BMBF-Forschungsschwerpunkt
ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC

FSP 103
ATLAS

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

ATLAS
EXPERIMENT

Coupling measurements for the 125 GeV Higgs Boson in the fermion decay channels with the ATLAS detector

Albert-Ludwigs-Universität Freiburg

UNI
FREIBURG

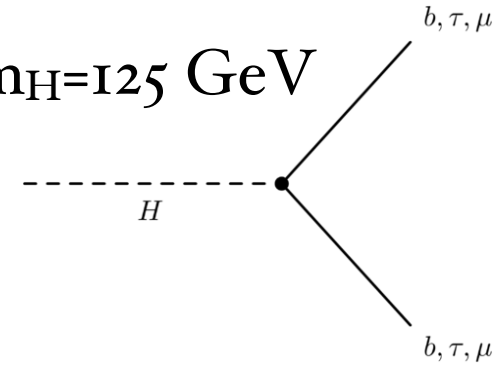
Duc Bao Ta
for the ATLAS collaboration

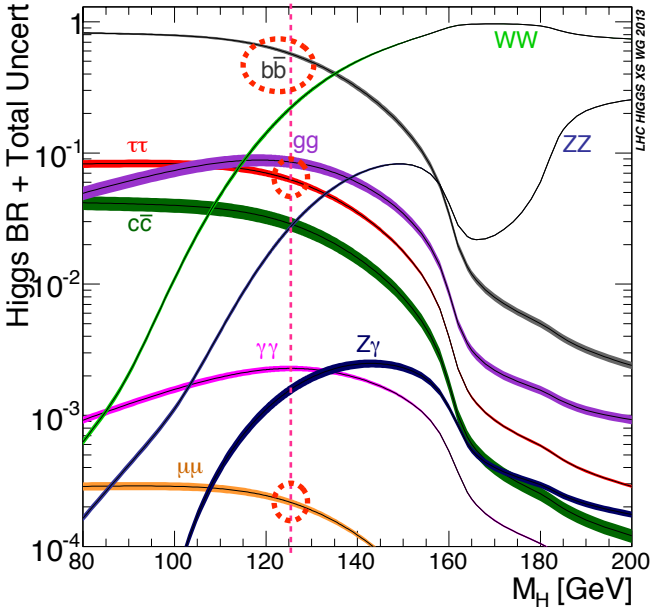
DIS 2017 - Birmingham

Introduction

- Measurement with fermion decay channels
  - Establish Higgs Yukawa couplings
- Quite challenging
  - b-quark pairs (BR ~58%): largest decay mode
    - dominated by b-jet background
    - need good b-tagging
  - tau-lepton pairs (BR ~6.3%): largest leptonic decay mode
    - main background from multi-jet or Z events
    - need good trigger and tau identification
  - μ pairs (BR ~0.022%): clean signature
    - extremely small coupling

m_H=125 GeV

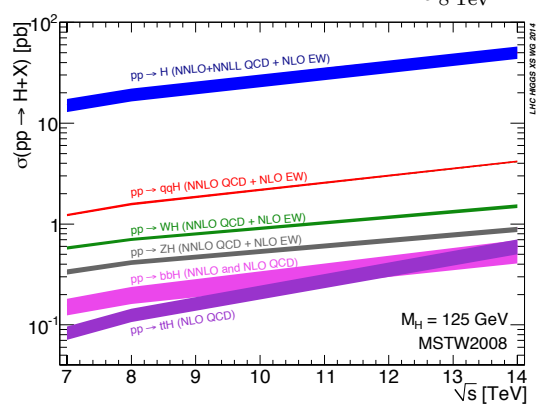


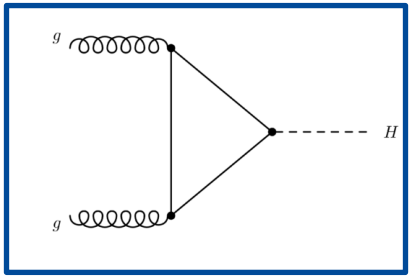


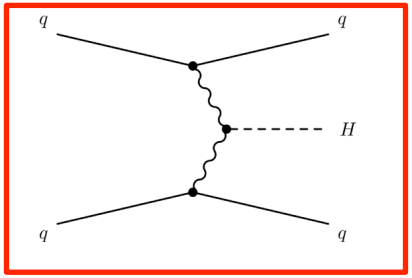
Introduction

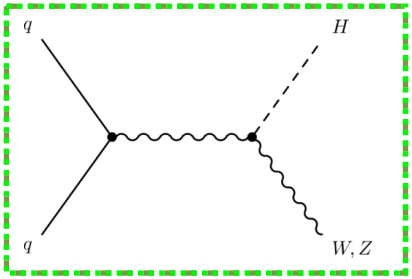
- Important production modes
  - gluon-fusion (ggF) (+jets)
    - experimentally accessible with leptonic decay modes:
      - background suppression, trigger
    - presence of extra jet lead to boost of H
  - vector boson fusion (VBF)
    - exploitable topology for background suppression:
      - decay products between “forward” jets
  - associated production with vector boson (VH)
    - use signature of associated vector boson for background suppression, trigger:
      - lepton(s), missing energy

most production modes $\frac{\sigma_{13\,\mathrm{TeV}}}{\sigma_{8\,\mathrm{TeV}}} \sim 2$









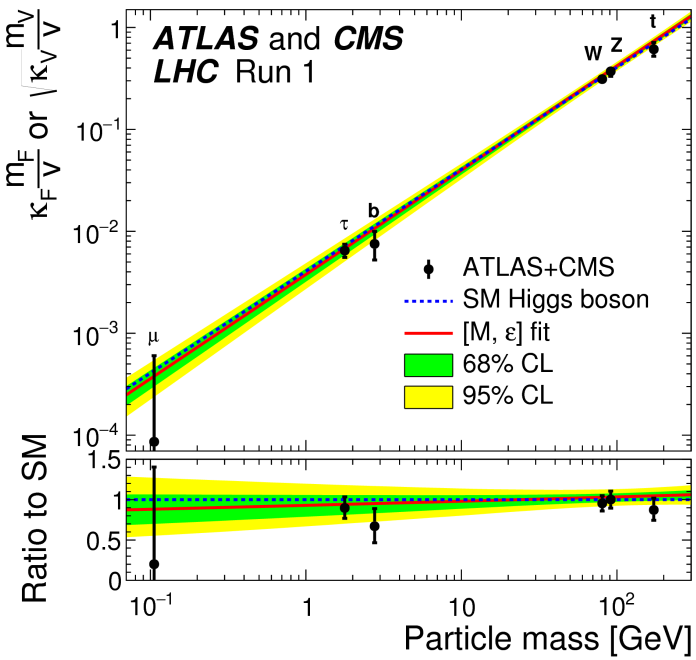
Introduction

- Cross section measurements
  - $H \to \tau\tau$ (run-1)
  - $VH, H \to \tau\tau$ (8 TeV)
  - VBF, $H \to b\bar{b}$ (8 TeV)
  - VBF+γ, $H \to b\bar{b}$ (13 TeV)
  - $VH, H \to b\bar{b}$ (13 TeV)
  - $H \to \mu\mu$ (13 TeV)
- Expressed in terms of signal strength μ

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

  - results can be interpreted as coupling strengths (in decay and/or production)

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

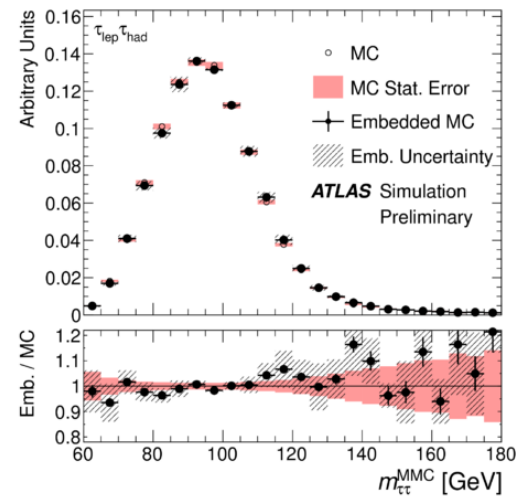


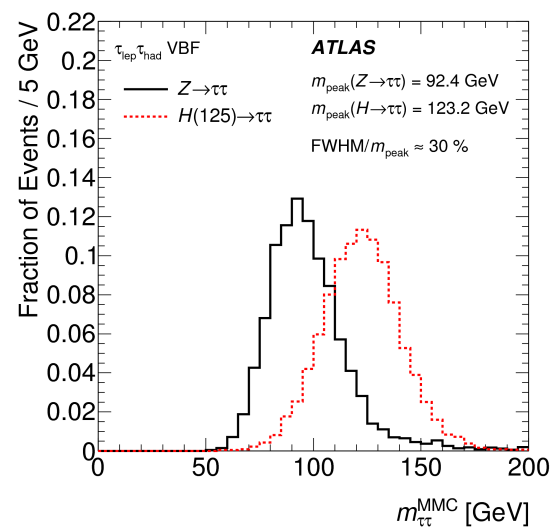
$H \to \tau\tau$

$H \to \tau\tau$

JHEP 04 (2015) 117

- Full run-1 dataset (4.5+20.3 fb^{-1})
- Using all tau decay modes: leplep, lephad, hadhad
  - leptonic modes: isolated leptons
  - hadronic modes: tau lepton identification using MVA
- Background modelling with data-driven methods
  - most important background $Z \to \tau\tau$: using $Z \to \mu\mu$ events and replace μ with simulated tau and tau decay
- Mass reconstruction with 2-4 neutrinos in final state (MMC)
  - reconstruct mass from most probable kinematic configuration of neutrinos using matrix element probability

