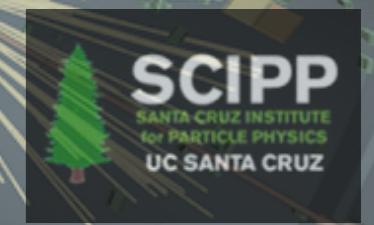


Measurements and searches of Higgs boson decays to two quarks with the ATLAS experiment at the LHC

Marco Battaglia
on behalf of the ATLAS Collaboration



The importance of H \rightarrow bb in the study of the Higgs boson profile

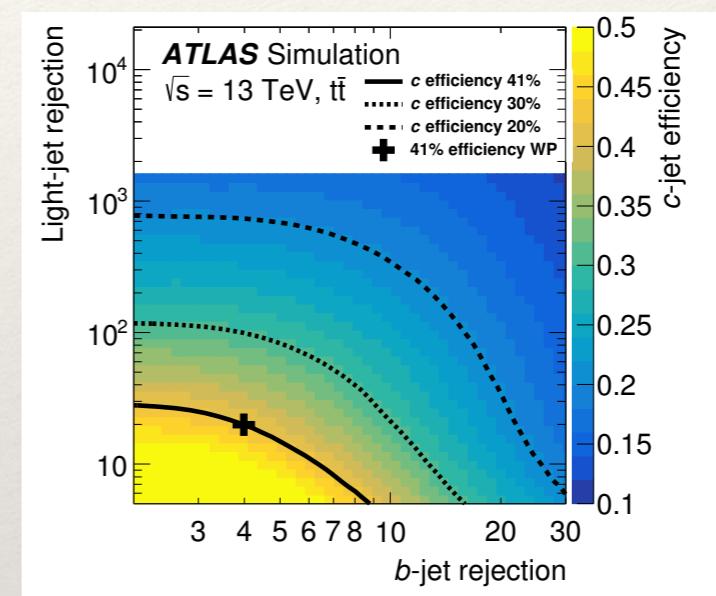
Having the largest BR (~ 0.58), H \rightarrow bb controls the Higgs total width and therefore BRs of all other decays;

Testing the couplings of the Higgs boson to fermions is important for understanding the origin of fermion masses and H \rightarrow bb is sensitive to New Physics shifting the relation between the Yukawa coupling and the b quark mass (for example: Δ_b effect in SUSY);

Through efficient flavour tagging, H \rightarrow bb is the main Higgs hadronic decay channel accessible at LHC and allows best statistics in Higgs processes with small cross section and in corners of phase space.

H \rightarrow cc still limited by the flavour tagging capabilities having to reduce both light-flavoured jets from backgrounds and b-jets from Higgs (and other) decays:

Early ATLAS analysis in ZH associate production on 36 fb $^{-1}$ provided an observed (expected) UL at 95% C.L. of $\sigma(pp \rightarrow ZH) \times \mathcal{B}(H \rightarrow c\bar{c})$ is 2.7 ($3.9^{+2.1}_{-1.1}$) pb corresponding to an observed UL on μ of 110.



