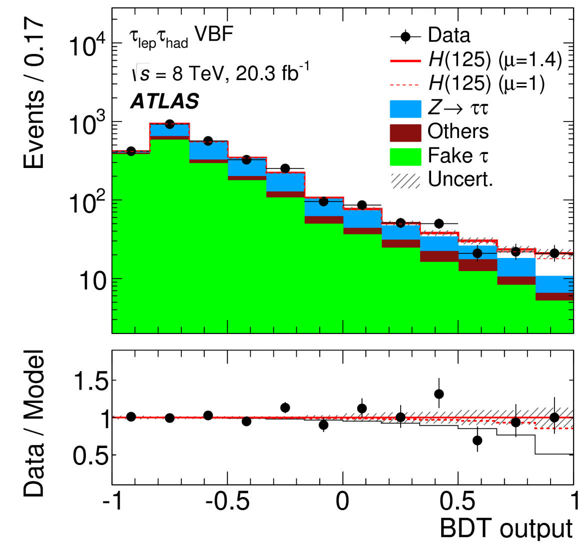
- **Categories *based on Higgs production and tau decay***
  - VBF, ggF and VH production
  - All tau decays (lep-lep, lep-had, had-had)

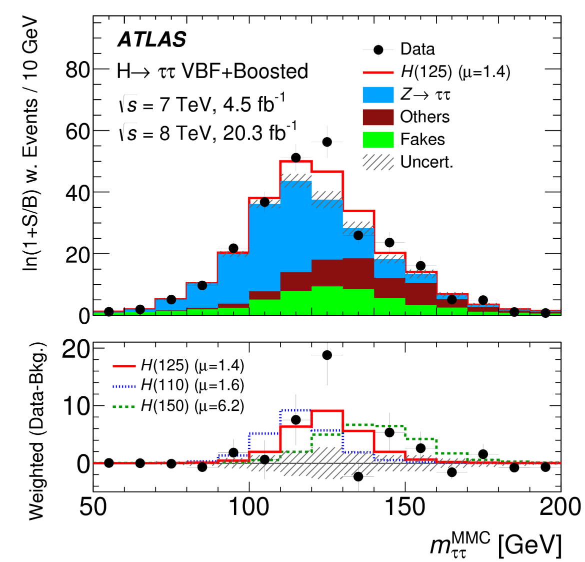
- **Missing Mass Calculater *(MMC)***
  - Reconstructs invariant mass of di-tau system
  - Gives most probable kinematic configuration of neutrinos using matrix element probability

- **Separate BDTs used for VBF and ggF**
  - BDT outputs used as final discriminating distribution

- **Main backgrounds**
  - $Z(\tau\tau)$: estimated with embedding technique
    - select $Z(\mu\mu)$ events in data
    - replace muons with simulated taus
    - everything except tau decays comes from data
  - Other:
    - $Z(ee)$, $Z(\mu\mu)$, W+jets, tt, diboson, multijet

- **Results** *:* Combining all categories/decay channels
  - Observed (expected) significance for $H \rightarrow \tau\tau$: 4.5σ (3.4σ)
  - $\mu = 1.43^{+0.43}_{-0.37}$





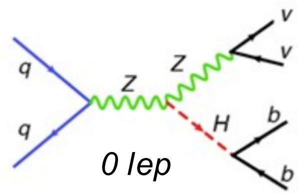
Search for $H \rightarrow \tau\tau$ in VH production mode: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2014-01/

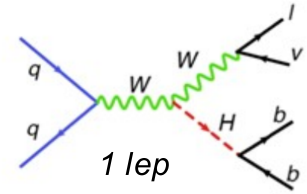
$VH, H \rightarrow bb$

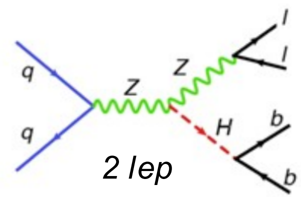
Submitted to JHEP, arXiv: 1708.03299

Event selection

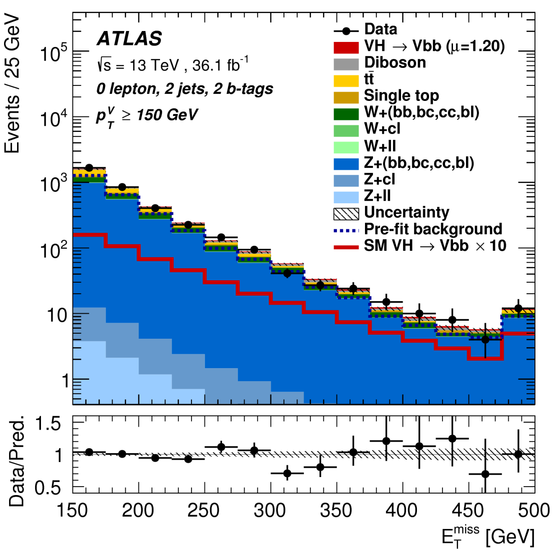
- **Lepton channels**
  - 0/1/2 leptons
- ***Require* 2 b-tagged jets**
- ***Event* categories *to maximize sensitivity***
  - 2/3 jets
  - high V p_T regions



