Measurements of VHbb with the ATLAS detector

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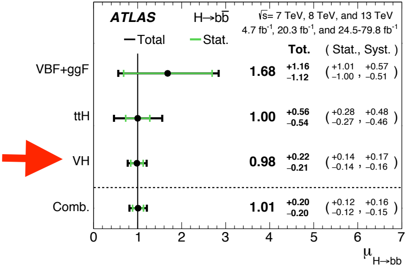
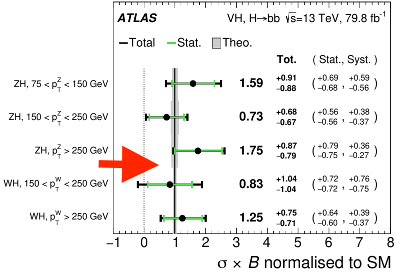
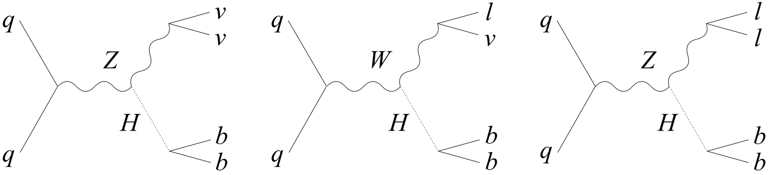
Introduction





- Observation of Hbb (left) and STXS at 80 fb-1 (right) [HIGG-2018-04] [HIGG-2018-50]
- Resolved VHbb full Run2 140 fb-1 results are presented [HIGG-2018-51] [HIGG-2018-52]

Analysis overview



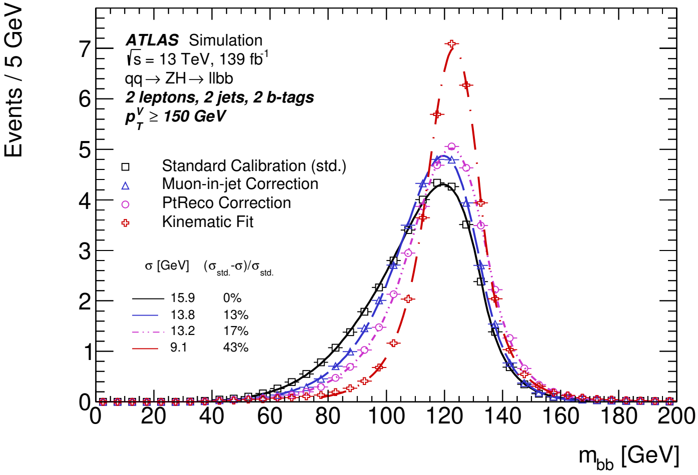
- Channels: 0-lepton (left), 1-lepton (middle), 2-lepton (right)
- Backgrond: V+jets, ttbar, single top, diboson, multi-jet
- b-jet energy correction to improve the Higgs mass resolution
- Multivariate analysis: BDT(VH) for the main results, BDT(VZ) and mBB(VH) as croscheck results

Event selection and categorization

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	Exactly 1 *tight* electron 0 additional *loose* leptons $p_{\mathrm{T}} > 27$ GeV	Exactly 1 *tight* muon 0 additional *loose* leptons $p_{\mathrm{T}} > 25$ GeV	Exactly 2 *loose* leptons $p_{\mathrm{T}} > 27$ GeV Same-flavour Opposite-sign charges ($\mu\mu$)
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–	–	81 GeV $< m_{\ell\ell} <$ 101 GeV
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			
Jet categories	Exactly 2 / Exactly 3 jets	Exactly 2 / Exactly 3 jets		Exactly 2 / ≥ 3 jets
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)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120^{\circ}$	–		–
$\Delta\phi(\vec{b_1}, \vec{b_2})$	$< 140^{\circ}$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^{\circ}$	–		–
p_{T}^{V} regions	– 150 GeV $< p_{\mathrm{T}}^{V} <$ 250 GeV $p_{\mathrm{T}}^{V} > 250$ GeV	– 150 GeV $< p_{\mathrm{T}}^{V} <$ 250 GeV $p_{\mathrm{T}}^{V} > 250$ GeV		75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV 150 GeV $< p_{\mathrm{T}}^{V} <$ 250 GeV $p_{\mathrm{T}}^{V} > 250$ GeV
Signal regions	$\Delta R(\vec{b_1}, \vec{b_2})$ signal selection			
Control regions	High and low $\Delta R(\vec{b_1}, \vec{b_2})$ side-bands			