Phys. Rev. Lett. 120 (2018) 211802

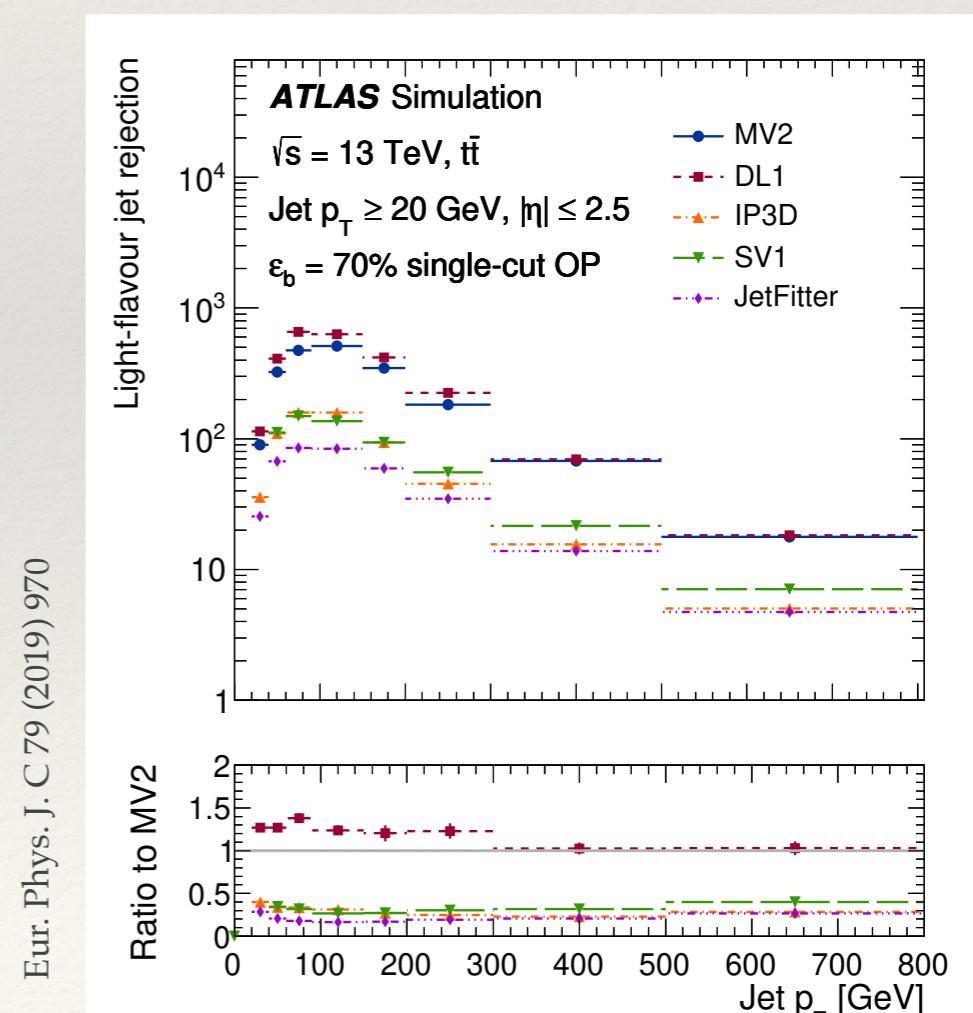
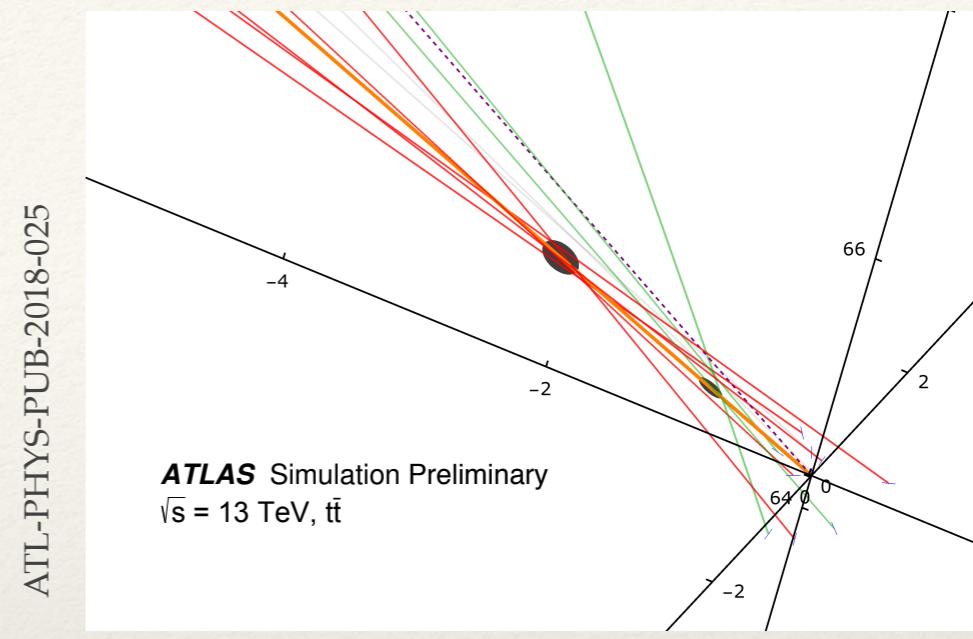
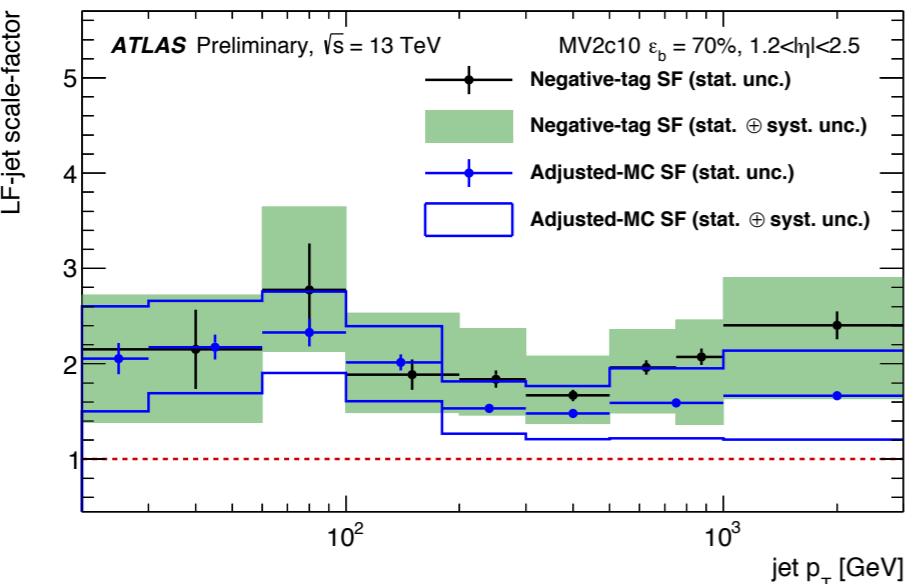
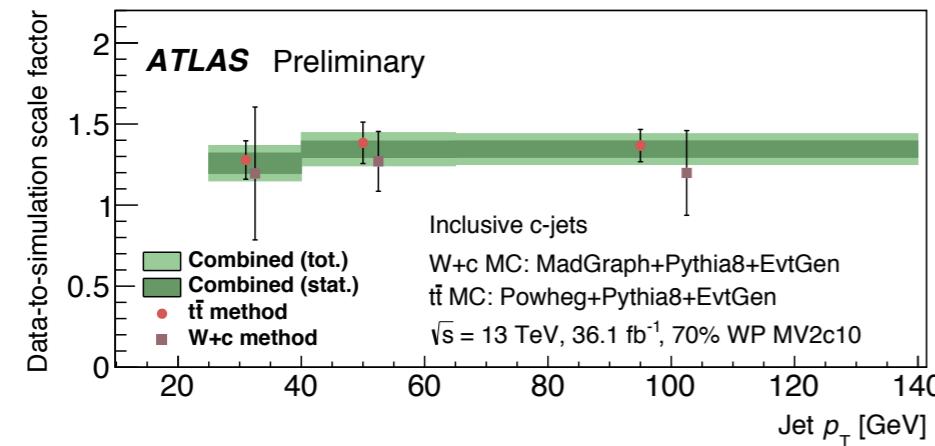
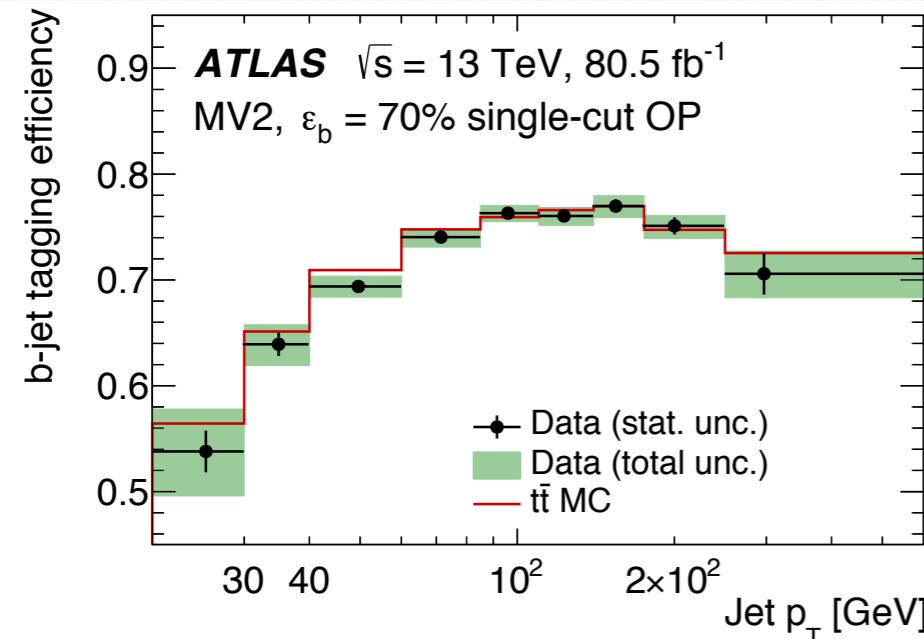
With Run 2 statistics, not only the static properties (coupling) but also the dynamical properties (differential cross sections) of the Higgs boson are becoming accessible in bb final state:

Higgs boson production at high transverse momentum provides enhanced sensitivity to New Physics models by giving access to new contributions in Higgs production with effects encoded in effective field theory (EFT): EFTs describe low-energy remnant of phenomenology at scales beyond the LHC reach (new heavy particles or new strong interactions with large energy cut-off) with ggH sensitive to loop nature of effective ggH coupling, VH & VBF pin down tensor structure of HVV couplings.

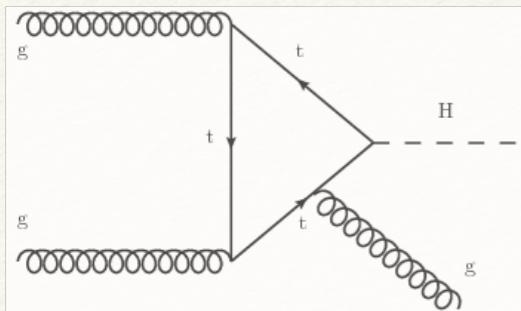
Jet Flavour Tagging in ATLAS

Flavour Tagging combines response of track- and vertex-based physics taggers into high-level discriminants with multivariate classifiers (BDT discriminant MV2 and Deep Learning Neural Network DL1);

Fixed efficiency working points are defined and efficiency for b, c and light jets is measured on calibration samples:

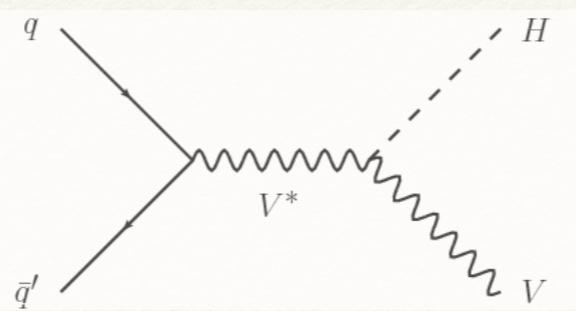


Production Channels and Signal Signatures

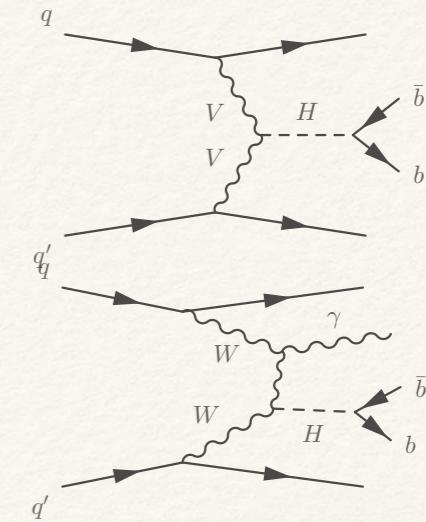


Dominant gluon–gluon fusion production mode very challenging due to large QCD multi-jet bkg; bb γ events with hard gluon radiation giving significant pT to Higgs boson; Main bkg from QCD events with g \rightarrow bb;

(ttH production discussed in Jelena Jovicevic's talk tomorrow)



Associated VH (V=W, Z) production most sensitive mode for H \rightarrow bb due to V leptonic decay triggering and reduction of QCD background.



Vector-boson fusion (VBF), as ggF, yields jet-only final state difficult to distinguish from non-resonant b-quark production; VBF + γ improves triggering and bkg rejection.

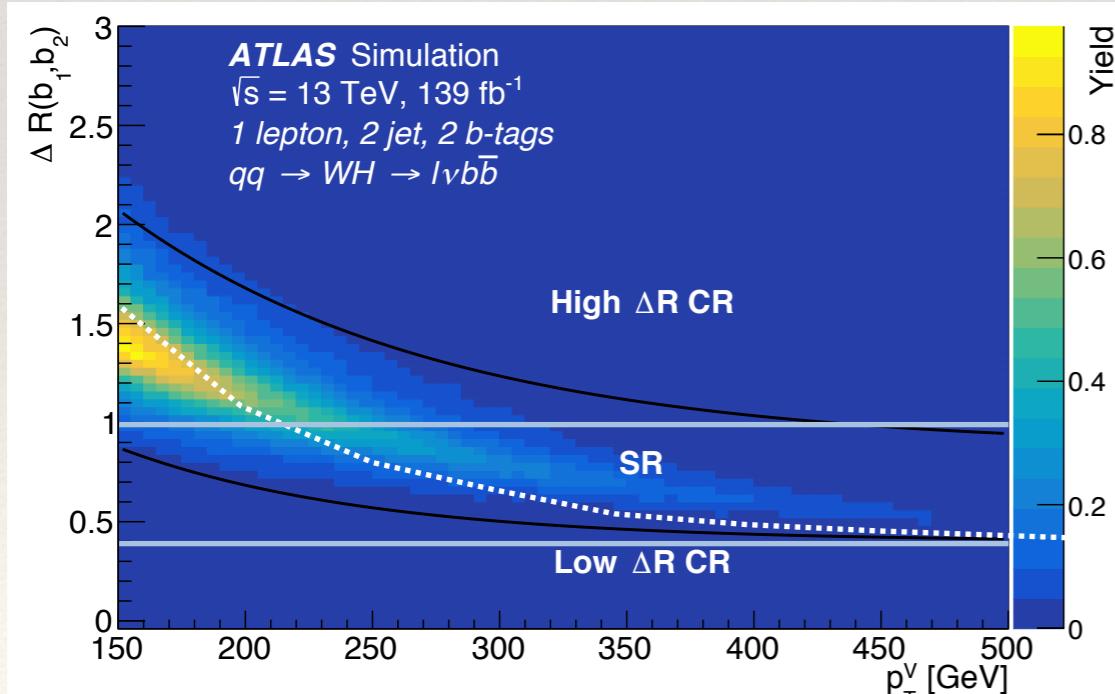
Resolved vs. Boosted Topologies

Signal-to-background ratio increases with Higgs boson pT;

$$\Delta R(j, j) \propto \frac{2m_H}{p_T^H}$$

2-jet opening angle scales as $1/p_T^H$ inducing transition from resolved to “boosted” topology in the range 450-650 GeV

At lower pT Higgs boson reconstructed as pair of R=0.4 calorimetric b-tagged jets at high pT as single R=1.0 jet with variable-radius (VR) track jets reconstructed with pT-dependent radius parameter used for flavour tagging in combination with large-R jets.