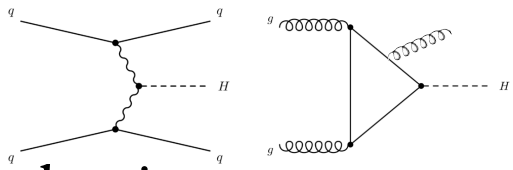




$H \to \tau\tau$

JHEP 04 (2015) 117

- Event categories optimised for VBF and ggF+jet production

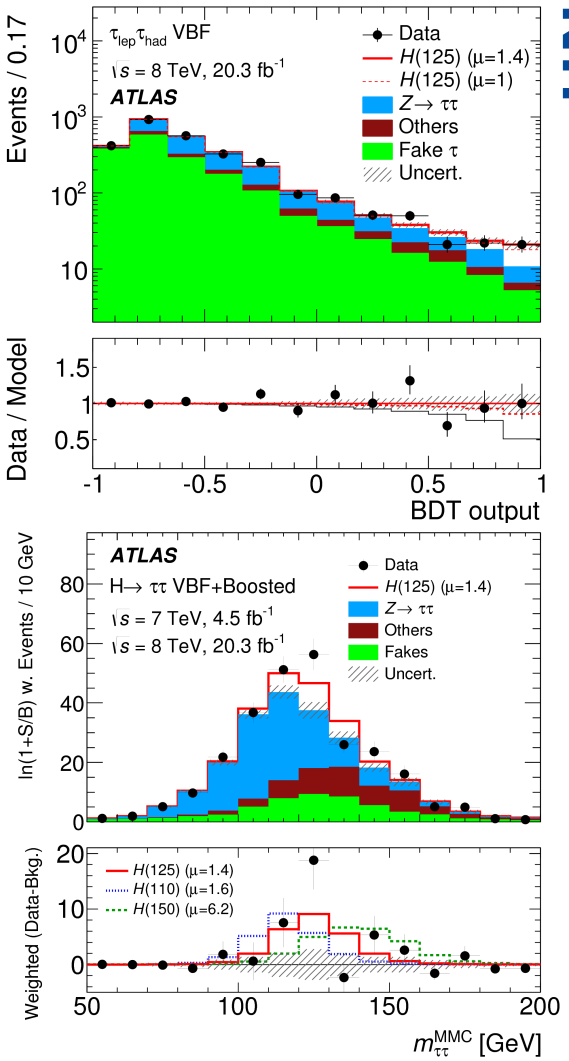


  - multivariate analysis: maximum likelihood fit to boosted decision tree (BDT) outputs
  - for each center-of-mass energy, signal/background region, channel and category
- Evidence for $H \to \tau\tau$ decay with 4.5σ significance

$$\mu = 1.43\ ^{+0.27}_{-0.26}(\text{stat.})\ ^{+0.32}_{-0.25}(\text{syst.})\ \pm 0.09(\text{theory syst.})$$

(m_H=125.36GeV)

- Combined ATLAS+CMS run-1 result 5.5σ significance

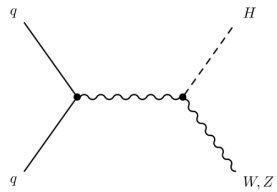


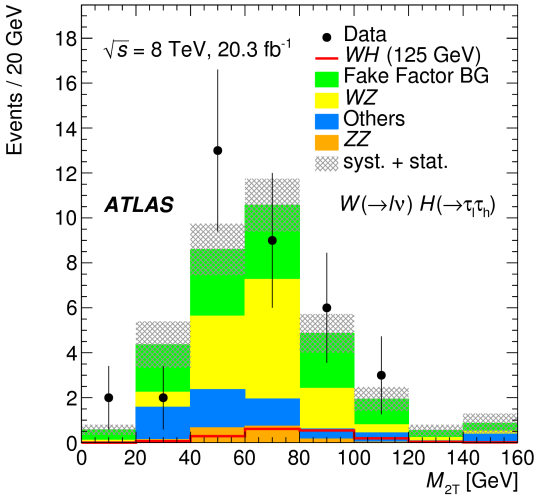
VH, $H \to \tau\tau$

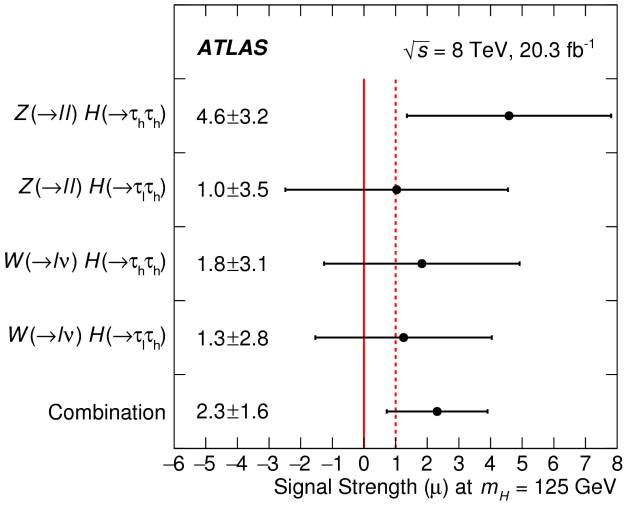
Phys. Rev. D 93

- Full 8 TeV dataset (20.3 fb^{-1})
- Exploit leptonic decay modes (l=e,μ) of W and Z
  - background suppression and triggering of event
- Analysis channels WH or ZH / lephad or hadhad with dedicated selections:
  - **for** $Z(\to ll)H$: opposite-charge, same-flavour leptons
  - **for** $W(\to l\nu)H$: one lepton, b-tag veto
  - **for** $H \to \tau\tau$ **hadhad**: opposite charged taus
  - **WH, lephad:** same charge e+μ, opposite charge tau
  - **ZH, lephad:** 3 same-flavour lepton: opposite-charge and same-flavour pair (Z), 3rd lepton (H) opposite charge to tau
- Mass reconstruction
  - MMC (ZH) or M_{2T} (WH): lower-bound on transverse tau-tau mass
- Fit to mass variable

  μ =2.3 ± 1.6, μ < 5.6 (exp. 3.5) @95%CL







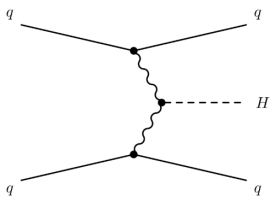
ATLAS EXPERIMENT

$$H \to b\bar{b}$$

VBF, $H \to b\bar{b}$

JHEP 11 (2016) 112

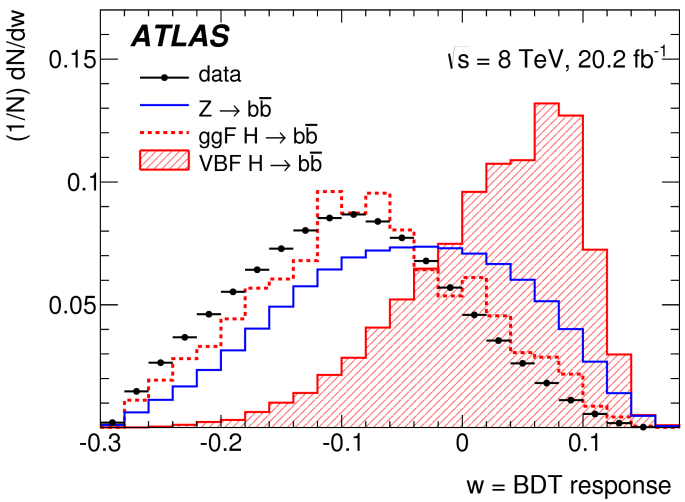
- Full 8 TeV dataset (20.2 fb^{-1})
- Selection of 2 jet + 2 b-jets events with VBF topology

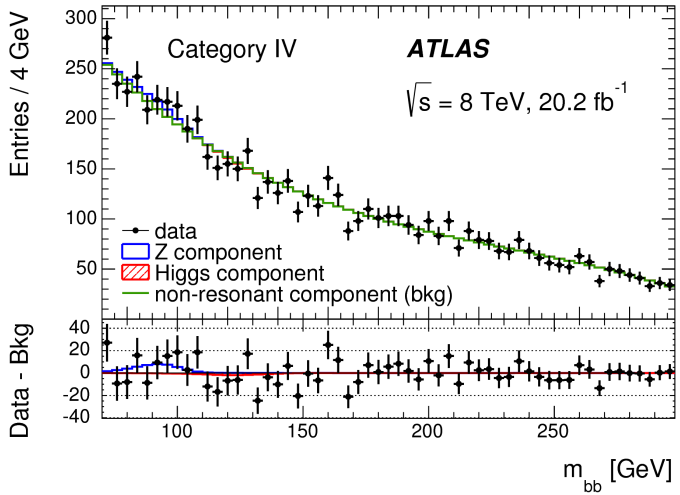


  - one or two b-tags required for triggering
  - high p_T of the $b\bar{b}$ system
- Multivariate analysis: BDT
  - fit to $m_{b\bar{b}}$ invariant mass spectrum in four categories defined by MVA
- More data beyond Run-1 needed to reach SM sensitivity

$\mu = -0.8 \pm 2.3$ and $\mu < 4.4$ (5.4) @95%CL

(m_H=125GeV)



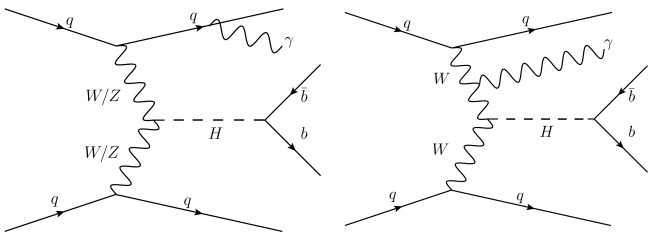


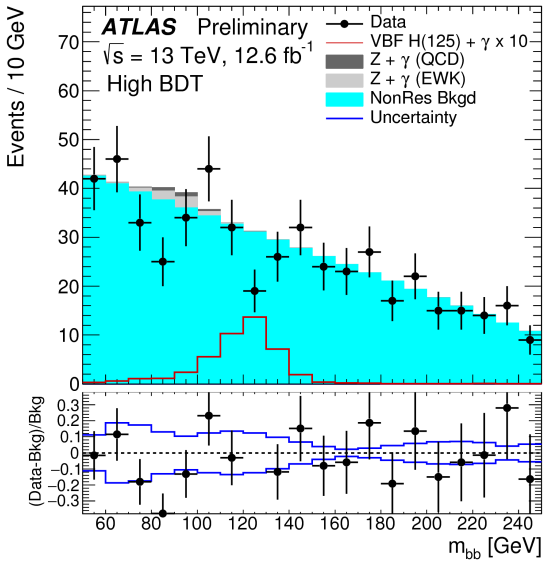
VBF+γ, $H \to b\bar{b}$

ATLAS-CONF-2016-063

- Run-2 13TeV using 12.6 fb^{-1}
- Better background suppression by additional high-p_T γ requirement
  - photon for triggering
  - suppression of non-resonant background
    - destructive interference of initial and final state photon radiation diagrams
- Event selection of 2 b-jets and 2 jets with high invariant di-jet mass
- Multivariate analysis: BDT
  - perform fit on $m_{b\bar{b}}$ in three regions by defined by BDT output