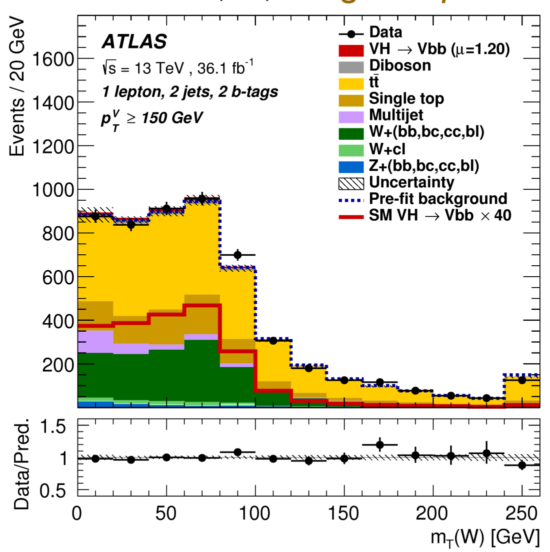




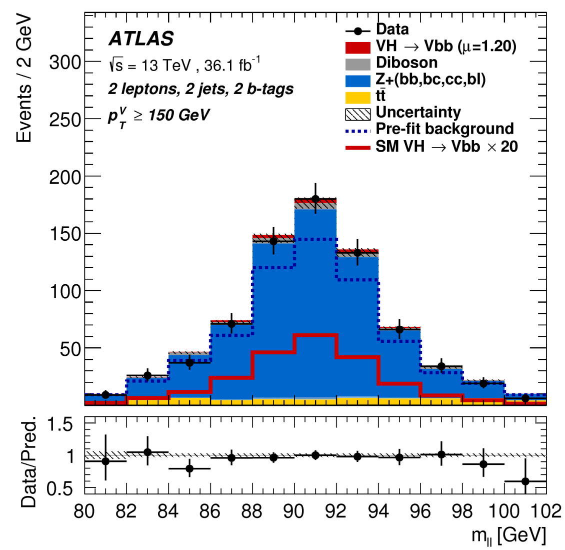
Z+hf, W+hf, tt



W+hf, tt, single-top



Z+hf, tt



Submitted to JHEP, arXiv: 1708.03299

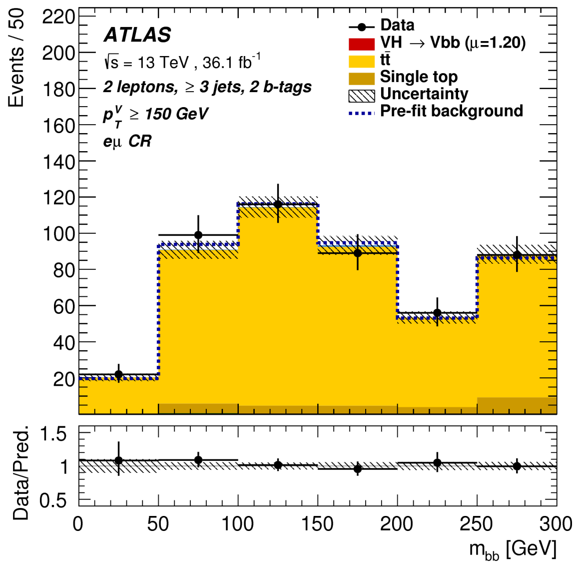
Analysis strategy

- ***3 versions of the analysis***
  - *Nominal :* BDT VH, H(bb)
  - BDT VZ, Z(bb)
  - Cut-based m(bb) VH, H(bb)

- **Simultaneous fit *to discriminating variable in all regions***
  - Normalisation of tt and Z/W+hf freely floating
  - Uncertainties on overall and relative normalisation between regions
  - Shape uncertainties on all non-negligible backgrounds

- Nominal :
  - 8 signal regions, 6 control regions

2 lepton tt CR (eμ events)



Channel	SR/CR	Categories			
		75 GeV $< p_T^V <$ 150 GeV		$p_T^V >$ 150 GeV	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

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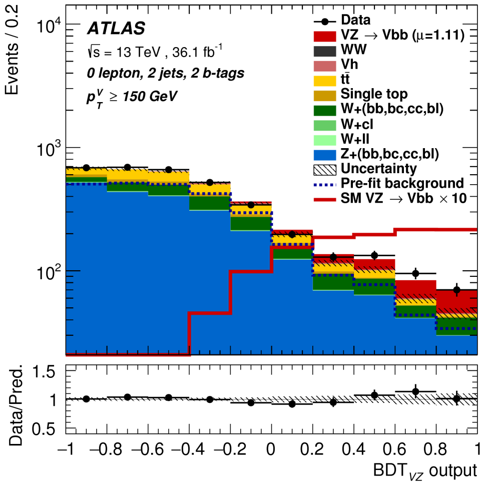
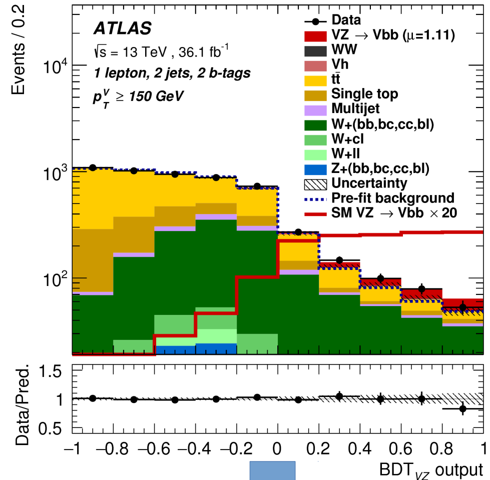
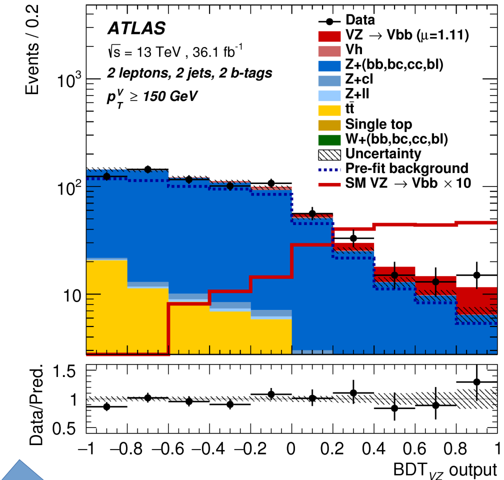
VZ, Z(bb) Cross-check