H \rightarrow qq Reconstruction

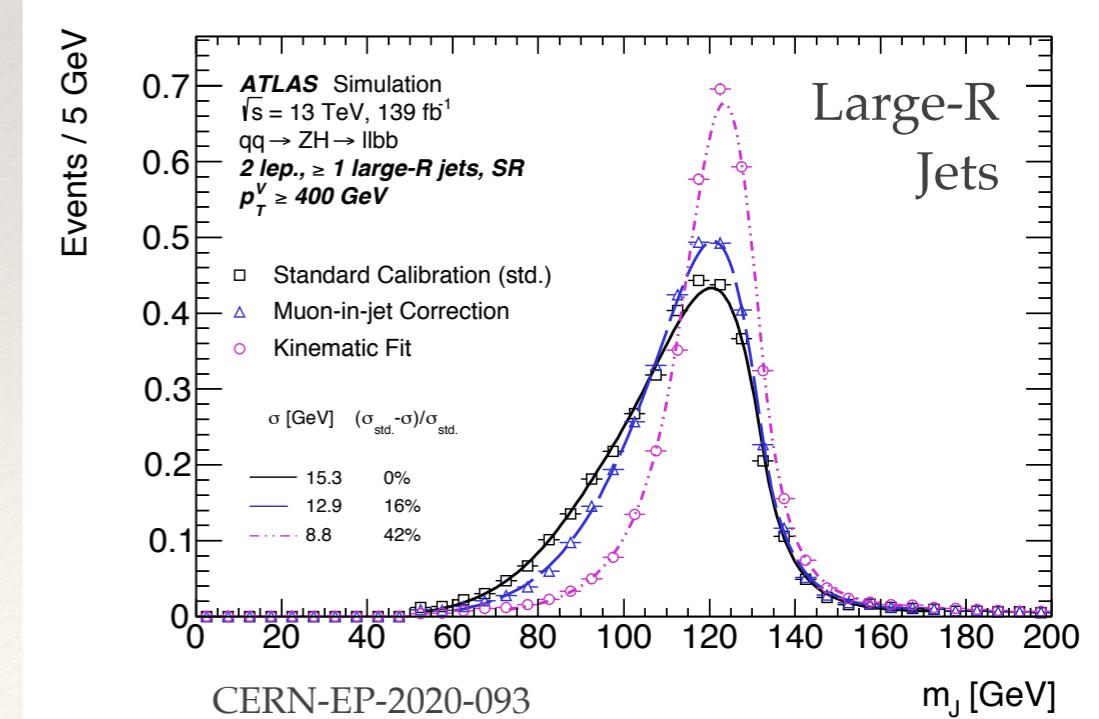
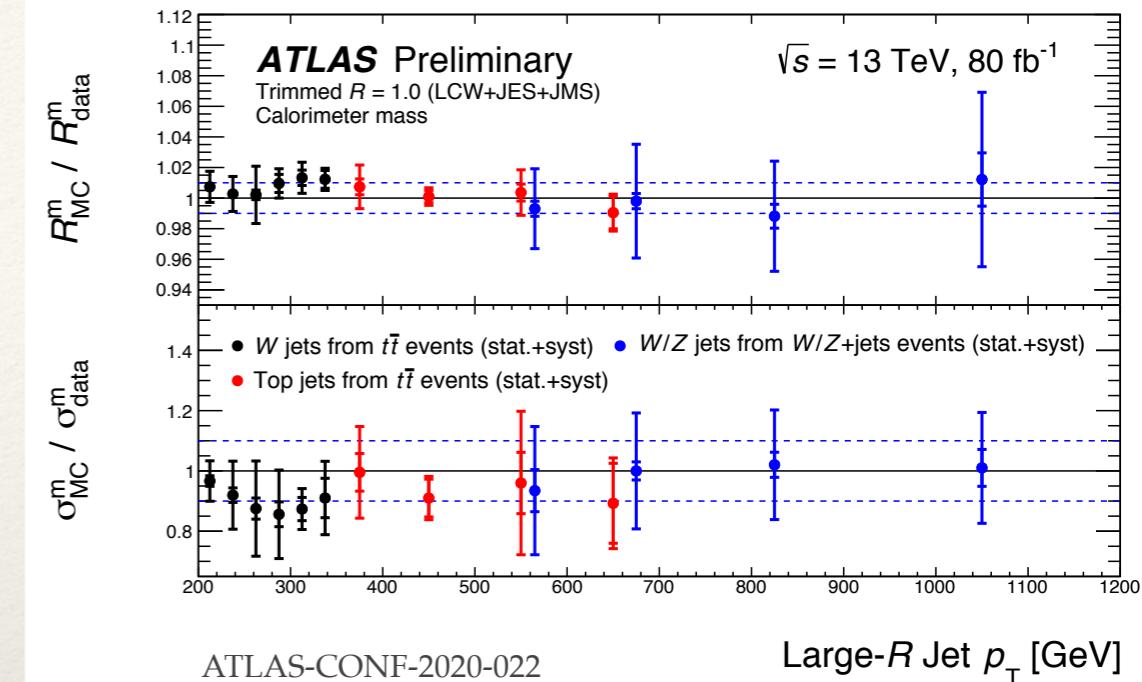
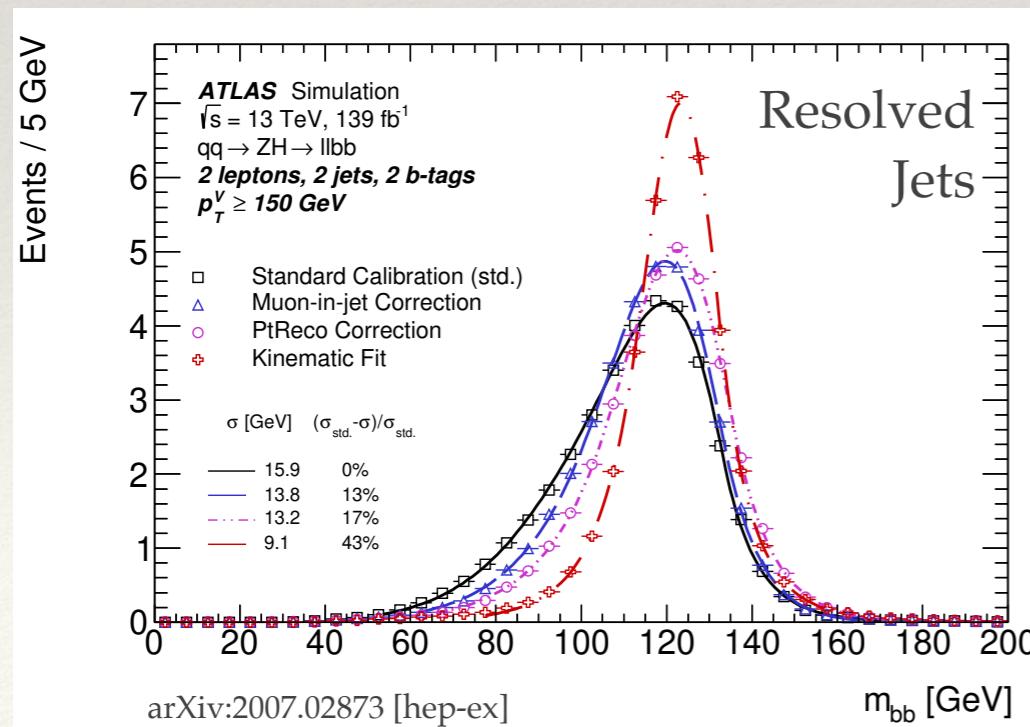
Jets reconstructed from noise-suppressed topological clusters of calorimeter energy deposits with anti- k_t algorithm ($R = 1.0$ large-R jets, 0.4 small-R resolved jets). Large-R jets groomed using trimming to improve jet mass resolution and stability to PU;

Large-R jet mass combines tracking and calorimetric information;
 Mass calibration using W, Z and top needs to be verified for H \rightarrow bb;
 Residual systematics still significant in H \rightarrow bb results.

Improved resolution by applying analysis-specific corrections including:

- contributions of muons from heavy hadron s.l. decays (Muon-in-Jet),
- ratio of particle-level to reconstructed jet energy (PtReco)
- event kinematic fit constraining bb system to be balanced in the transverse plane and di-lepton to m_Z by scaling all objects in event.

Improvement in mass resolution from 5% up to 40%
 and migration of events from low tail to bulk of Higgs mass peak:



WH and ZH production in the H \rightarrow bb channel

arXiv:2007.02873 [hep-ex]

Events categorised into 0-, 1- and 2-lepton channels to target ZH \rightarrow vvbb $^{-}$, WH \rightarrow lvbb $^{-}$ and ZH \rightarrow llbb; Higgs-candidate reconstructed as 2 b-tagged anti-k_t R=0.4 jets in 2 and 3 ($>=3$) jets categories;

Main improvements of new analysis:

- p_T^V split at 250 GeV to better align with STXS bins;
- Improved BDT and CR/SR separation to harmonise main BDT and cross-check with m_{bb} analysis
- use eμbb for data-driven ttbar & Wt estimate in 2-lepton channel
- use BDT to perform multi-dimensional parametrisation of ttbar and W+jets shape uncertainties.