- New SR/CR definition using pTV dependent dRBB cut
- New pTV split at 250 GeV for the STXS

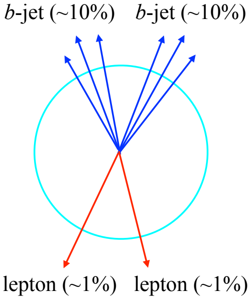
b-jet energy corrections



- 10–40% gain in the Higgs mass resolution by muon-in-jet correction, pT dependent correction, and Kinematic Fit

Kinematic Fit

- Constrains llbb system to be balanced in the transverse plane and improve b-jet energy correction



$$-2\ln L =$$ ← Maximize likelihood

$$\Sigma_i \frac{(p_\mathrm{T} - p_\mathrm{T}^\mathrm{fit})}{\sigma^2}$$ ← Leptons, 3rd jet, MET soft term: Gaussian

$$-\Sigma_j 2\ln L(p_\mathrm{T}, p_\mathrm{T}^{fit})$$ ← *b*-jets: Trasnfer Functions

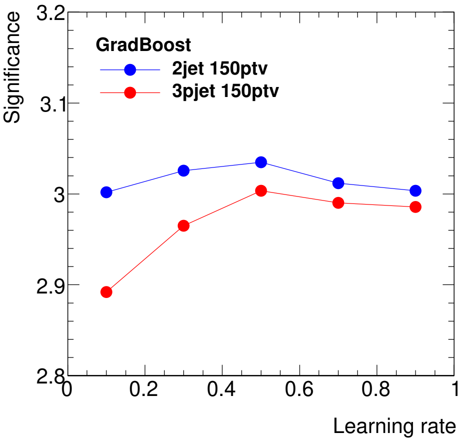
$$+\frac{(\Sigma_{i,j} p_\mathrm{x})^2}{\sigma_\mathrm{bal}^2} + \frac{(\Sigma_{i,j} p_\mathrm{y})^2}{\sigma_\mathrm{bal}^2}$$ ← Balance constraint: Gaussian

$$+2\ln\{(m_{ll}^2 - m_Z^2)^2 + m_Z^2\Gamma_Z^2\}$$ ← *Z* mass constraint: Breit-Wigner

- Newly using MET soft term → 10% improvement in ggZH

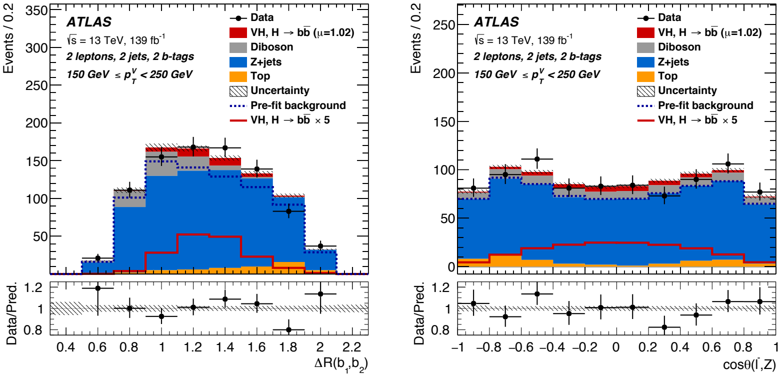
Multivariate analysis

Variable	0-lepton	1-lepton	2-lepton
m_{bb}	×	×	×
$\Delta R(\vec{b_1}, \vec{b_2})$	×	×	×
$p_{\mathrm{T}}^{b_1}$	×	×	×
$p_{\mathrm{T}}^{b_2}$	×	×	×
p_{T}^{V}	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	×	×
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$\mathrm{MV2}(b_1)$	×	×	
$\mathrm{MV2}(b_2)$	×	×	
$\lvert\Delta\eta(\vec{b_1}, \vec{b_2})\rvert$	×		
m_{eff}	×		
$p_{\mathrm{T}}^{\mathrm{miss,st}}$	×		
$E_{\mathrm{T}}^{\mathrm{miss}}$	×	×	
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
m_{T}^{W}		×	
$\lvert\Delta y(\vec{V}, \vec{bb})\rvert$		×	
m_{top}		×	
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			×
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$			×
$m_{\ell\ell}$			×
$\cos\theta(\vec{\ell^-}, \vec{Z})$			×
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	×	×	×
m_{bbj}	×	×	×