$\mu = -3.9^{+2.8}_{-2.7}$ and μ<4.0 @95%CL

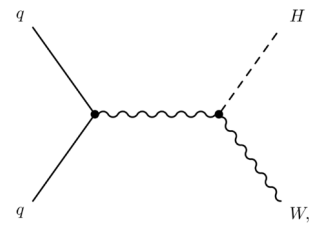


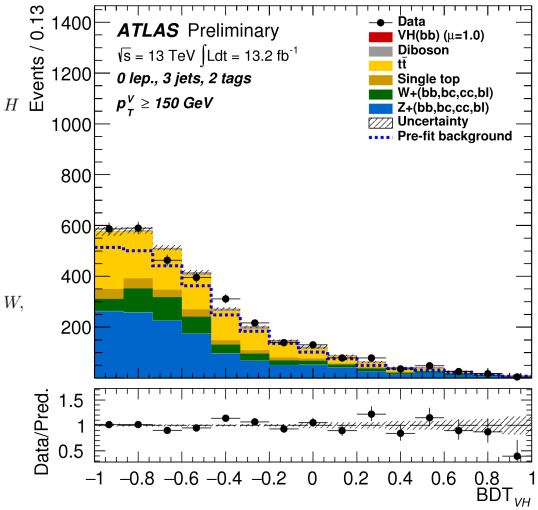


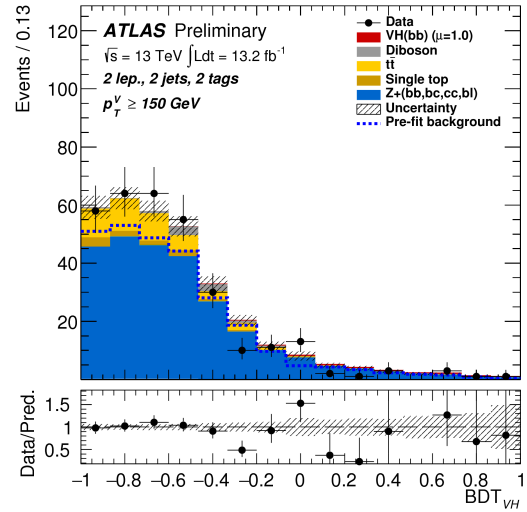
VH, $H \to b\bar{b}$

ATLAS-CONF-2016-091

- Run-2 13TeV using 13.2fb^{-1}
- Maximise sensitivity by event categorisation in events with 2 b-jets and
  - 0, 1 and 2 leptons (e, μ)
  - p_T^V >150 GeV for 0, 1 lepton events
  - two categories separated by p_T^V =150 GeV for 2 lep
  - $p_T^V = |\vec{E}_T^{miss}|$, $p_T(\vec{E}_T^{miss} + \text{lep})$, $p_T(2\ \text{lep})$
  - zero or one additional jet (inclusive for 2 lep events)
- Multivariate analysis (BDT) in each category



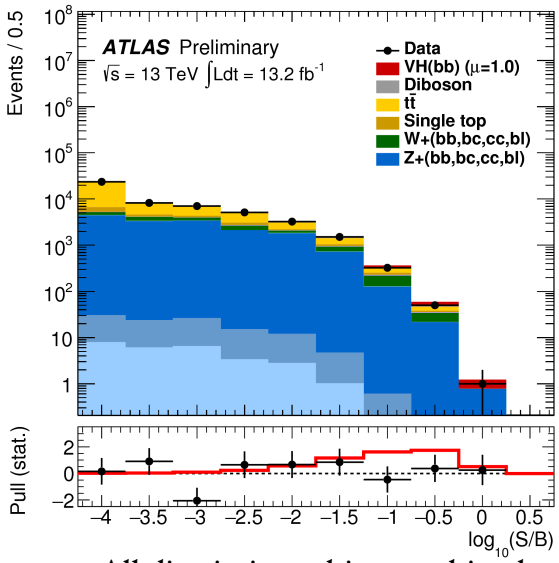




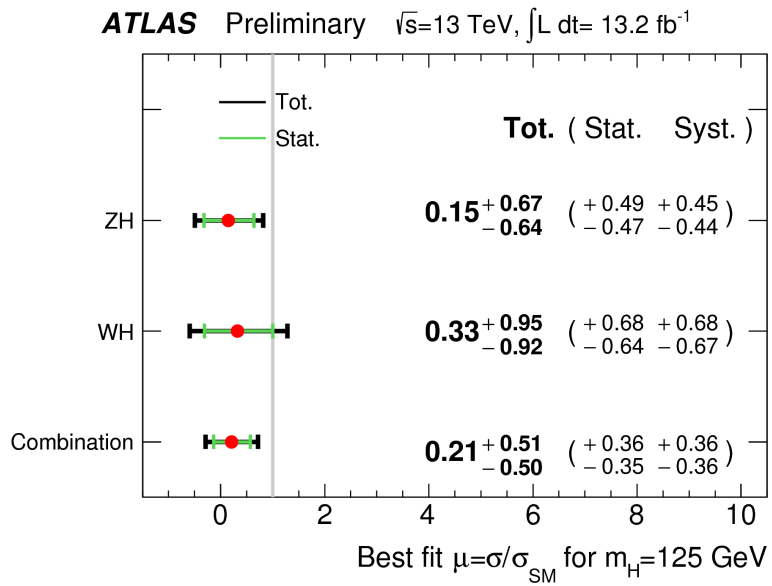
VH, $H \to b\bar{b}$

ATLAS-CONF-2016-091

- Simultaneous fit of all BDT outputs from all categories
  - Fit for signal strengths in each lepton category, for WH and ZH and all combined



All discriminant bins combined



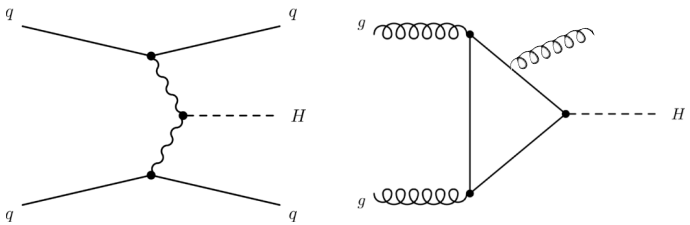
$\mu = 0.21^{+0.36}_{-0.35}(\text{stat.}) \pm 0.36(\text{syst.})$ with significance of 0.42 σ (exp. 1.94 σ) and μ<1.2 (exp. 1.0) @95%CL

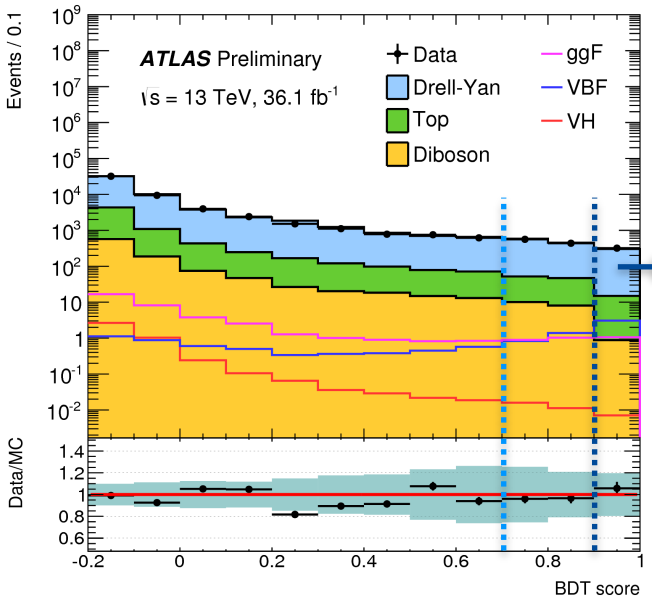
$H \to \mu\mu$

$H \to \mu\mu$

ATLAS-CONF-2017-014

- Run-2 13TeV using 36.1 fb^{-1}
- Search for opposite charged dimuon resonance in VBF and ggF production mode
- New for run-2: selection of VBF events with MVA (BDT)
- Events with b-jet veto categorised
  - in two VBF categories with BDT targeting VBF topology
  - in six ggF categories according to $p_T(\mu\mu)$ and $\eta(\mu)$
  - Most sensitivity from VBF tight category





VBF tight

$H \to \mu\mu$

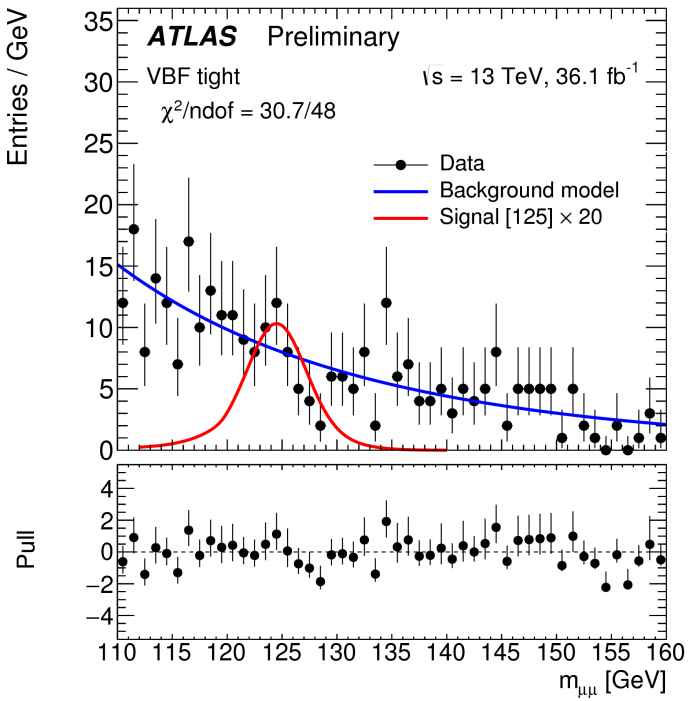
ATLAS-CONF-2017-014

- Parametric functions for signal and background pdfs for $m_{\mu\mu}$ distributions:
  - signal: Crystal-ball + Gaussian
  - purely data-driven background: exponential + BW + Gaussian for Z
- Simultaneous fit of $m_{\mu\mu}$ distributions in all eight categories