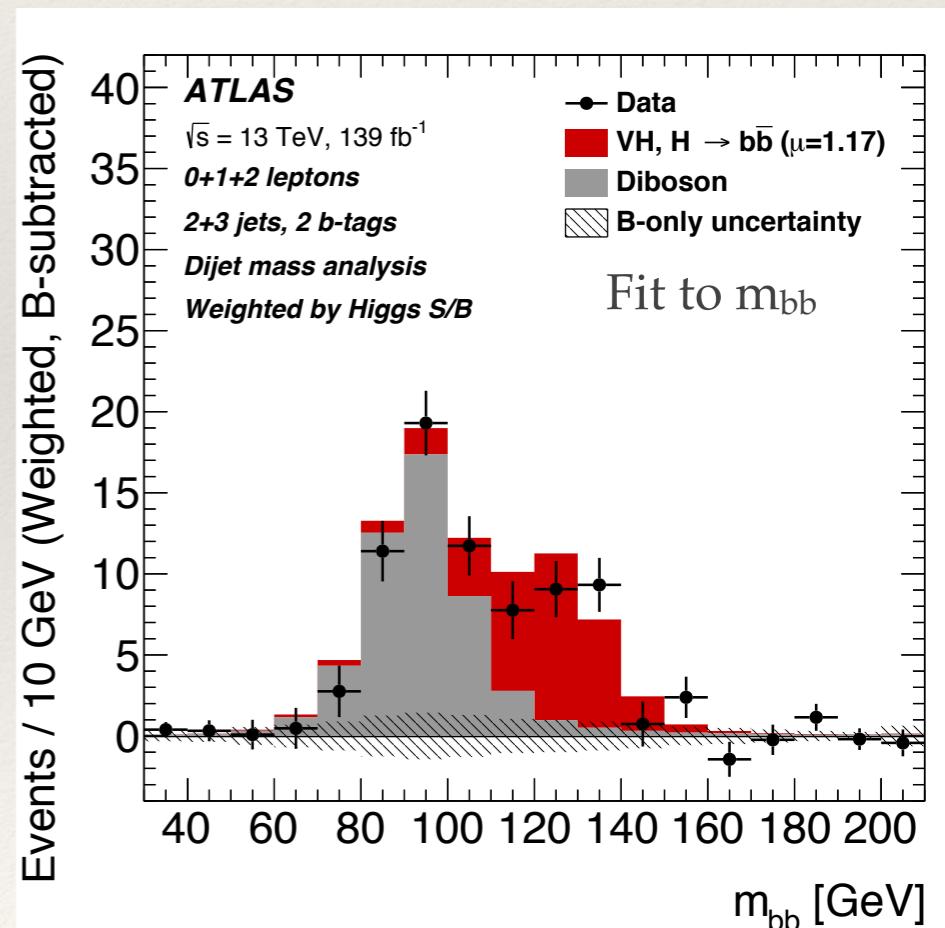
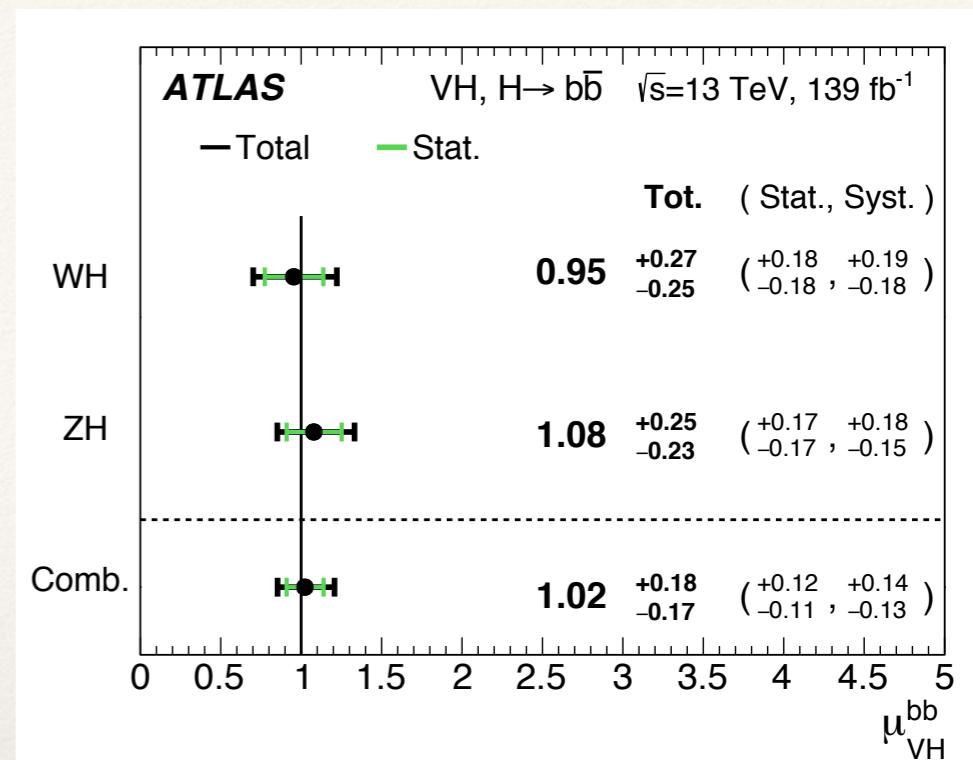
3 lepton channels, 2 jet categories and 2(3) p_T^V for 14 total analysis regions. Each further split into signal region (SR) and 2 jet ΔR(b,b)-defined control regions (CR):

VH signal strength from simultaneous binned profile likelihood fit of 42 regions, normalisation of V+jets and tt bkgs unconstrained:

$$\mu_{\text{VH}}^{bb} = 1.02^{+0.18} = 1.02^{+0.12}(\text{stat.})^{+0.14}(\text{syst.})$$

VH 6.7 σ significance (=expected); ZH 5.3 σ , WH 4.0 σ ;

Main syst. uncertainties due to: signal modelling, flavour tagging response, jet energy scale calibration and resolution, V+j bkg modelling.



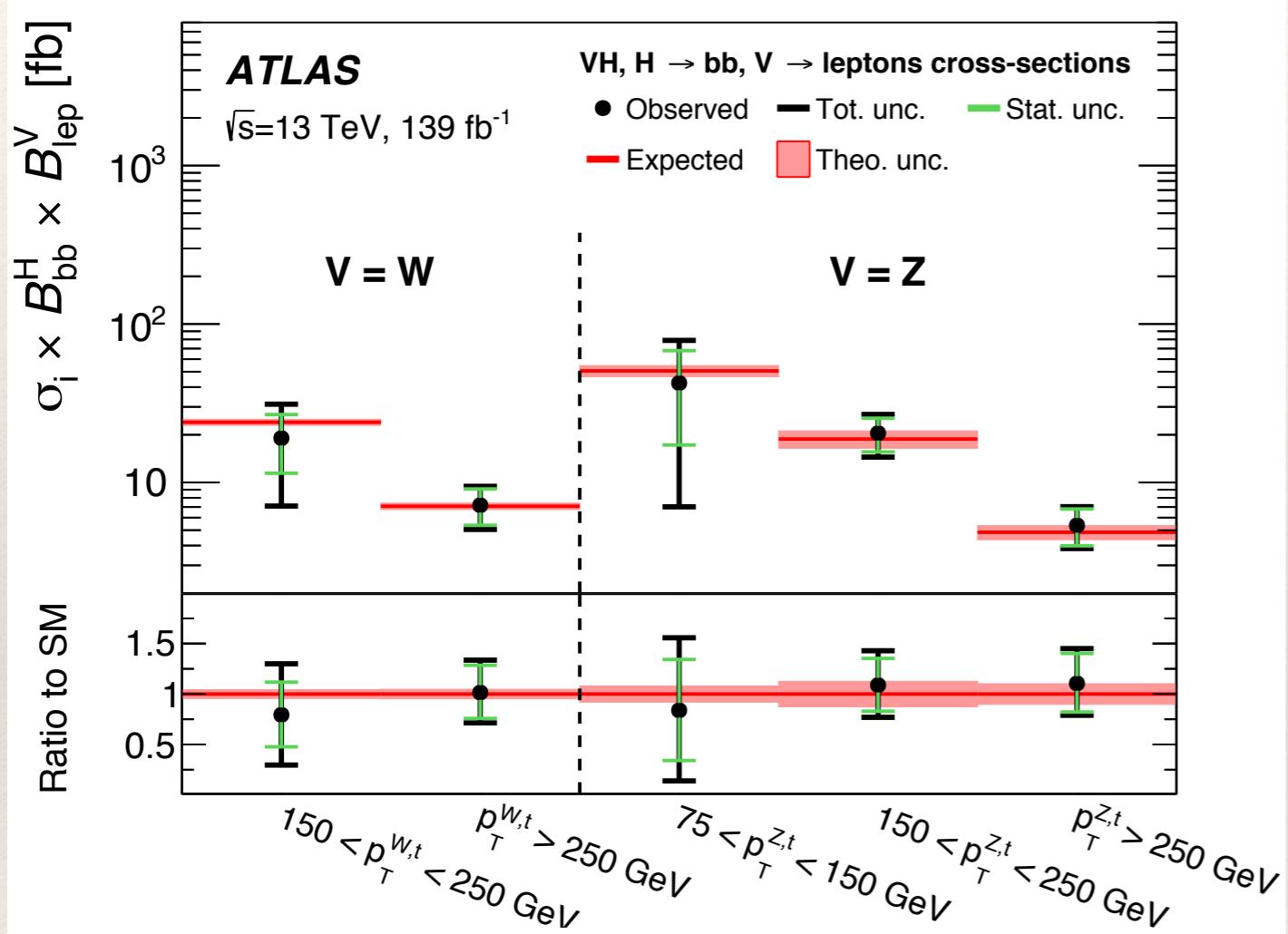
Cross check m_{bb} fit and nominal MVA analyses statistically compatible at 1.1 σ .