- WZ → lvbb, ZZ → vvbb, llbb
- Inclusive cross section ~9 times larger than VH
- Exactly the same events in data as for nominal analysis - but using different disciminant.

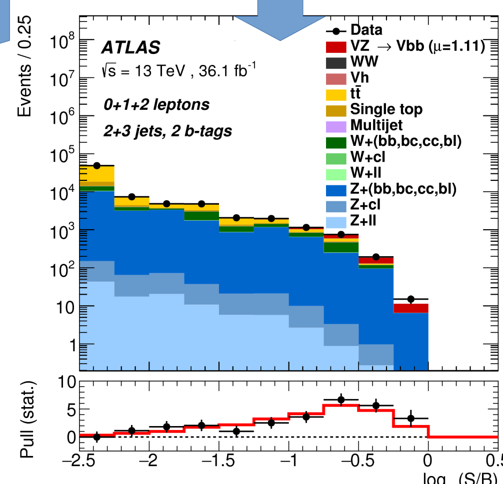


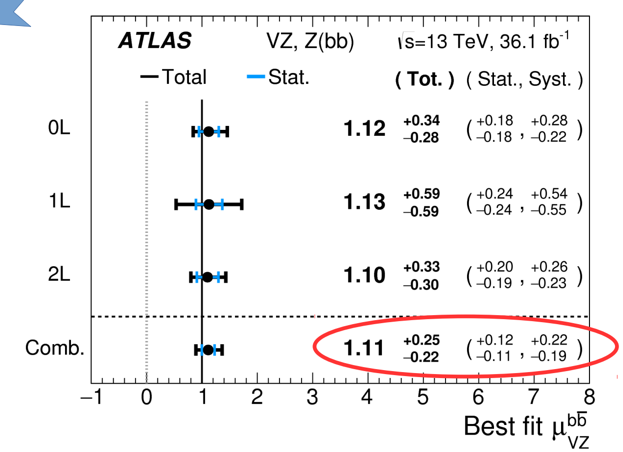




Diboson
WZ, Z(bb)
ZZ, Z(bb)

Significance:
Observed 5.8σ
Expected 5.3σ

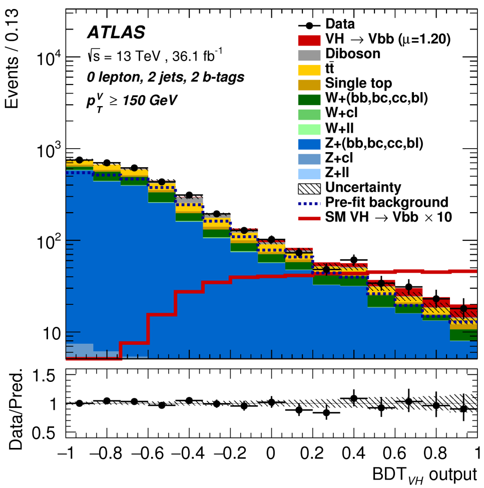




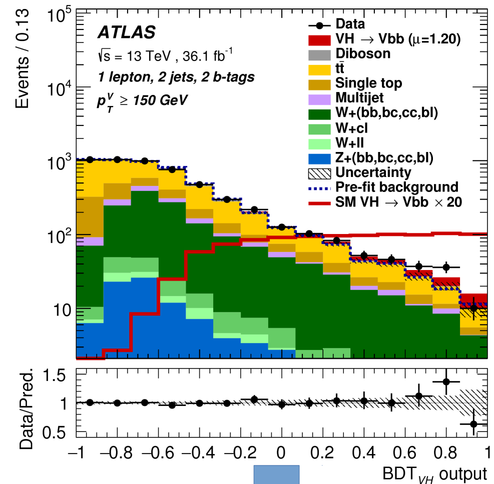
Submitted to JHEP, arXiv: 1708.03299

VH, H(bb) (BDT)