- New variables: MV2 in 01-lep, MET soft term in 0-lep, cosThetaLep in 2-lep, and re-opt. → 10% level improvements

BDT input variables

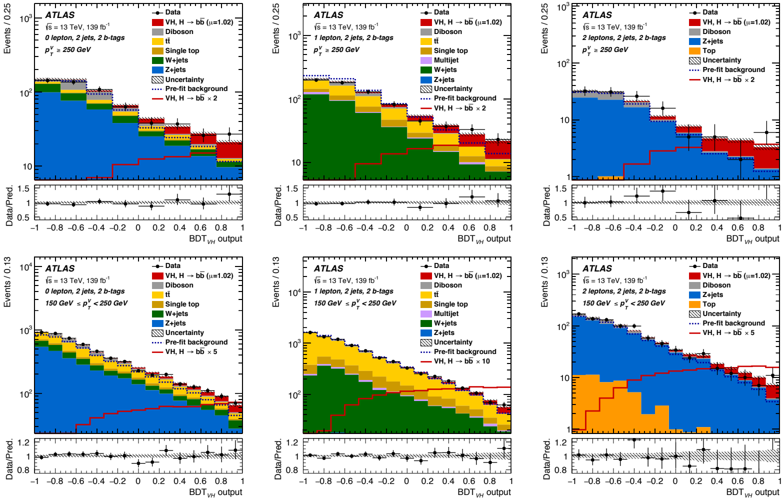


- dRBB (left) is the 2nd important variable after mBB
- New variable cosThetaLep (right) to use the fact that ZH signal is more transversely polarized than Zbb background [1805.06385]

Background estimation and signal extraction

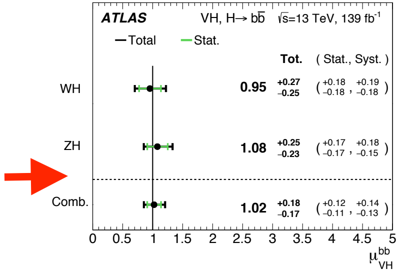
- Main backgrounds are estimated using simulated samples
- Systematic uncertainties are estimated using alt. samples
- New methods: All events with c-jets or light-jets weighted by the probablility to pass the b-tagging, W+jets and ttbar shape uncertainties using BDT ratio, 2-lepton top using emu CR data
- Maximum likelihood fit is performed to estimate background and extract the signal strength (μ), systematic uncertainties are included in the fit as nuisance parameters (θ):
  $L(\mu, \boldsymbol{\theta}) = \prod_{i \in bins} P(n_i | \mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta})) \prod_{j \in \boldsymbol{\theta}} G(\theta_j)$,
- Normalization of main backgrounds are floated and constrained by data in low BDT region, mBB sideband and CR

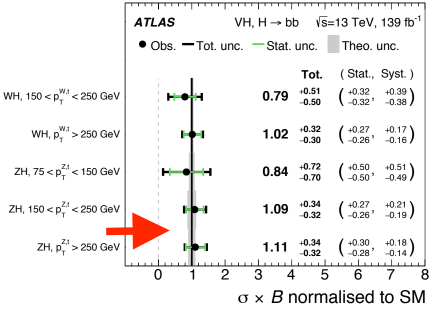
Postfit BDT(VH)



- 2jet pTV = 250– GeV (top) and 150–250 GeV (bottom)