  $\mu = -0.07 \pm 1.5$ with $\mu < 3.0$ (3.1) @95%CL

- In combination with run-1 result:

  $\mu = -0.13 \pm 1.4$ with $\mu < 2.8$ (2.9) @95%CL

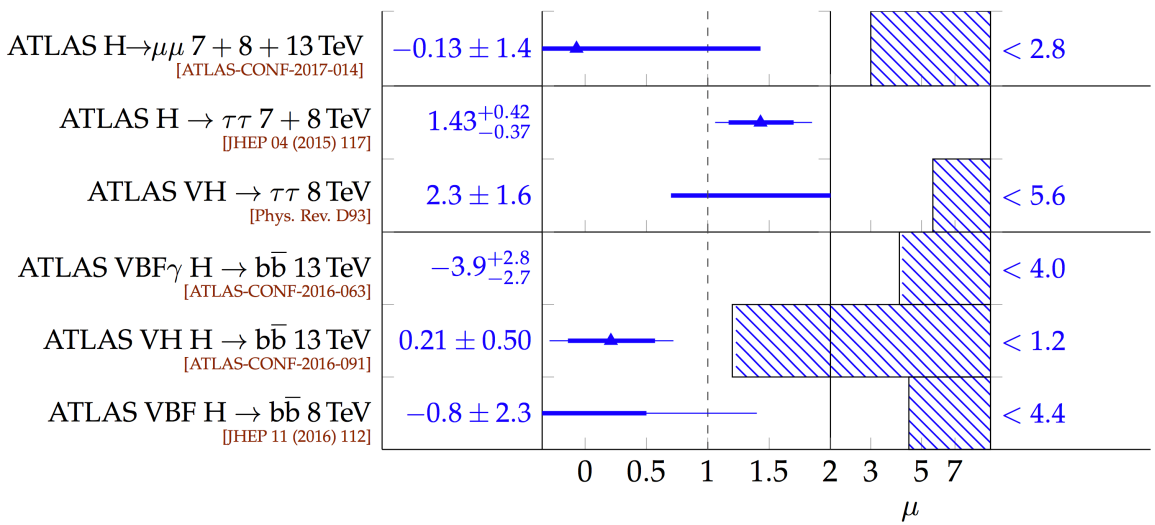


Summary

Summary

- Measurement with fermion decay channels still quite challenging
- New result with run-2 data on
  - $H \to b\bar{b}$, still no evidence with first run-2 (13 fb^{-1}) data
  - improved limits on $H \to \mu\mu$
  - improved measurement for $H \to \tau\tau$ in near future
- 13 TeV data expected to at least double this year

Summary of all measurement μ's and limits @95%CL shown here



Backup

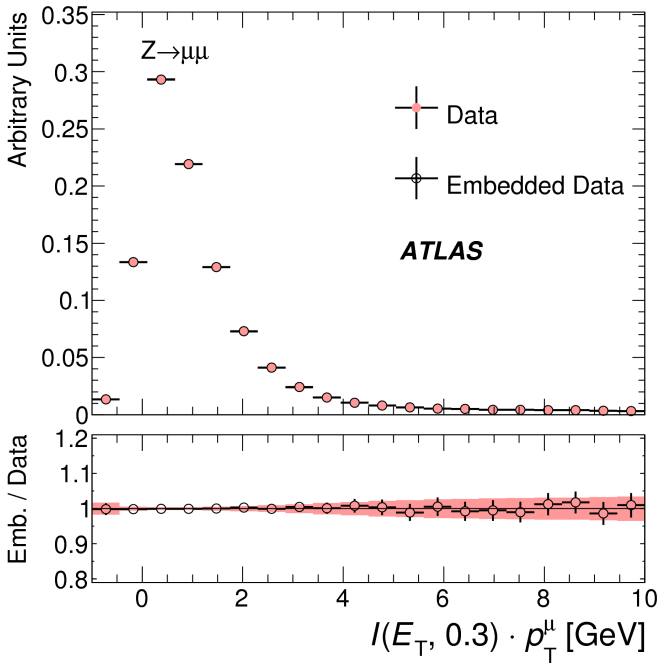
$H \to \tau\tau$

Signal ($m_H = 125$ GeV)	MC generator	$\sigma \times \mathcal{B}$ [pb] $\sqrt{s} = 8$ TeV		
ggF, $H \to \tau\tau$	POWHEG [42–45] + PYTHIA8 [46]	1.22	NNLO+NNLL	[48–53, 84]
VBF, $H \to \tau\tau$	POWHEG + PYTHIA8	0.100	(N)NLO	[57–59, 84]
WH, $H \to \tau\tau$	PYTHIA8	0.0445	NNLO	[62, 84]
ZH, $H \to \tau\tau$	PYTHIA8	0.0262	NNLO	[62, 84]
Background	**MC generator**	**$\sigma \times \mathcal{B}$ [pb] $\sqrt{s} = 8$ TeV**		
$W(\to \ell\nu)$, $(\ell = e, \mu, \tau)$	ALPGEN [77]+PYTHIA8	36800	NNLO	[85, 86]
$Z/\gamma^*(\to \ell\ell)$, 60 GeV$< m_{\ell\ell} <$ 2 TeV	ALPGEN+PYTHIA8	3910	NNLO	[85, 86]
$Z/\gamma^*(\to \ell\ell)$, 10 GeV$< m_{\ell\ell} <$ 60 GeV	ALPGEN+HERWIG [87]	13000	NNLO	[85, 86]
VBF $Z/\gamma^*(\to \ell\ell)$	SHERPA [88]	1.1	LO	[88]
$t\bar{t}$	POWHEG + PYTHIA8	$253^\dagger$	NNLO+NNLL	[89–94]
Single top : Wt	POWHEG + PYTHIA8	$22^\dagger$	NNLO	[95]
Single top : s-channel	POWHEG + PYTHIA8	$5.6^\dagger$	NNLO	[96]
Single top : t-channel	AcerMC [80]+PYTHIA6 [73]	$87.8^\dagger$	NNLO	[97]
$q\bar{q} \to WW$	ALPGEN+HERWIG	$54^\dagger$	NLO	[98]
$gg \to WW$	GG2WW [79]+HERWIG	$1.4^\dagger$	NLO	[79]
WZ, ZZ	HERWIG	$30^\dagger$	NLO	[98]
$H \to WW$	same as for $H \to \tau\tau$ signal	$4.7^\dagger$		

Channel	Preselection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	Exactly two isolated opposite-sign leptons Events with $\tau_{\rm had}$ candidates are rejected 30 GeV $< m_{\tau\tau}^{\rm vis} <$ 100 (75) GeV for DF (SF) events $\Delta\phi_{\ell\ell} < 2.5$ $E_{\rm T}^{\rm miss} >$ 20 (40) GeV for DF (SF) events $E_{\rm T}^{\rm miss,HPTO} >$ 40 GeV for SF events $p_{\rm T}^{\ell_1} + p_{\rm T}^{\ell_2} >$ 35 GeV Events with a b-tagged jet with $p_{\rm T} >$ 25 GeV are rejected $0.1 < x_{\tau_1}, x_{\tau_2} < 1$ $m_{\tau\tau}^{\rm coll} > m_Z -$ 25 GeV
$\tau_{\rm lep}\tau_{\rm had}$	Exactly one isolated lepton and one medium $\tau_{\rm had}$ candidate with opposite charges $m_{\rm T} <$ 70 GeV Events with a b-tagged jet with $p_{\rm T} >$ 30 GeV are rejected
$\tau_{\rm had}\tau_{\rm had}$	One isolated medium and one isolated tight opposite-sign $\tau_{\rm had}$-candidate Events with leptons are vetoed $E_{\rm T}^{\rm miss} >$ 20 GeV $E_{\rm T}^{\rm miss}$ points between the two visible taus in ϕ, or $\min[\Delta\phi(\tau, E_{\rm T}^{\rm miss})] < \pi/4$ $0.8 < \Delta R(\tau_{\rm had_1}, \tau_{\rm had_2}) < 2.4$ $\Delta\eta(\tau_{\rm had_1}, \tau_{\rm had_2}) < 1.5$
Channel	**VBF category selection cuts**
$\tau_{\rm lep}\tau_{\rm lep}$	At least two jets with $p_{\rm T}^{j_1} >$ 40 GeV and $p_{\rm T}^{j_2} >$ 30 GeV $\Delta\eta(j_1, j_2) > 2.2$
$\tau_{\rm lep}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} >$ 50 GeV and $p_{\rm T}^{j_2} >$ 30 GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{\rm vis} >$ 40 GeV
$\tau_{\rm had}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} >$ 50 GeV and $p_{\rm T}^{j_2} >$ 30 GeV $p_{\rm T}^{j_2} >$ 35 GeV for jets with $\lvert\eta\rvert > 2.4$ $\Delta\eta(j_1, j_2) > 2.0$
Channel	**Boosted category selection cuts**
$\tau_{\rm lep}\tau_{\rm lep}$	At least one jet with $p_{\rm T} >$ 40 GeV
All	Failing the VBF selection $p_{\rm T}^{H} >$ 100 GeV