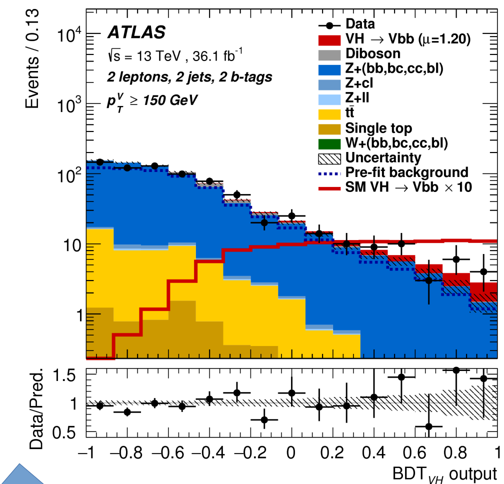
0 lepton (2b, 2jet)



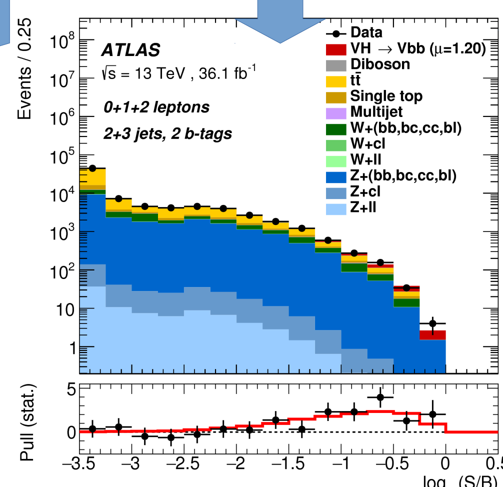
1 lepton (2b, 2jet)



2 lepton (2b, 2jet)



VH signal
WZ, Z(bb)
ZZ, Z(bb)

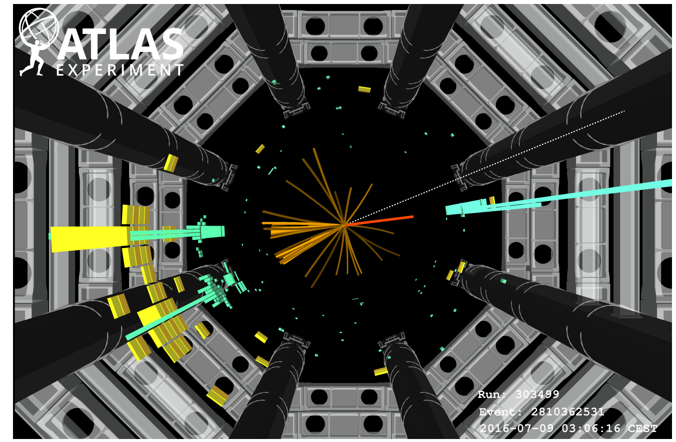


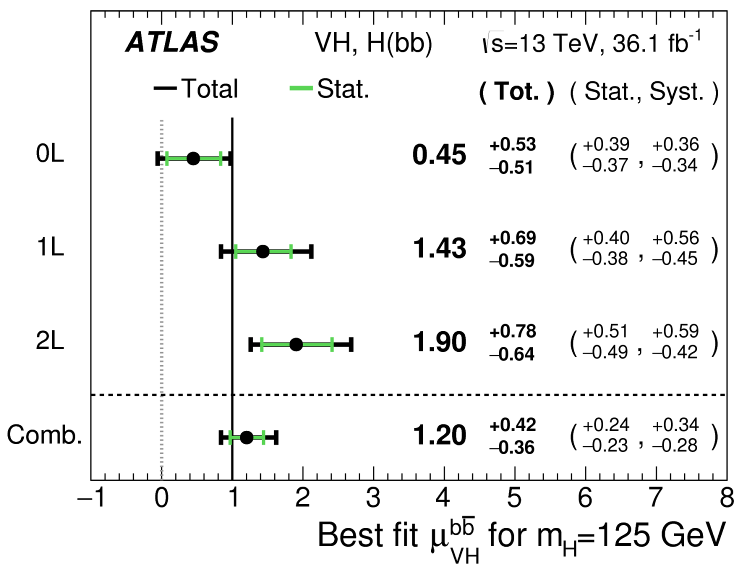
Submitted to JHEP, arXiv: 1708.03299

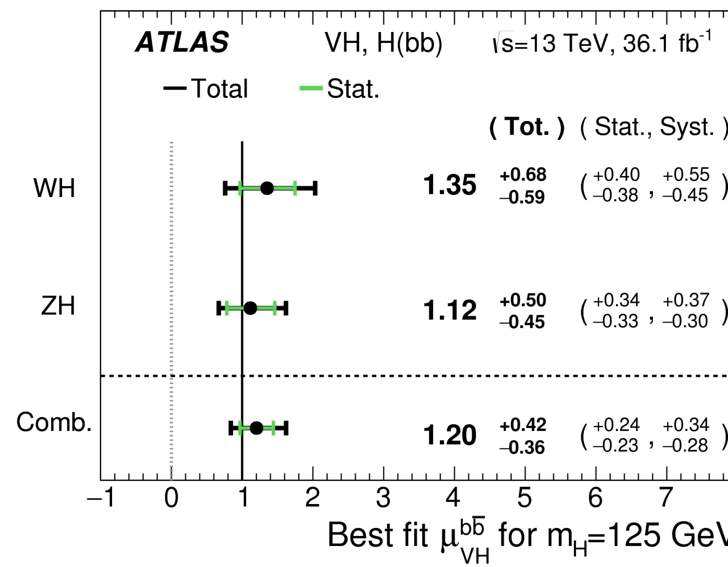
Results

- *Evidence* for H → bb
  - Observed : 3.5σ
  - Expected : 3.0σ
  - $\mu = 1.20^{+0.42}_{-0.36}$
  - Lepton channel compatibility: 10%
- *Dominant uncertainties*
  - Signal modelling
  - MC statistics
  - b-tagging