WH and ZH production in the $H \rightarrow b\bar{b}$ channel

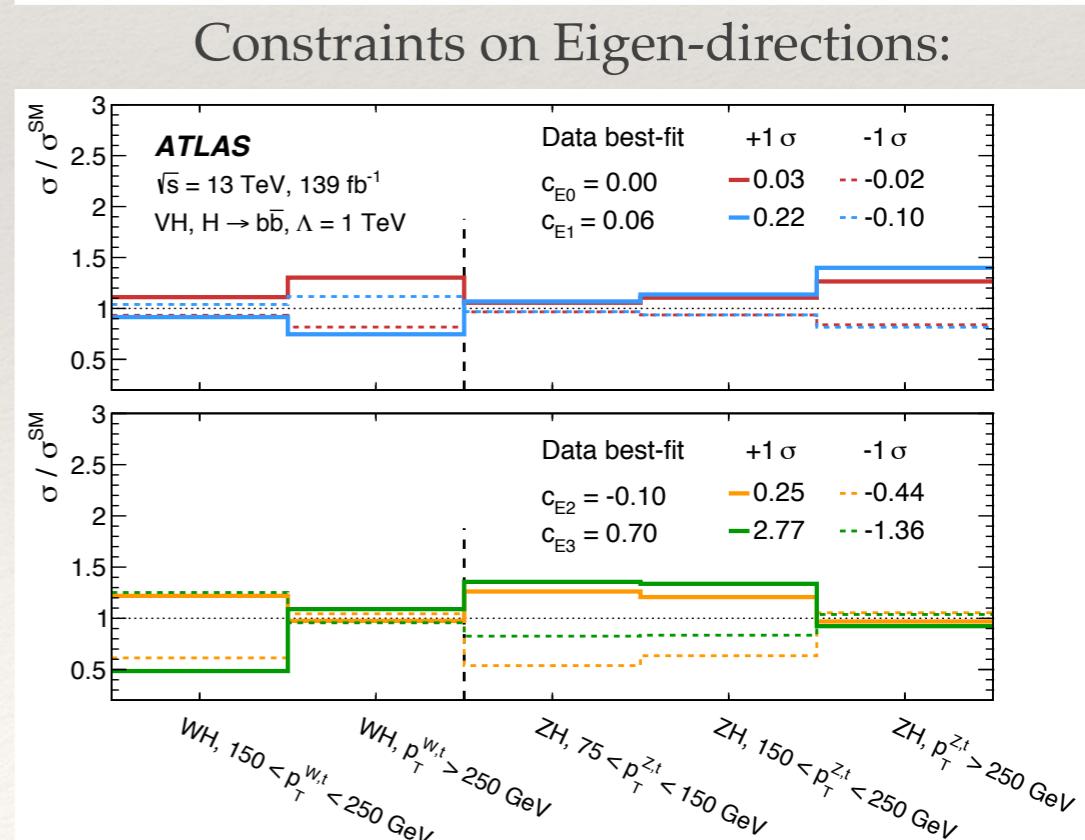
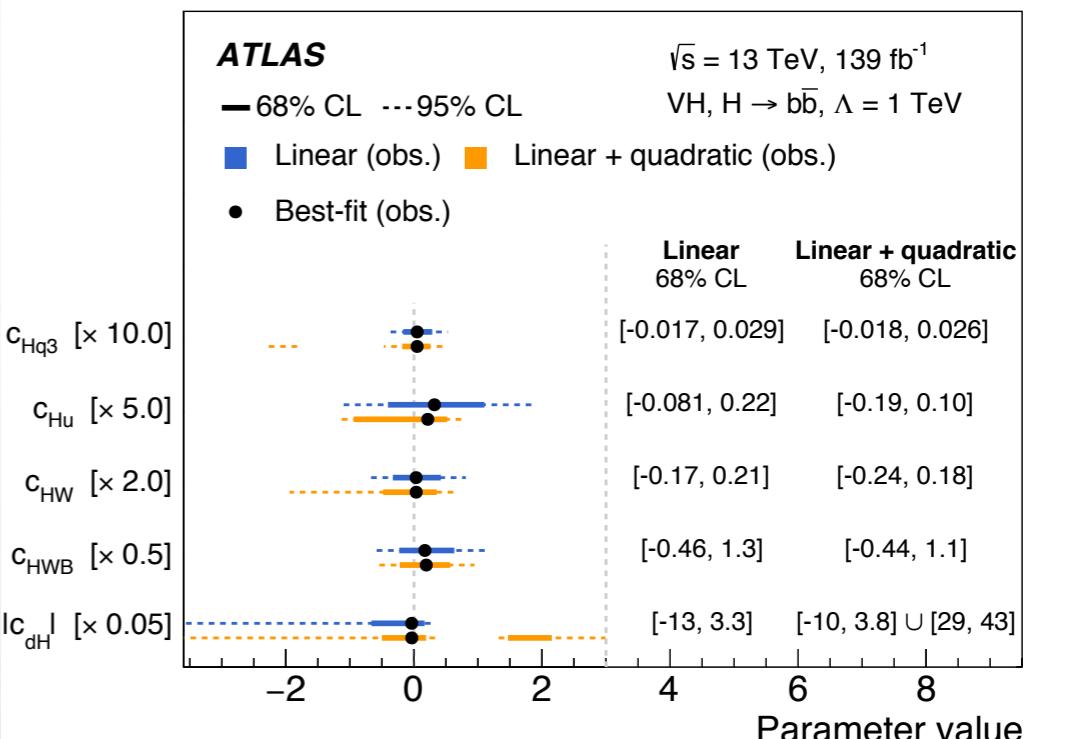
arXiv:2007.02873 [hep-ex]

Differential measurement of $VH, H \rightarrow b\bar{b}$ cross-section in kinematic fiducial volumes in simplified template cross-section (STXS) framework

Set limits on effective Lagrangian parameters sensitive to anomalous Higgs boson couplings with EW gauge bosons and $b\bar{b}$.
(dim-6 operators in Warsaw Lagrangian base)



Good correlation between reco and truth p_T^V ensures small correlation between STXS bins (<10%)



VBF Production

Phys. Rev. D 98 (2018) 052003

Set of complementary search channels sensitive to Higgs production through VBF with decay into bb:

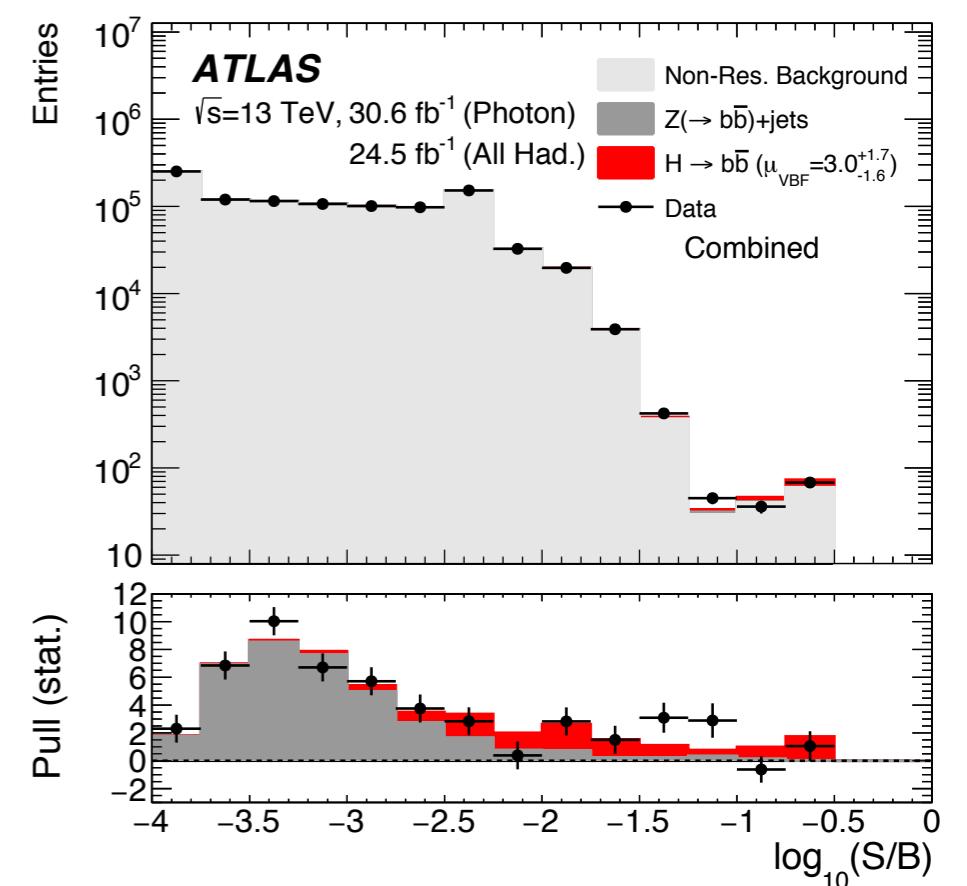
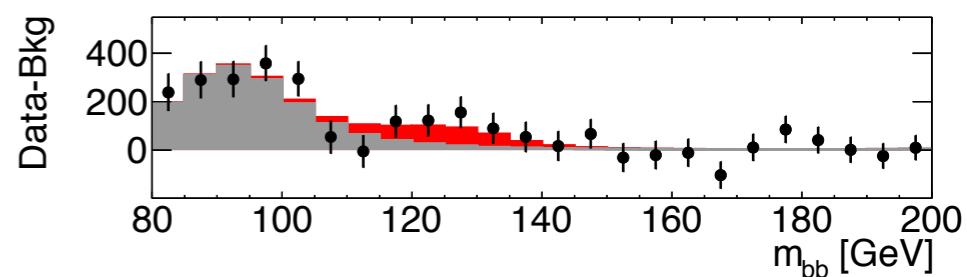
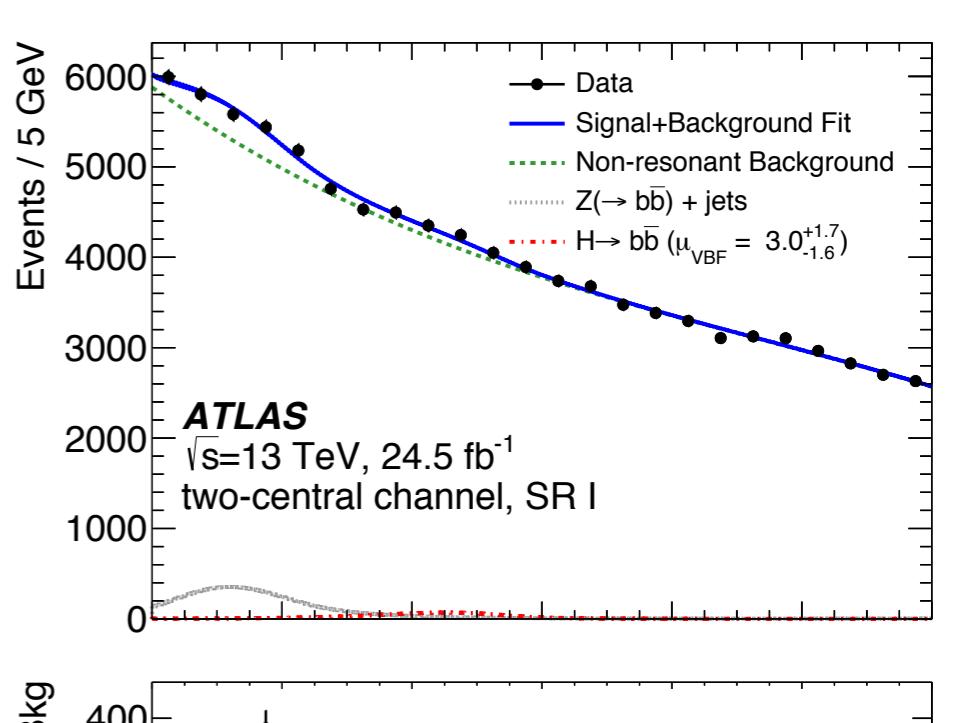
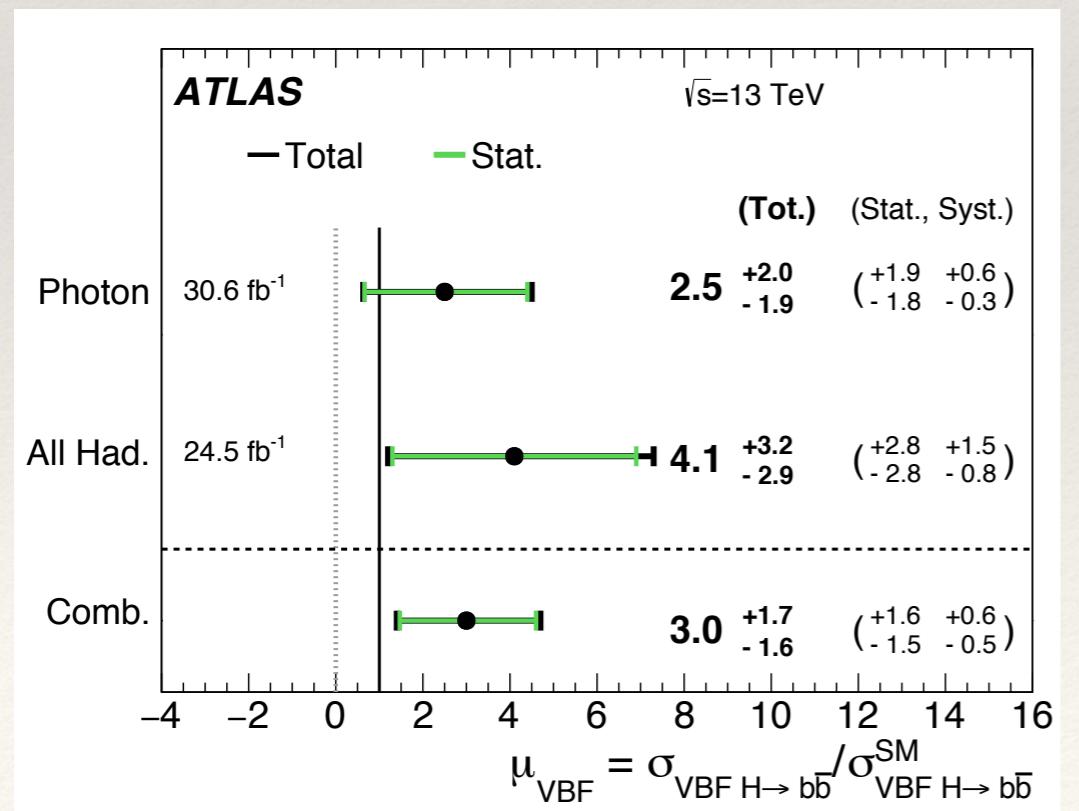
- qqH(\rightarrow bb) with central and forward jets;
- qqH(\rightarrow bb) γ production in association with energetic photon, suppresses the gluon-rich dominant non-resonant bbjj bkg.