$H \to \tau\tau$

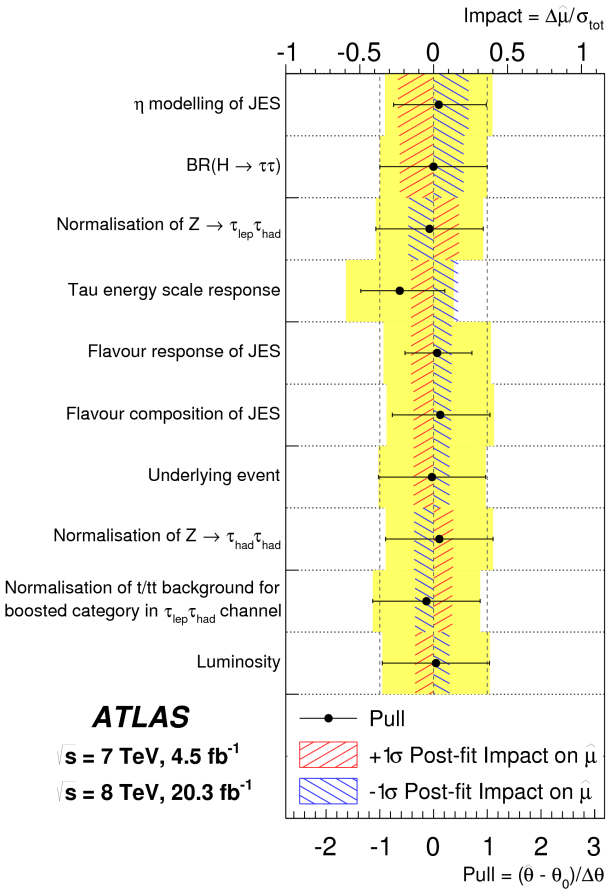
Variable	VBF			Boosted		
	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$m_{\tau\tau}^{\text{MMC}}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\text{T}}^{\text{Total}}$		•	•			
Sum p_{T}					•	•
$p_{\text{T}}^{\tau_1}/p_{\text{T}}^{\tau_2}$					•	•
$E_{\text{T}}^{\text{miss}}\phi$ centrality		•	•	•	•	•
m_{ℓ,ℓ,j_1}				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi(\ell_1, \ell_2)$				•		
Sphericity				•		
$p_{\text{T}}^{\ell_1}$				•		
$p_{\text{T}}^{j_1}$				•		
$E_{\text{T}}^{\text{miss}}/p_{\text{T}}^{\ell_2}$				•		
m_{T}		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\text{jets}})$	•					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	•					
$C_{\eta_1,\eta_2}(\eta_\ell)$		•				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	•					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			•			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			•			



$H \to \tau\tau$

Source	Relative signal and background variations [%]											
	$\tau_{lep}\tau_{lep}$ VBF		$\tau_{lep}\tau_{lep}$ Boosted		$\tau_{lep}\tau_{had}$ VBF		$\tau_{lep}\tau_{had}$ Boosted		$\tau_{had}\tau_{had}$ VBF		$\tau_{had}\tau_{had}$ Boosted	
	S	B	S	B	S	B	S	B	S	B	S	B
Experimental												
Luminosity	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1
Tau trigger*	–	–	–	–	–	–	–	–	$^{+7.7}_{-8.8}$	< 0.1	$^{+7.8}_{-8.9}$	< 0.1
Tau identification	–	–	–	–	± 3.3	± 1.2	± 3.3	± 1.8	± 6.6	± 3.8	± 6.6	± 5.1
Lepton ident. and trigger*	$^{+1.4}_{-2.1}$	$^{+1.3}_{-1.7}$	$^{+1.4}_{-2.1}$	$^{+1.1}_{-1.5}$	± 1.8	± 0.5	± 1.8	± 0.8	–	–	–	–
b-tagging	± 1.3	± 1.6	± 1.6	± 1.6	< 0.1	± 0.2	± 0.4	± 0.2	–	–	–	–
τ energy scale†	–	–	–	–	± 2.4	± 1.3	± 2.4	± 0.9	± 2.9	± 2.5	± 2.9	± 2.5
Jet energy scale and resolution†	$^{+8.5}_{-9.1}$	± 9.2	$^{+4.7}_{-4.9}$	$^{+3.7}_{-3.0}$	$^{+9.5}_{-8.7}$	± 1.0	± 3.9	± 0.4	$^{+10.1}_{-8.0}$	± 0.3	$^{+5.1}_{-6.2}$	± 0.2
E_T^{miss} soft scale & resolution	$^{+0.0}_{-0.2}$	$^{+0.0}_{-1.2}$	$^{+0.0}_{-0.1}$	$^{+0.0}_{-1.2}$	$^{+0.8}_{-0.3}$	± 0.2	± 0.4	< 0.1	± 0.5	± 0.2	± 0.1	< 0.1
Background Model												
Modelling of fake backgrounds*†	–	± 1.2	–	± 1.2	–	± 2.6	–	± 2.6	–	± 5.2	–	± 0.6
Embedding†	–	$^{+3.8}_{-4.3}$	–	$^{+6.0}_{-6.5}$	–	± 1.5	–	± 1.2	–	± 2.2	–	± 3.3
$Z \to \ell\ell$ normalisation*	–	± 2.1	–	± 0.7	–	–	–	–	–	–	–	–
Theoretical												
Higher-order QCD corrections†	$^{+11.3}_{-9.1}$	± 0.2	$^{+19.8}_{-15.3}$	± 0.2	$^{+9.7}_{-7.6}$	± 0.2	$^{+19.3}_{-14.7}$	± 0.2	$^{+10.7}_{-8.2}$	< 0.1	$^{+20.3}_{-15.4}$	< 0.1
UE/PS	± 1.8	< 0.1	± 5.9	< 0.1	± 3.8	< 0.1	± 2.9	< 0.1	± 4.6	< 0.1	± 3.8	< 0.1
Generator modelling	± 2.3	< 0.1	± 1.2	< 0.1	± 2.7	< 0.1	± 1.3	< 0.1	± 2.4	< 0.1	± 1.2	< 0.1
EW corrections	± 1.1	< 0.1	± 0.4	< 0.1	± 1.3	< 0.1	± 0.4	< 0.1	± 1.1	< 0.1	± 0.4	< 0.1
PDF†	$^{+4.5}_{-5.8}$	± 0.3	$^{+6.2}_{-8.0}$	± 0.2	$^{+3.9}_{-3.6}$	± 0.2	$^{+6.6}_{-6.1}$	± 0.2	$^{+4.3}_{-4.0}$	± 0.2	$^{+6.3}_{-5.8}$	± 0.1
BR ($H \to \tau\tau$)	± 5.7	–	± 5.7	–	± 5.7	–	± 5.7	–	± 5.7	–	± 5.7	–

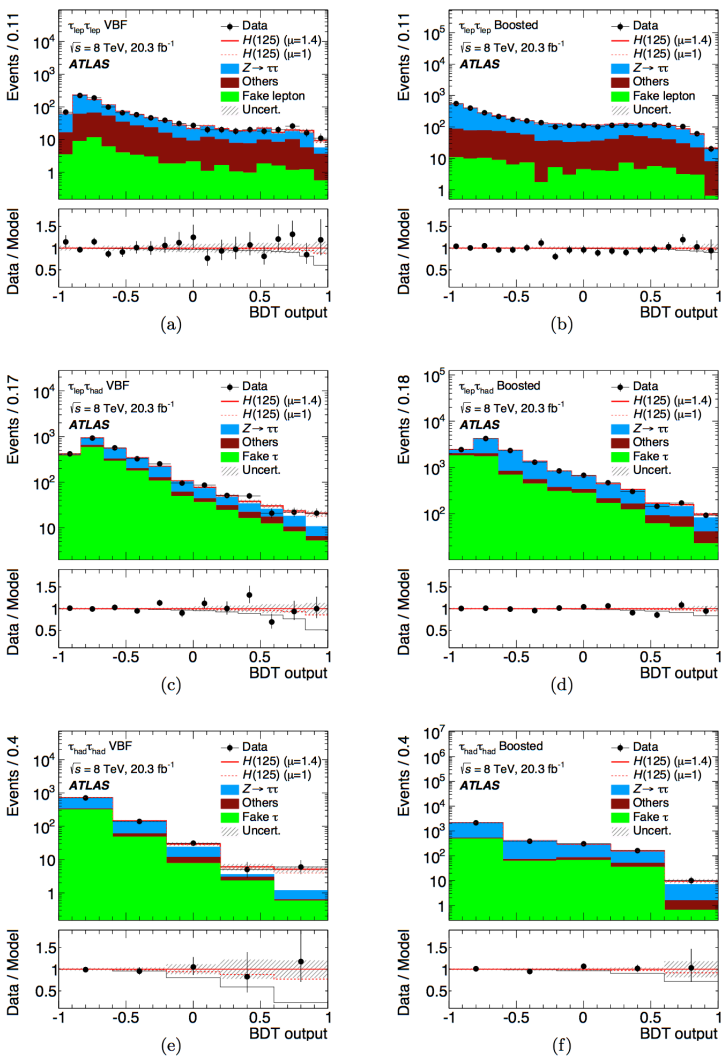
$H \rightarrow \tau\tau$

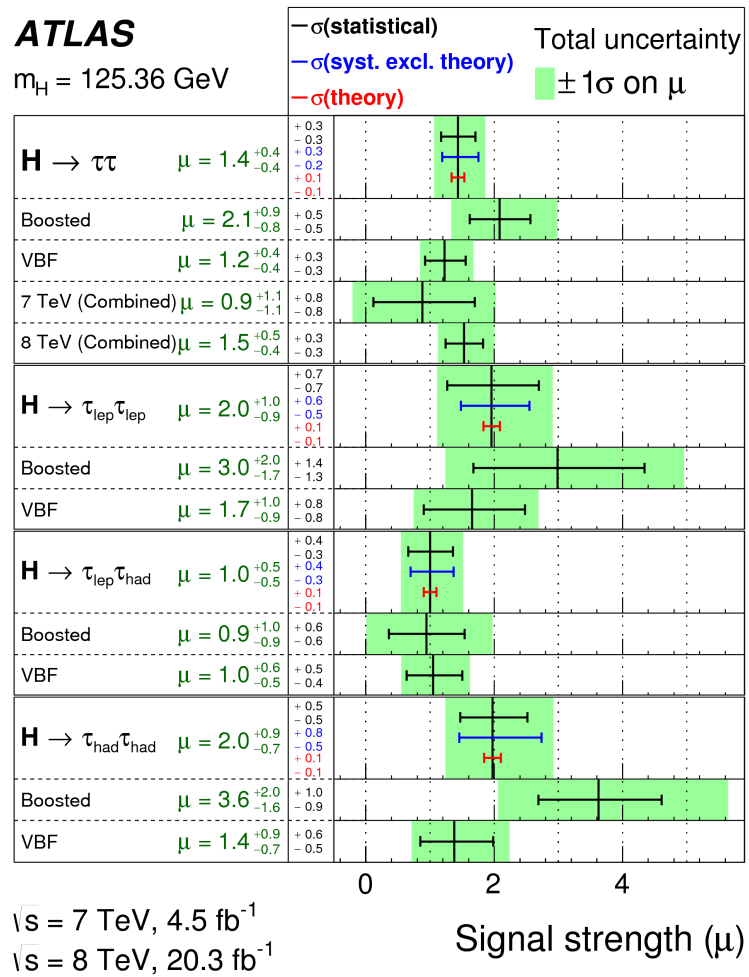


Channel and Category	Expected Significance (σ)	Observed Significance (σ)
$\tau_{lep}\tau_{lep}$ VBF	1.15	1.88
$\tau_{lep}\tau_{lep}$ Boosted	0.57	1.72
$\tau_{lep}\tau_{lep}$ Total	1.25	2.40
$\tau_{lep}\tau_{had}$ VBF	2.11	2.23
$\tau_{lep}\tau_{had}$ Boosted	1.11	1.01
$\tau_{lep}\tau_{had}$ Total	2.33	2.33
$\tau_{had}\tau_{had}$ VBF	1.70	2.23
$\tau_{had}\tau_{had}$ Boosted	0.82	2.56
$\tau_{had}\tau_{had}$ Total	1.99	3.25
Combined	3.43	4.54