1 lepton event







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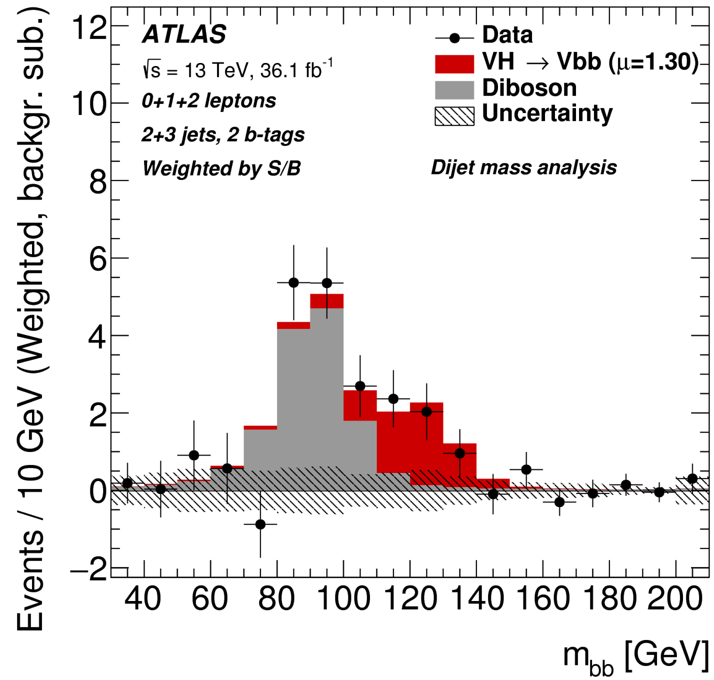
Cross check with cut-based analysis

- *Di-jet m(bb) mass as discriminating variable*
  - m(bb) after background subtraction (except diboson)
  - Weighted by S/B of each m(bb) bin
  - Signal scaled to best fit value of μ
- *Results*
  - Significance
    - Observed : 3.5σ
    - Expected : 2.8σ
  - $\mu = 1.30\ ^{+0.28}_{-0.27}$ (stat.) $^{+0.37}_{-0.29}$ (syst.)



Additional selection in cut based analysis

Selection	Channel 0-lepton	Channel 1-lepton	Channel 2-lepton
m_T^W	-	< 120 GeV	-
$E_T^{miss}/\sqrt{S_T}$	-	-	$< 3.5\sqrt{\text{GeV}}$

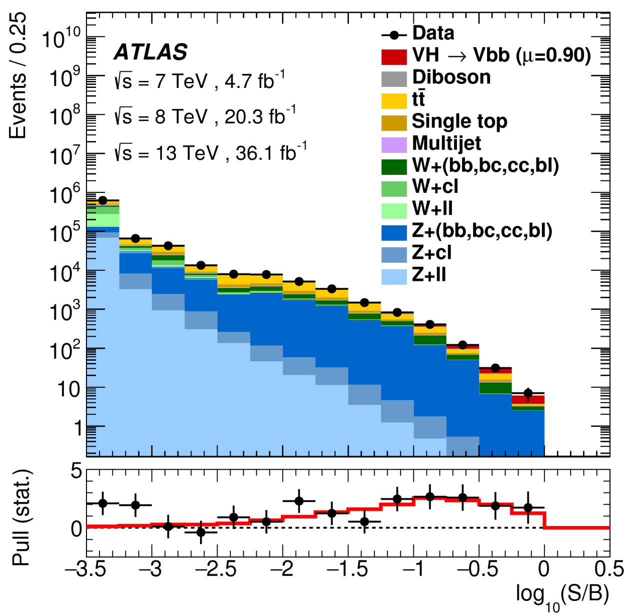
	p_T^V regions		
p_T^V	(75, 150] GeV (2-lepton only)	(150, 200] GeV	(200, ∞) GeV
$\Delta R(\vec{b}_1, \vec{b}_2)$	<3.0	<1.8	<1.2