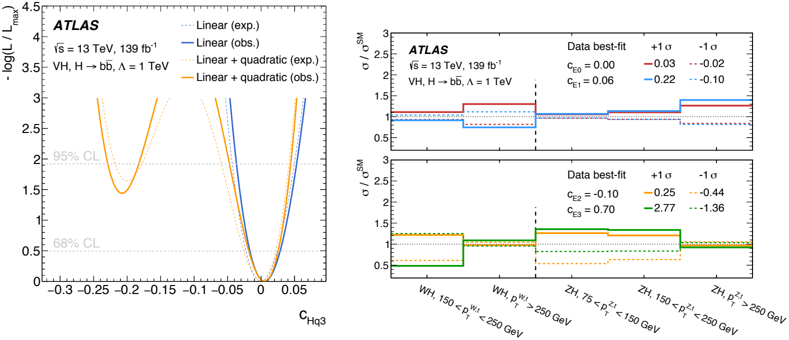
Main results





- 2 POI fit (left): Observed (expected) 5.3 (5.1) σ for ZH and 4.0 (4.1) σ for WH, $\mu_{VH}^{b\bar{b}} = 1.02^{+0.12}_{-0.11}(\text{stat.})^{+0.14}_{-0.13}(\text{syst.})$
- 5 POI fit (right): Slightly increasing as function of pTV, but still consistent with the SM → Constraints on effective interactions

Constraints on effective interactions



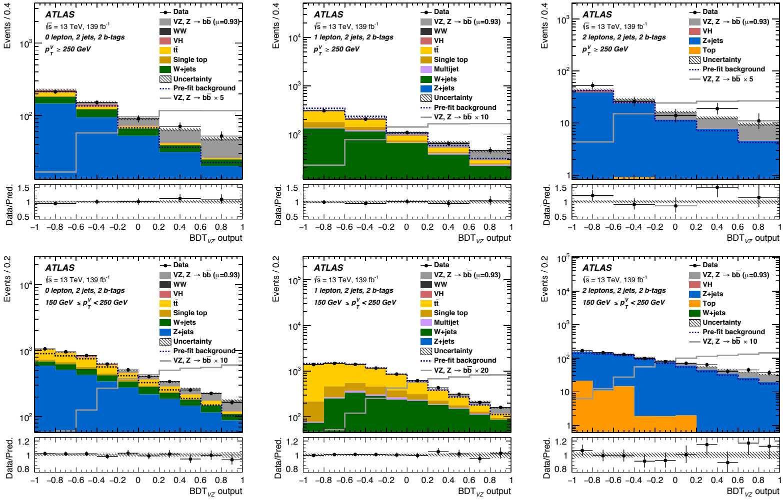
- Limits on the coefficients of effective Lagrangian operators $(\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}^{(D)}, D = 6)$
- The greatest sensitivity from high pT bins → a few%

Breakdown of uncertainties

Source of uncertainty		σ_μ VH	WH	ZH
Total		0.177	0.260	0.240
Statistical		0.115	0.182	0.171
Systematic		0.134	0.186	0.168
Statistical uncertainties				
Data statistical		0.108	0.171	0.157
$t\bar{t}$ $e\mu$ control region		0.014	0.003	0.026
Floating normalisations		0.034	0.061	0.045
Experimental uncertainties				
Jets		0.043	0.050	0.057
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.015	0.045	0.013
Leptons		0.004	0.015	0.005
b-tagging	b-jets	0.045	0.025	0.064
	c-jets	0.035	0.068	0.010
	light-flavour jets	0.009	0.004	0.014
Pile-up		0.003	0.002	0.007
Luminosity		0.016	0.016	0.016
Theoretical and modelling uncertainties				
Signal		0.052	0.048	0.072
Z + jets		0.032	0.013	0.059
W + jets		0.040	0.079	0.009
$t\bar{t}$		0.021	0.046	0.029
Single top quark		0.019	0.048	0.015
Diboson		0.033	0.033	0.039
Multi-jet		0.005	0.017	0.005
MC statistical		0.031	0.055	0.038