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	$^{+0.27}_{-0.26}$
Jet energy scale	$\pm$ 0.13
Tau energy scale	$\pm$ 0.07
Tau identification	$\pm$ 0.06
Background normalisation	$\pm$ 0.12
Background estimate stat.	$\pm$ 0.10
BR ($H \rightarrow \tau\tau$)	$\pm$ 0.08
Parton shower/Underlying event	$\pm$ 0.04
PDF	$\pm$ 0.03
Total sys.	$^{+0.33}_{-0.26}$
Total	$^{+0.43}_{-0.37}$

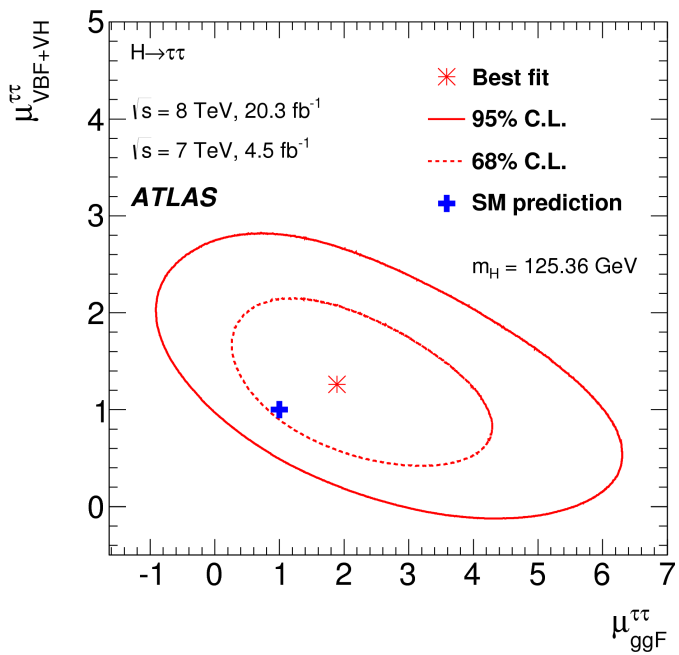
$H \rightarrow \tau\tau$

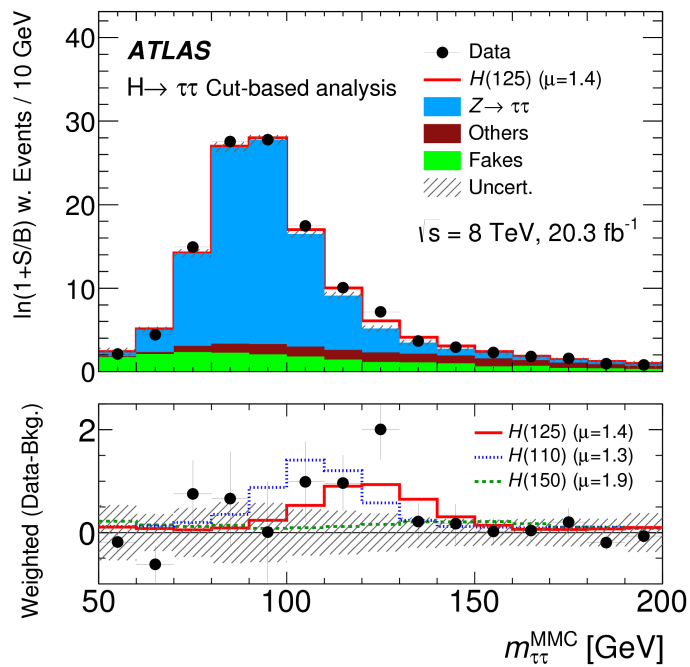




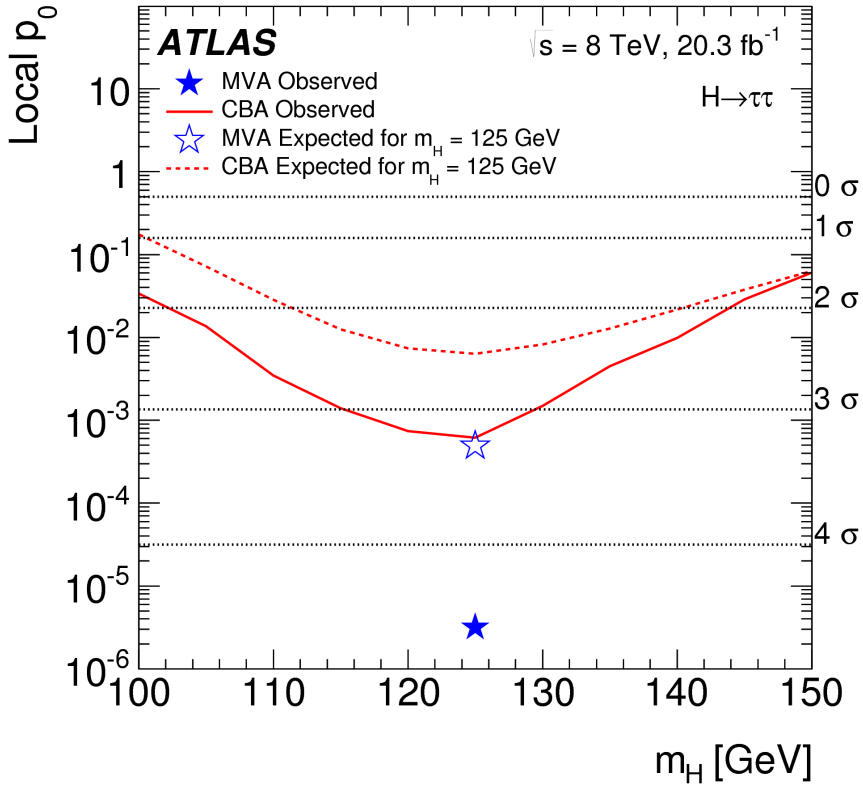
$H \to \tau\tau$

	Measured $\sigma\times$BR [pb]	Predicted $\sigma\times$BR [pb]
7 TeV	$1.0\ ^{+0.9}_{-0.8}(\text{stat.})^{+0.9}_{-0.8}(\text{syst.})$	1.09 ± 0.11
8 TeV	$2.1 \pm 0.4(\text{stat.})^{+0.5}_{-0.4}(\text{syst.})$	1.39 ± 0.14
Gluon fusion, 8 TeV	$1.7 \pm 1.1(\text{stat.})^{+1.5}_{-1.1}(\text{syst.})$	1.22 ± 0.14
VBF+VH, 8 TeV	$0.26 \pm 0.09(\text{stat.})^{+0.06}_{-0.05}(\text{syst.})$	0.17 ± 0.01