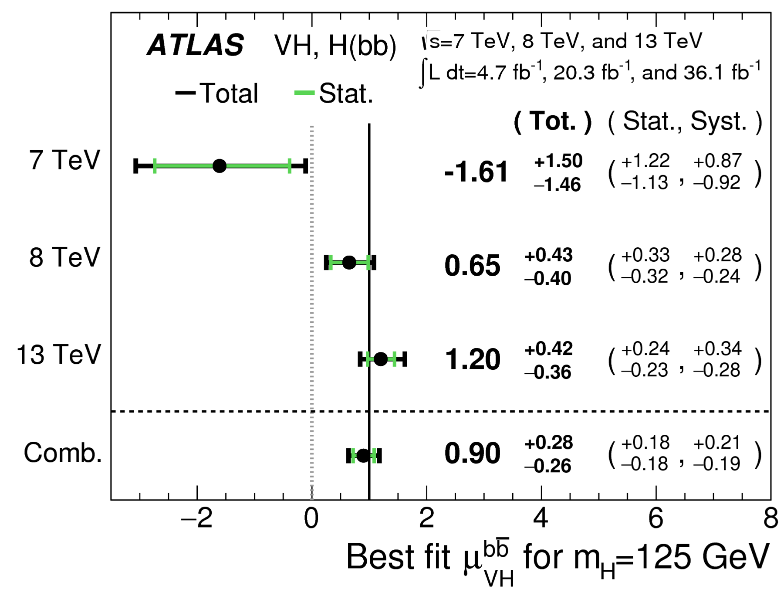
Submitted to JHEP, arXiv: 1708.03299

Run 1+2 combination

- *Combine with 4.7 fb^{-1} and 20.3 fb^{-1} Run 1 result*
  - Correlate signal theoretical uncertainty and b-jet energy scale uncertainty
  - Other uncertainties de-correlated

- *Results*
  - Significance
    - Observed : 3.6σ
    - Expected : 4.0σ
  - $\mu = 0.90^{+0.28}_{-0.26}$





VBF + γ, H → bb

ATLAS-CONF-2016-063

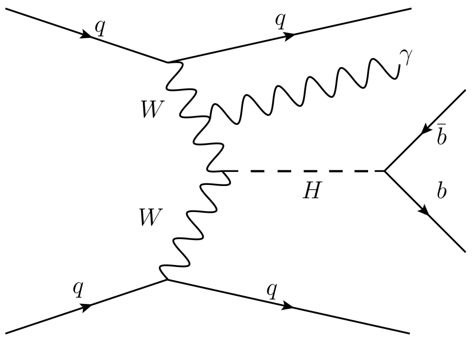
Search for H(bb) in VBF events with high pT photon

- *Theoretical motivations for VBF + photon*
  - While having smaller cross section than incl. VBF there are several *advantages* :

    → Photon provides clean signature for triggering
      - difficult to trigger on fully hadronic state for low p_T

    → Gluon induced non-resonant background suppressed
      - gluons don't radiate photons

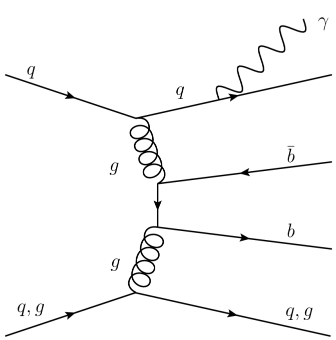
    → Destructive inference between diagrams in background
      - FSR vs. ISR of photon



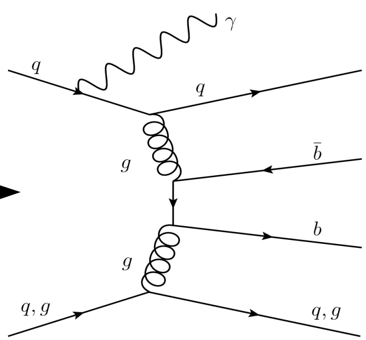
Signal process

- Non-resonant background reduced by *more than O(10)* compared to simple scaling with α_{EM}

Background processes



Negative interference

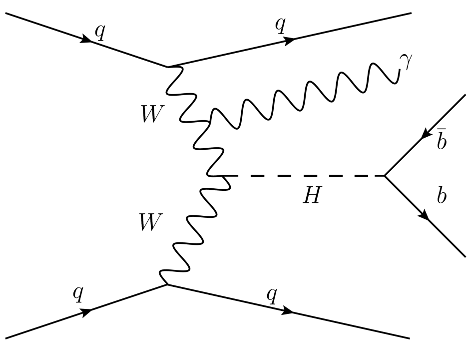


VBF + γ, H → bb

ATLAS-CONF-2016-063

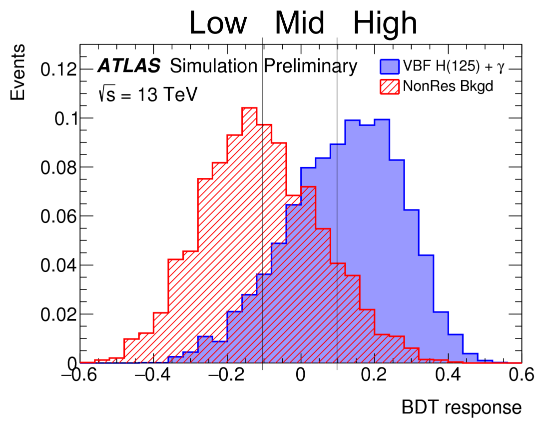
Search for H(bb) in VBF events with high pT photon

- *Event Selection*
  - 2 b-tagged jets
  - 2 forward jets (m(jj) > 800 GeV)
  - *1 central photon*
    - |eta| < 2.37
    - extra handle to trigger on
    - reduction of backgrounds