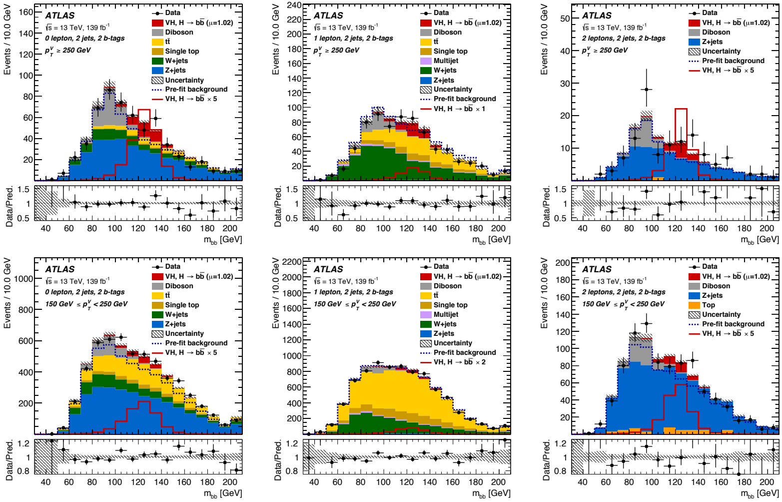
- Highly ranked nuisance parameters are studied
- Experimental: b-tag efficiency (B0, C0, C1), jet energy scale (FlavComp, bJES, modeling1)
- Background: W+jets (BDTr Generator), Diboson (mBB shape), Z+jets (CR-SR extrapolation, normalization, mBB and pTV shape), ttbar (norm and flav 1-lepton)
- Signal: qqVH (QCD scale), ggZH (QCD scale), branching ratio

Postfit BDT(VZ)



- 2jet pTV = 250– GeV (top) and 150–250 GeV (bottom)

Postfit mBB(VH)



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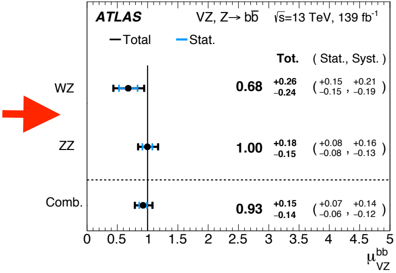
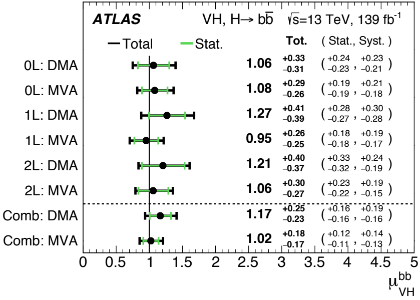
Crosscehck results





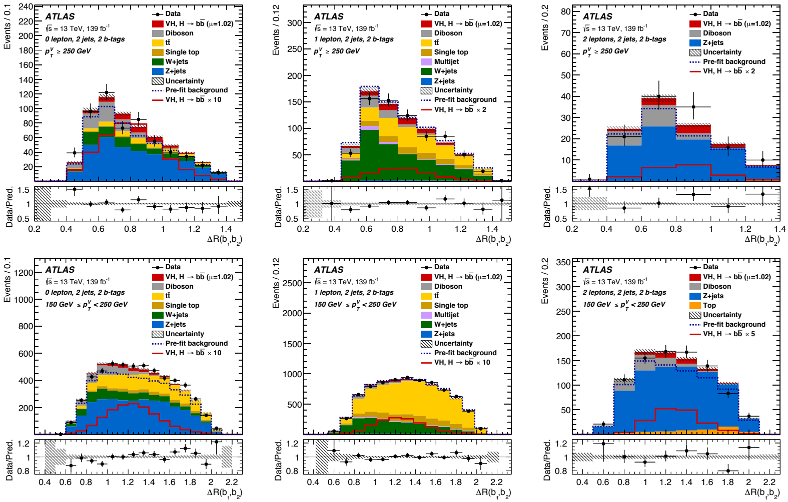
- BDT(VZ) 2 POI fit results (left): WZ is low but still consistent with SM, providing validation of MVA
- Dijet Mass Analysis (DMA) vs MVA (right): Good agreement within uncertainty, better sensitivity in MVA

Summary

- Resolved VHbb full Run2 140 fb-1 results are presented [HIGG-2018-51] [HIGG-2018-52]
- Observation of ZH and strong evidence of WH are established, $\mu_{VH}^{b\bar{b}} = 1.02^{+0.12}_{-0.11}(\text{stat.})^{+0.14}_{-0.13}(\text{syst.})$
- Total error is 18% for the $\mu_{VH}^{b\bar{b}}$ and 30–70% for the STXS
- Limits on the coefficients of effective Lagrangian operators
- The greatest sensitivity from high pT bins → a few%

Backup

Postfit dRBB(VH)



- 2jet pTV = 250– GeV (top) and 150–250 GeV (bottom)