$H \rightarrow \tau\tau$

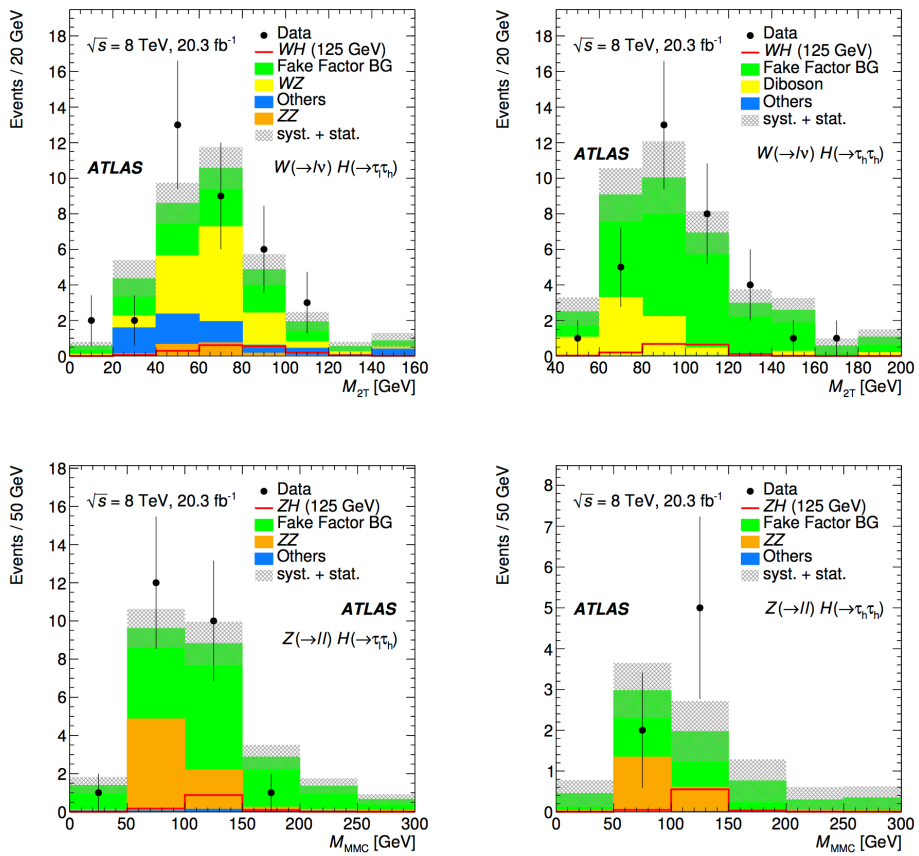


VH, $H \to \tau\tau$

Channel	Selections
$W \to \mu\nu/e\nu$, $H \to \tau_{\text{lep}}\tau_{\text{had}}$	Exactly one isolated electron and one isolated muon Exactly one τ_{had} passing medium BDT ID $p_{\text{T}}(\tau_{\text{had}}) > 25$ GeV Same-charge e and μ, oppositely charged τ_{had} Events containing b-tagged jets with $p_{\text{T}} > 30$ GeV are vetoed $\lvert p_{\text{T}}(\tau_{\text{had}})\rvert + \lvert p_{\text{T}}(\mu)\rvert + \lvert p_{\text{T}}(e)\rvert > 80$ GeV $\Delta R(\tau_{\text{had}}, \tau_{\text{lep}}) < 3.2$
$W \to \mu\nu/e\nu$, $H \to \tau_{\text{had}}\tau_{\text{had}}$	Exactly one isolated electron or one isolated muon Exactly two τ_{had} passing medium BDT ID of opposite charge $p_{\text{T}}(\tau_{\text{had}}) > 20$ GeV $\lvert p_{\text{T}}(\tau^1_{\text{had}})\rvert + \lvert p_{\text{T}}(\tau^2_{\text{had}})\rvert > 100$ GeV $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) > 20$ GeV $0.8 < \Delta R(\tau^1_{\text{had}}, \tau^2_{\text{had}}) < 2.8$ Events containing b-tagged jets with $p_{\text{T}} > 30$ GeV are vetoed
$Z \to \mu\mu/ee$, $H \to \tau_{\text{lep}}\tau_{\text{had}}$	Exactly three electrons or muons, One opposite-charge and same-flavor lepton pair with invariant mass $80 < m_{\ell\ell} < 100$ GeV Exactly one τ_{had} passing medium BDT ID, with opposite charge to the lepton assigned to the Higgs boson $p_{\text{T}}(\tau_{\text{had}}) > 20$ GeV $\lvert p_{\text{T}}(\tau_{\text{had}})\rvert + \lvert p_{\text{T}}(\tau_{\text{lep}})\rvert > 60$ GeV
$Z \to \mu\mu/ee$, $H \to \tau_{\text{had}}\tau_{\text{had}}$	Exactly two electrons or two muons of opposite charge Exactly two τ_{had} passing medium BDT ID of opposite charge $p_{\text{T}}(\tau_{\text{had}}) > 20$ GeV $60 < m_{\ell\ell} < 120$ GeV $\lvert p_{\text{T}}(\tau^1_{\text{had}})\rvert + \lvert p_{\text{T}}(\tau^2_{\text{had}})\rvert > 88$ GeV

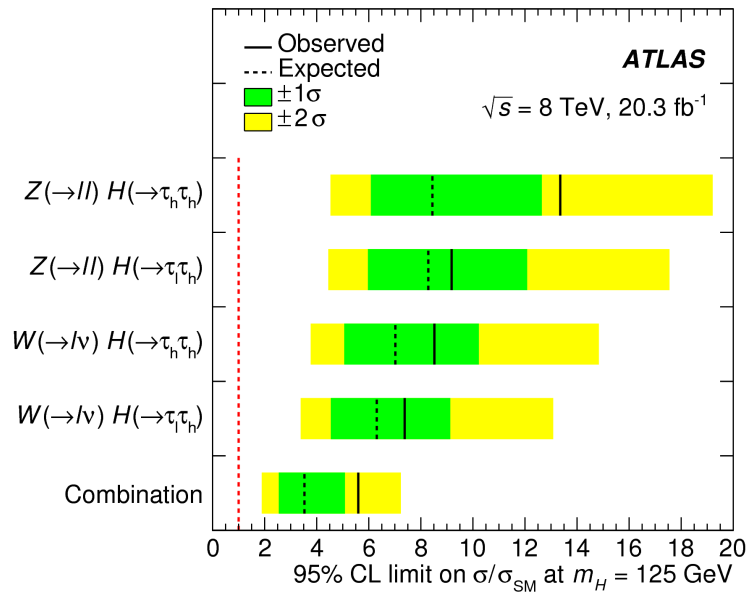
VH, $H \to \tau\tau$

Channel	Obs.	Signal	Σ Background	Fake Factor	Diboson	Other
$W \to \mu\nu/e\nu,\ \ H \to \tau_{\text{lep}}\tau_{\text{had}}$	35	1.95 ± 0.05	32.4 ± 1.9	13.1 ± 1.3	13.54 ± 0.35	5.7 ± 1.4
$W \to \mu\nu/e\nu,\ \ H \to \tau_{\text{had}}\tau_{\text{had}}$	33	1.84 ± 0.04	35.5 ± 2.7	28.1 ± 2.4	7.4 ± 1.2	-
$Z \to \mu\mu/ee,\ \ H \to \tau_{\text{lep}}\tau_{\text{had}}$	24	1.14 ± 0.03	24.6 ± 1.5	17.1 ± 1.5	7.28 ± 0.16	0.20 ± 0.01
$Z \to \mu\mu/ee,\ \ H \to \tau_{\text{had}}\tau_{\text{had}}$	7	0.64 ± 0.02	6.8 ± 1.2	4.7 ± 1.2	2.09 ± 0.09	0.012 ± 0.003



VH, $H \to \tau\tau$

Source	Impact on event yield [%]	Impact on μ
Experimental		
Luminosity	± 2.8	± 0.30
Tau identification	± 2–6	± 0.41
Lepton identification and trigger	± 1–1.8	± 0.15
b-tagging	±2	± 0.16
τ energy scale	± 0– 2.9	± 0.57
Jet energy scale and resolution	± 4	-
E_T^{miss} soft scale & resolution	± 0.1–0.5	-
Background Model		
Modeling of BG from misidentified jets	± 15 – 38	± 0.72
Theoretical		
Higher-order QCD corrections	± 2–8	± 0.26
Underlying event/parton shower modeling	± 1–4	± 0.07
Generator modeling	± 1.4	± 0.05
EW corrections	± 2	± 0.06
PDF	± 3-4	± 0.18
$\mathcal{B}(H \to \tau\tau)$	± 3-7	± 0.17



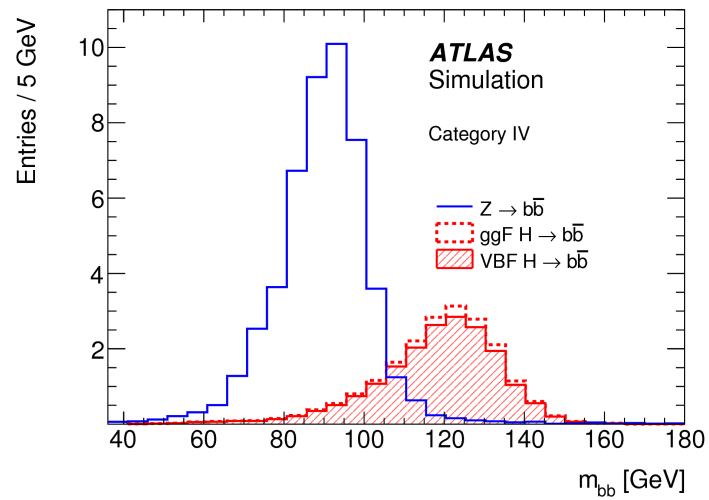
Channel	Expected significance	Observed significance
$W \to \mu\nu/e\nu,\ H \to \tau_{lep}\tau_{had}$	0.36 σ	0.44 σ
$W \to \mu\nu/e\nu,\ H \to \tau_{had}\tau_{had}$	0.32 σ	0.60 σ
$Z \to \mu\mu/ee,\ H \to \tau_{lep}\tau_{had}$	0.28 σ	0.29 σ
$Z \to \mu\mu/ee,\ H \to \tau_{had}\tau_{had}$	0.32 σ	1.38 σ

VBF, $H \to b\bar{b}$

Process	Cross-section × BR [pb]	Acceptance
VBF $H \to b\bar{b}$	0.9	6.9×10^{-3}
ggF $H \to b\bar{b}$	11.1	4.2×10^{-4}
$Z \to b\bar{b}$ + 1, 2, or 3 partons	5.9×10^{2}	3.1×10^{-4}

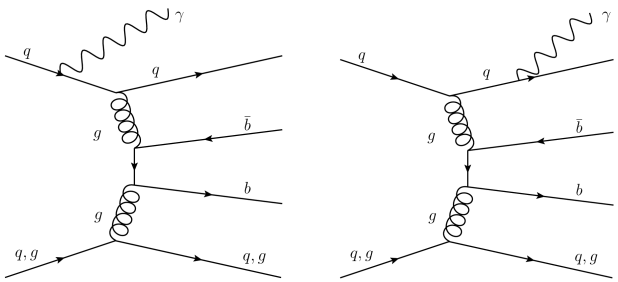
Process	Pre-selection	Category I (−0.08 to 0.01)	Category II (0.01 to 0.06)	Category III (0.06 to 0.09)	Category IV (> 0.09)
VBF $H \to b\bar{b}$	130	39	33	23	19
ggF $H \to b\bar{b}$	94	31	8.5	3.8	1.6
$Z \to b\bar{b}$	3700	1100	350	97	49
Data	554302	176073	46912	15015	6493

	category I	category II	category III	category IV
Nominal	4th Pol.	3rd Pol.	3rd Pol.	3rd Pol.
Alternative	2nd Pol. × exponential	3 exponentials	2 exponentials	exponential