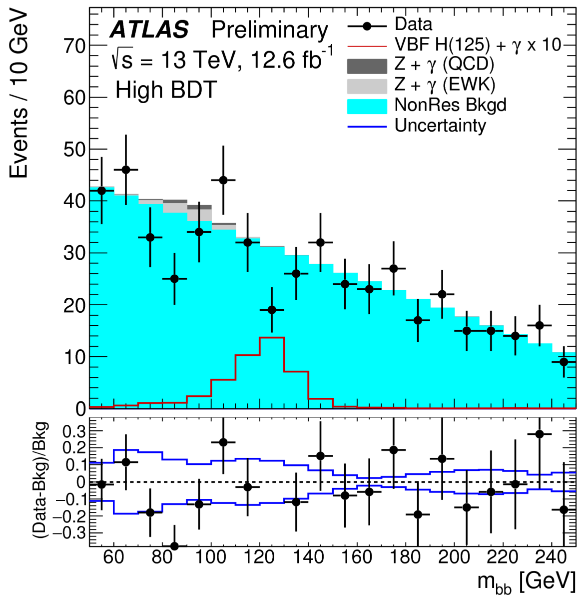


- *BDT used to separate signal from background*
  - Divide BDT output into different sensitivity categories
  - Fit m(bb) in each category to extract signal

- *Results* (95% CL limit)
  - Observed : $\mu < 4$
  - Expected : $\mu < 6^{+2.3}_{-1.7}$



High sensitivity category



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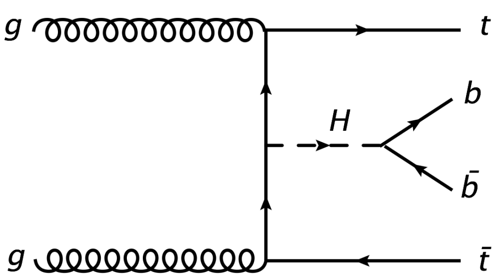
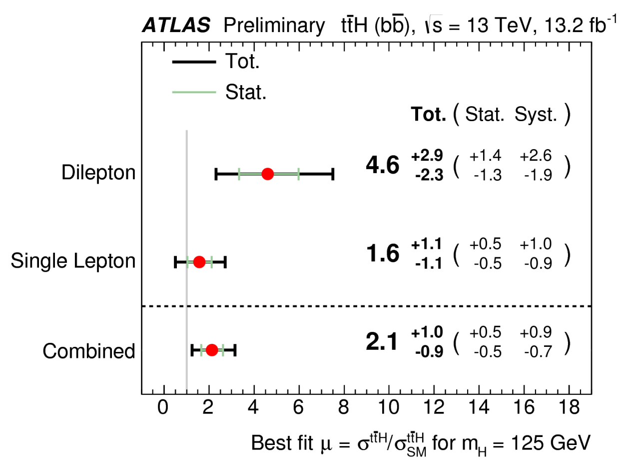
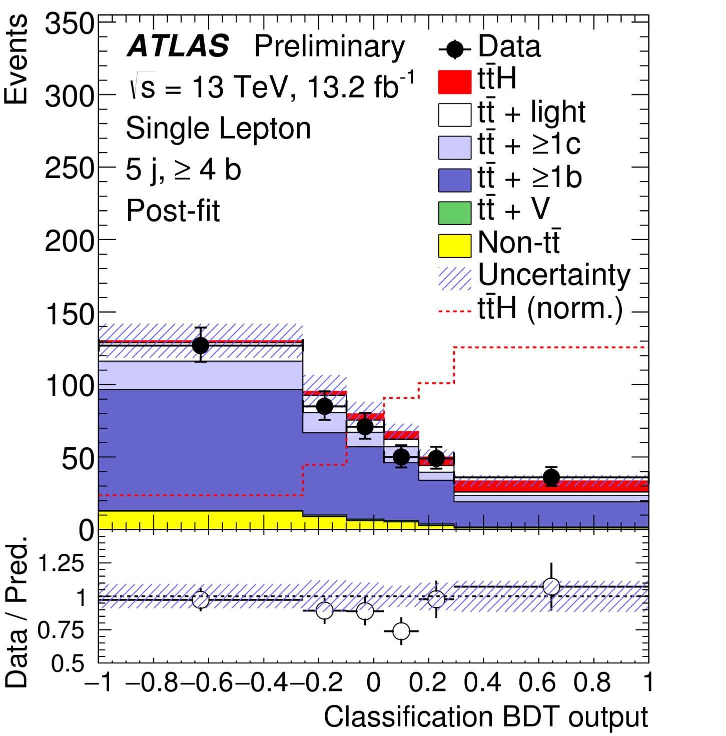
Search for H(bb) in association with tt

- *Will provide direct observation of ttH coupling*
- *Event selection*
  - Search for leptonically decaying W's (1 or 2 leptons)
  - Categorise according to
    - jet multiplicity
    - b-tagged jet multiplicity
- *BDT used to separate signal from background*
  - BDT output used as discriminating variable in fit
- *Results*
  - $\mu = 2.10^{+1.0}_{-0.9}$
  - Only using 13 fb^{-1} – already reached Run 1 sensitivity!