VH breakdown and NP ranking

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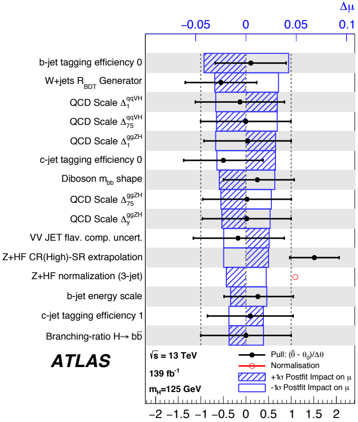
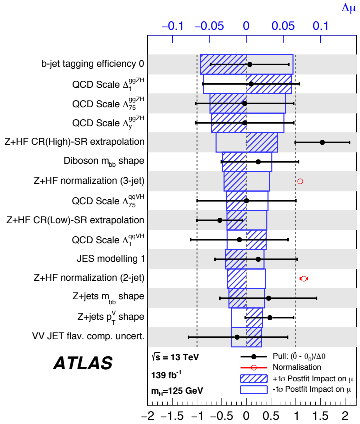


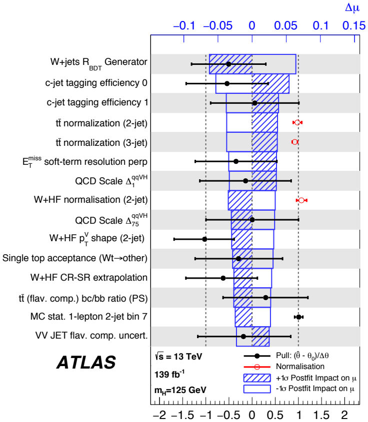
WH breakdown and NP ranking

Source of uncertainty		Uncertainty in $\sigma \times B$ w.r.t. the SM prediction 150 GeV$< p_T^{W,t} <$ 250 GeV	$p_T^{W,t} > 250$ GeV
Total		0.502	0.311
Statistical		0.320	0.263
Systematic		0.386	0.166
Statistical uncertainties			
Data statistical		0.298	0.252
$t\bar{t}$ $e\mu$ control region		0.032	0.007
Floating normalisations		0.157	0.050
Experimental uncertainties			
Jets		0.145	0.054
E_T^{miss}		0.171	0.009
Leptons		0.019	0.018
b-tagging	b-jets	0.049	0.023
	c-jets	0.109	0.060
	light-flavour jets	0.004	0.005
Pile-up		0.017	0.015
Luminosity		0.017	0.015
Theoretical and modelling uncertainties			
Signal		0.035	0.050
Z + jets		0.038	0.011
W + jets		0.159	0.072
$t\bar{t}$		0.152	0.037
Single top quark		0.135	0.032
Diboson		0.040	0.034
Multi-jet		0.015	0.019
MC statistical		0.112	0.068



ZH breakdown and NP ranking

Source of uncertainty	Uncertainty in $\sigma \times B$ w.r.t. the SM prediction		
	$75 < p_T^{Z,t} < 150$ GeV	$150 < p_T^{Z,t} < 250$ GeV	$p_T^{Z,t} > 250$ GeV
Total	0.710	0.330	0.330
Statistical	0.501	0.262	0.291
Systematic	0.503	0.200	0.156
Statistical uncertainties			
Data statistical	0.421	0.243	0.284
$t\bar{t}$ $e\mu$ control region	0.221	0.039	0.023
Floating normalisations	0.181	0.095	0.047
Experimental uncertainties			
Jets	0.266	0.082	0.040
E_T^{miss}	0.235	0.027	0.016
Leptons	0.027	0.007	0.007
b-tagging: b-jets	0.176	0.082	0.041
b-tagging: c-jets	0.028	0.020	0.006
b-tagging: light-flavour jets	0.006	0.013	0.015
Pile-up	0.012	0.016	0.017
Luminosity	0.012	0.016	0.017
Theoretical and modelling uncertainties			
Signal	0.110	0.096	0.091
Z + jets	0.271	0.089	0.071
W + jets	0.020	0.019	0.008
$t\bar{t}$	0.108	0.036	0.025
Single top quark	0.044	0.015	0.015
Diboson	0.073	0.044	0.029
Multi-jet	0.009	0.008	0.005
MC statistical	0.168	0.057	0.055



Expected sensitivity