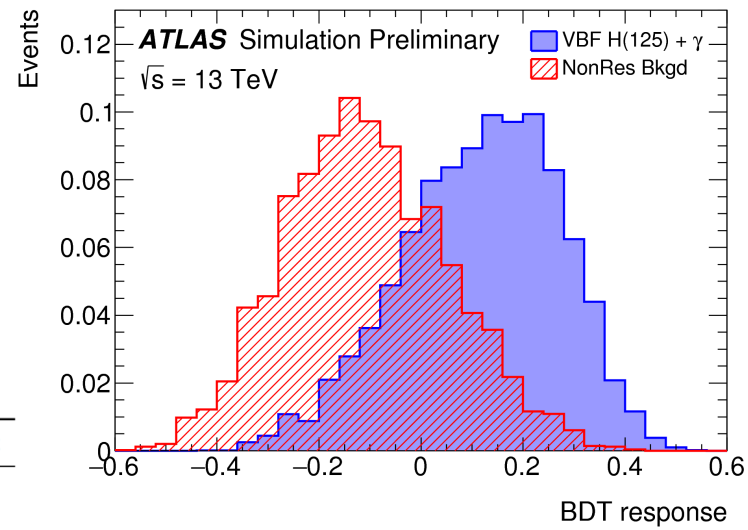


Source of uncertainty		Uncertainty on μ	
		MVA	Cut-based
Experimental uncertainties	Detector-related	$+0.2/-0.3$	$+1.6/-1.2$
	MC statistics	± 0.4	± 0.1
Theoretical uncertainties	MC signal modelling	± 0.1	± 1.3
	Z yield	$+0.6/-0.5$	± 1.4
Non-resonant background modelling	Choice of function	± 1.0	± 1.0
	Sideband statistics	± 1.7	± 3.7
Statistical uncertainties		± 1.3	
Total		± 2.3	$+4.6/-4.4$

VBF+γ, $H \to b\bar{b}$



https://arxiv.org/abs/hep-ph/0702119



Uncertainty source	Uncertainty $\Delta\mu$
Non-resonant background uncertainty in medium-BDT region	0.22
Non-resonant background uncertainty in high-BDT region	0.21
Non-resonant background uncertainty in low-BDT region	0.17
Parton shower uncertainty on $H + \gamma$ acceptance	0.16
QCD scale uncertainty on $H + \gamma$ cross section	0.13
Jet energy uncertainty from calibration across η	0.10
Jet energy uncertainty from flavour composition in calibration	0.09
Integrated luminosity uncertainty	0.08

Result	$H(\to b\bar{b}) + \gamma jj$
Expected significance	0.4
Expected p-value	0.4
Observed p-value	0.9
Expected limit	$6.0\ ^{+2.3}_{-1.7}$
Observed limit	4.0
Observed signal strength μ	$-3.9\ ^{+2.8}_{-2.7}$

VH, $H \to b\bar{b}$

Selection	0-lepton	1-lepton	2-lepton
Trigger	E_T^{miss}	E_T^{miss} (μ sub-channel)	
		Lowest unprescaled single lepton	
Leptons	0 loose lepton	1 tight lepton	2 loose leptons ($\geq$ 1 medium lepton)
Lepton pair	-	-	Same flavour opposite-charge for $\mu\mu$
E_T^{miss}	> 150 GeV	> 30 GeV (e sub-channel)	-
m_{ll}	-	-	$71 < m_{ll} < 121$ GeV
S_T	> 120 (2 jets), >150 GeV (3 jets)	-	-
Jets	Exactly 2 or 3 signal jets		Exactly 2 or $\geq$ 3 signal jets
b-jets	2 b-tagged signal jets		
Leading jet p_T	> 45 GeV		
min$\Delta\phi(E_T^{miss}, \text{jet})$	> 20°	-	-
$\Delta\phi(E_T^{miss}, h)$	> 120°	-	-
$\Delta\phi$(jet1,jet2)	< 140°	-	-
$\Delta\phi(E_T^{miss}, E_{T,trk}^{miss})$	< 90°	-	-
p_T^V regions	[0, 150] GeV (2-lepton), [150, ∞] GeV		

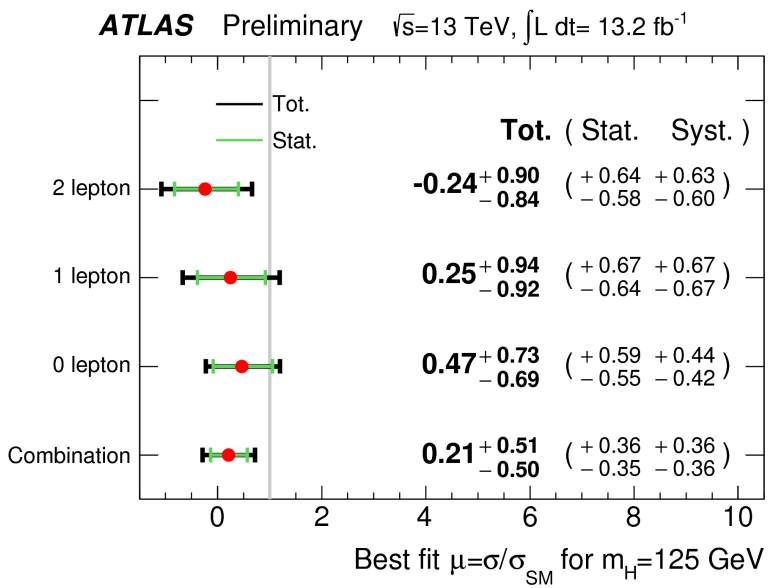
Variable	0-lepton	1-lepton	2-lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
H_T	×		
min$[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
m_{ll}			×
m_{Top}		×	
$\lvert\Delta Y(V, H)\rvert$		×	
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

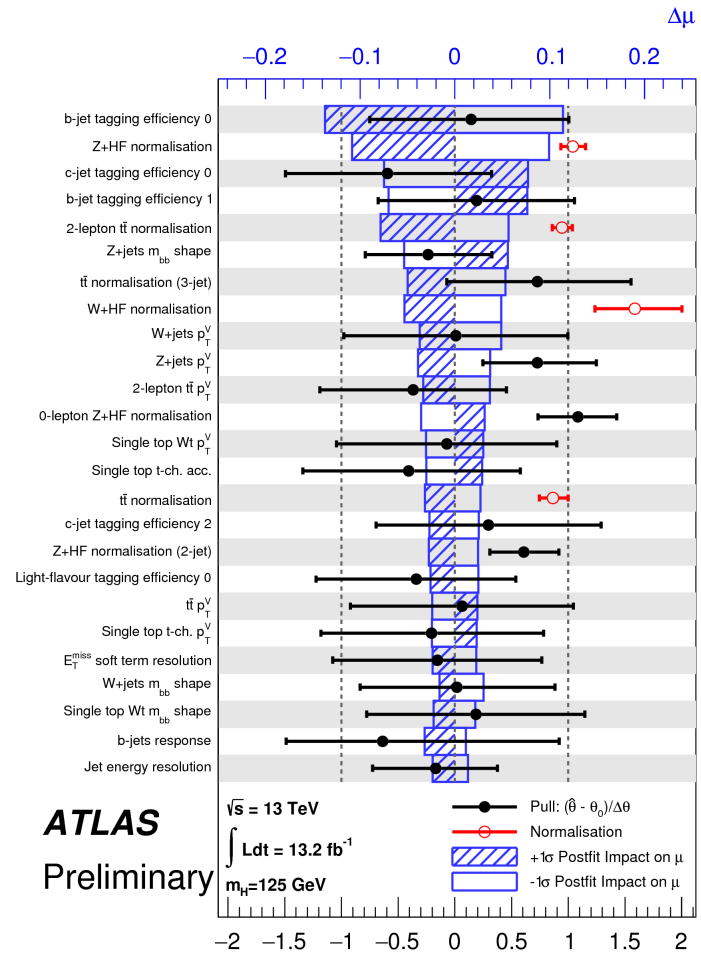
VH, $H \to b\bar{b}$

Sample	0-lepton		1-lepton		2-lepton			
	$p_T^V > 150$ GeV, 2-tag		$p_T^V > 150$ GeV, 2-tag		$p_T^V < 150$ GeV, 2-tag		$p_T^V > 150$ GeV, 2-tag	
	2-jet	3-jet	2-jet	3-jet	2-jet	3-jet	2-jet	3-jet
$Z + l$	1.5±0.1	3.3±2.2	–	–	4.6±0.1	15.4±0.5	0.4±0.0	2.9±0.1
$Z + cl$	4.2±1.8	6.7±2.6	0.9±0.6	–	13.9±5.9	49±21	1.0±0.4	10.0±4.3
Z + HF	864±49	1300±90	29.0±3.0	65.7±3.7	4000±120	8250±300	260±14	1192±49
$W + l$	2.3±1.5	3.8±2.2	4.3±0.1	9.6±0.3	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
$W + cl$	3.7±1.8	7.4±3.5	20±11	33±17	0.0±0.0	0.5±0.0	0.0±0.0	0.0±0.0
W + HF	184±37	440±96	741±114	1610±300	1.2±0.3	42±10	0.4±0.1	1.3±0.3
Single-top	45.5±7.7	204±39	331±55	1590±300	139±39	400±130	10.5±3.0	44±14
Multi-jet	–	–	101±63	210±140	–	–	–	–
$t\bar{t}$	136±14	1081±67	886±82	7520±360	4080±120	12210±340	42.3±4.3	402±36
Diboson	56±17	65±16	39±10	68±16	121±32	190±36	8.3±2.3	46.6±8.4
Total bkg.	1297±35	3110±52	2152±48	11120±110	8358±92	21150±150	322±13	1698±38
$VH(bb)$ (fit)	3.7±8.7	4.3±10.3	4.2±10.1	5.0±12.0	4.2±10.0	6.2±14.9	0.9±2.2	2.5±5.9
Data	1313	3120	2145	11124	8365	21163	316	1700

VH, $H \to b\bar{b}$

Dataset	Limit		p_0		Significance	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
0-lepton	$1.4^{+0.6}_{-0.4}$	2.0	0.07	0.15	1.45	1.02
1-lepton	$2.0^{+0.8}_{-0.6}$	2.1	0.15	0.46	1.04	0.10
2-lepton	$1.8^{+0.7}_{-0.5}$	1.7	0.13	0.57	1.14	−0.17
Combined	$1.0^{+0.4}_{-0.3}$	1.2	0.03	0.34	1.94	0.42





$H \to \mu\mu$

	Signal	Background	$S/\sqrt{B}$	Data
Central low $p_T^{\mu\mu}$	10.7	9406	0.11	9822
Non-central low $p_T^{\mu\mu}$	28.9	35728	0.15	38438
Central medium $p_T^{\mu\mu}$	24.5	7802	0.28	8199
Non-central medium $p_T^{\mu\mu}$	65.1	30605	0.37	30497
Central high $p_T^{\mu\mu}$	18.6	3685	0.31	3526
Non-central high $p_T^{\mu\mu}$	44.1	11587	0.41	11595
VBF loose	3.4	239	0.22	245
VBF tight	3.4	64	0.43	75