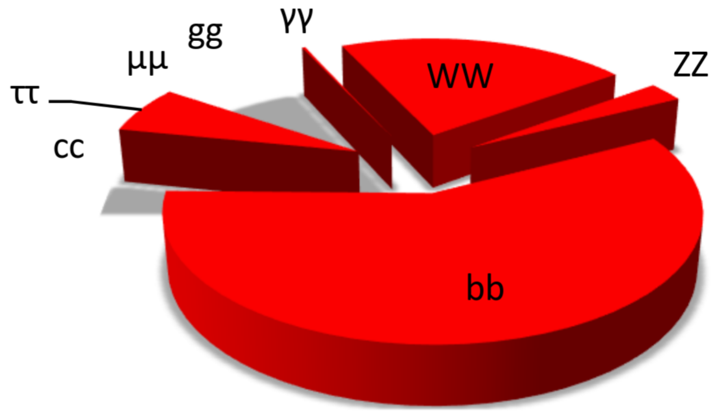




Conclusions

Searches for the 125 GeV Higgs boson decaying to fermions

- ***ATLAS is actively exploring direct fermionic decays of SM Higgs boson***
- **New results with Run 2 data**
  - ***Improved sensitivity to H $\rightarrow \mu\mu$***
  - ***Exploration of new production channel VBF H+γ***
  - ***Evidence for H $\rightarrow$ bb in VH production channel !***
- **More updates *are underway***
  - ***E.g. H $\rightarrow \tau\tau$, ttH, VBF, ...***



Evidence (or better) for ~88%

Back-up

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Simulated events

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order ace2.5cm
Signal					
$qq \rightarrow WH \rightarrow \ell\nu b\bar{b}$	Powheg-Box v2 [19] + GoSam [22] + MiNLO [23,24]	NNPDF3.0NLO$^{(\star)}$ [20]	Pythia8.212 [13]	AZNLO [21]	NNLO(QCD)+ NLO(EW) [25,26,27,28,29,30,31]
$qq \rightarrow ZH \rightarrow \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2 + GoSam + MiNLO	NNPDF3.0NLO$^{(\star)}$	Pythia8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)
$gg \rightarrow ZH \rightarrow \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2	NNPDF3.0NLO$^{(\star)}$	Pythia8.212	AZNLO	NLO+ NLL [32,33,34,35,36]
Top quark					
$t\bar{t}$	Powheg-Box v2 [37]	NNPDF3.0NLO	Pythia8.212	A14 [38]	NNLO+NNLL [39]
s-channel	Powheg-Box v1 [40]	CT10 [41]	Pythia6.428 [42]	P2012 [43]	NLO [44]
t-channel	Powheg-Box v1 [40]	CT10f4	Pythia6.428	P2012	NLO [45]
Wt	Powheg-Box v1 [46]	CT10	Pythia6.428	P2012	NLO [47]
Vector boson + jets					
$W \rightarrow \ell\nu$	Sherpa 2.2.1 [16,48,49]	NNPDF3.0NNLO	Sherpa 2.2.1 [50,51]	Default	NNLO [52]
$Z/\gamma^* \rightarrow \ell\ell$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
$Z \rightarrow \nu\nu$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
Diboson					
WW	Sherpa 2.1.1	CT10	Sherpa 2.1.1	Default	NLO
WZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
ZZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO

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Event selection

Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ sub-channel	2-lepton
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 medium 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 or 3 jets			Exactly 2 or ≥ 3 jets
Jet p_{T}	> 20 GeV			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20°$ (2 jets), $> 30°$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120°$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140°$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T,trk}}^{\mathrm{miss}})$	$< 90°$	–		–
p_{T}^{V} regions	> 150 GeV			(75, 150] GeV, > 150 GeV
Signal regions	✓	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charge ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons

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Signal acceptance

$m_H = 125$ GeV at $\sqrt{s} = 13$ TeV				
Process	Cross-section × B [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \rightarrow ZH \rightarrow \ell\ell b\bar{b}$	29.9	< 0.1	< 0.1	7.0
$gg \rightarrow ZH \rightarrow \ell\ell b\bar{b}$	4.8	< 0.1	< 0.1	15.7
$qq \rightarrow WH \rightarrow \ell\nu b\bar{b}$	269.0	0.2	1.0	–
$qq \rightarrow ZH \rightarrow \nu\nu b\bar{b}$	89.1	1.9	–	–
$gg \rightarrow ZH \rightarrow \nu\nu b\bar{b}$	14.3	3.5	–	–

BDT variables

Variable	0-lepton	1-lepton	2-lepton
p_{T}^{V}	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	$\times$	$\times$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\times$	$\times$	$\times$
$p_{\mathrm{T}}^{b_1}$	$\times$	$\times$	$\times$
$p_{\mathrm{T}}^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\vec{b}_1, \vec{b}_2)$	$\times$	$\times$	$\times$
$\|\Delta\eta(\vec{b}_1, \vec{b}_2)\|$	$\times$		
$\Delta\phi(\vec{V}, \vec{bb})$	$\times$	$\times$	$\times$
$\|\Delta\eta(\vec{V}, \vec{bb})\|$			$\times$
m_{eff}	$\times$		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		$\times$	
m_{T}^{W}		$\times$	
$m_{\ell\ell}$			$\times$
m_{top}		$\times$	
$\|\Delta Y(\vec{V}, \vec{bb})\|$		$\times$	
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	$\times$	$\times$	$\times$
m_{bbj}	$\times$	$\times$	$\times$

Break-down of uncertainties on signal strength

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z + jets		0.07
W + jets		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

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Results