Signal events characterised by 2 central b-jets + 2 light-quark jets with large rapidity gap (VBF jets);

Kinematic properties used as inputs to boosted decision trees (BDT);

Signal extracted from simultaneous fit to di-b-jet invariant mass in regions defined by BDT discriminant;

Systematics dominated by non-resonant bkg parameters, Z normalisation, jet en. scale, resolution & b-tagging uncertainties.



VBF + γ Production

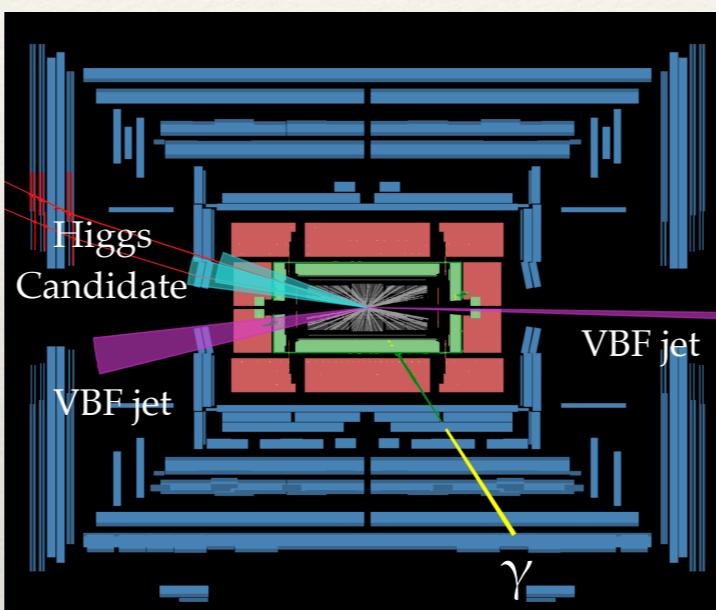
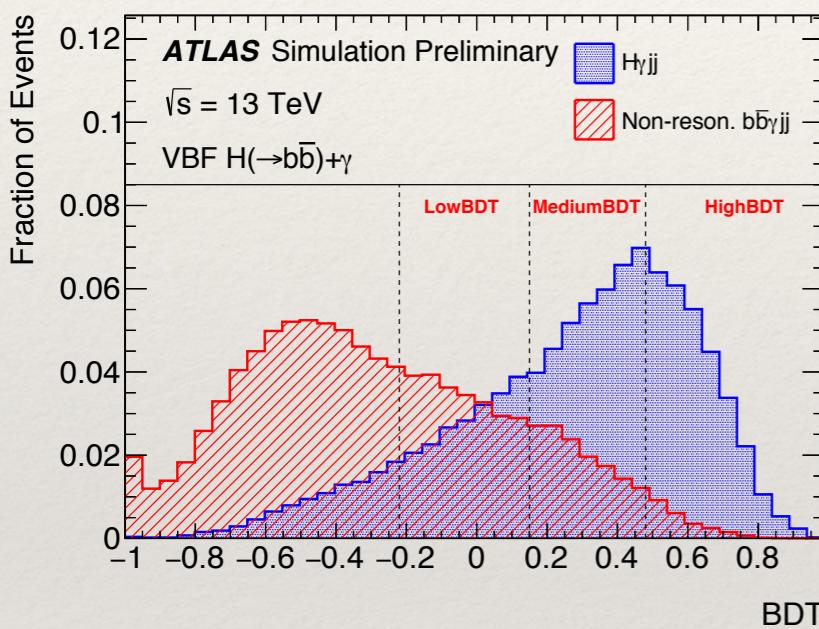
ATLAS-CONF-2020-044

New search for $H\gamma, H \rightarrow bb$ using full Run 2 dataset:

Main bkg: $Z(\rightarrow bb)\gamma jj$ and non-resonant $bb\gamma jj$.

Event-level BDT classifies events as signal- or background-like, based on set of kinematic variables chosen to optimise separation and show low correlation with mass to prevent distortions of m_{bb} spectrum;

BDT output defines increasingly signal-rich event categories:

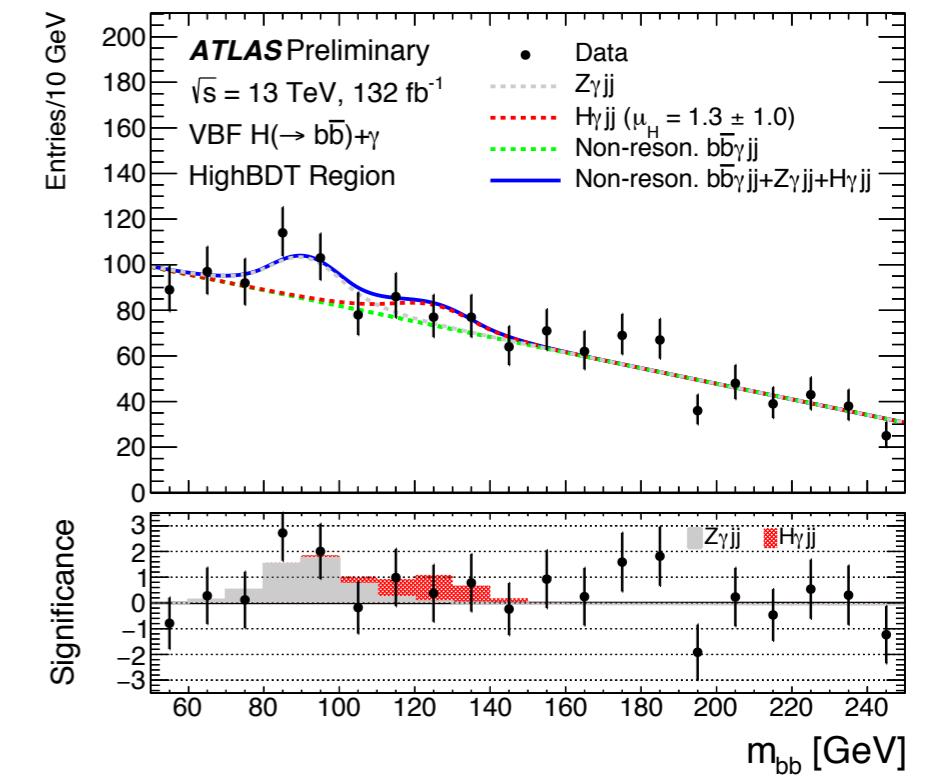


Higgs boson rate extracted from simultaneous fit to b-tagged jet pair invariant mass m_{bb} in multiple event categories;

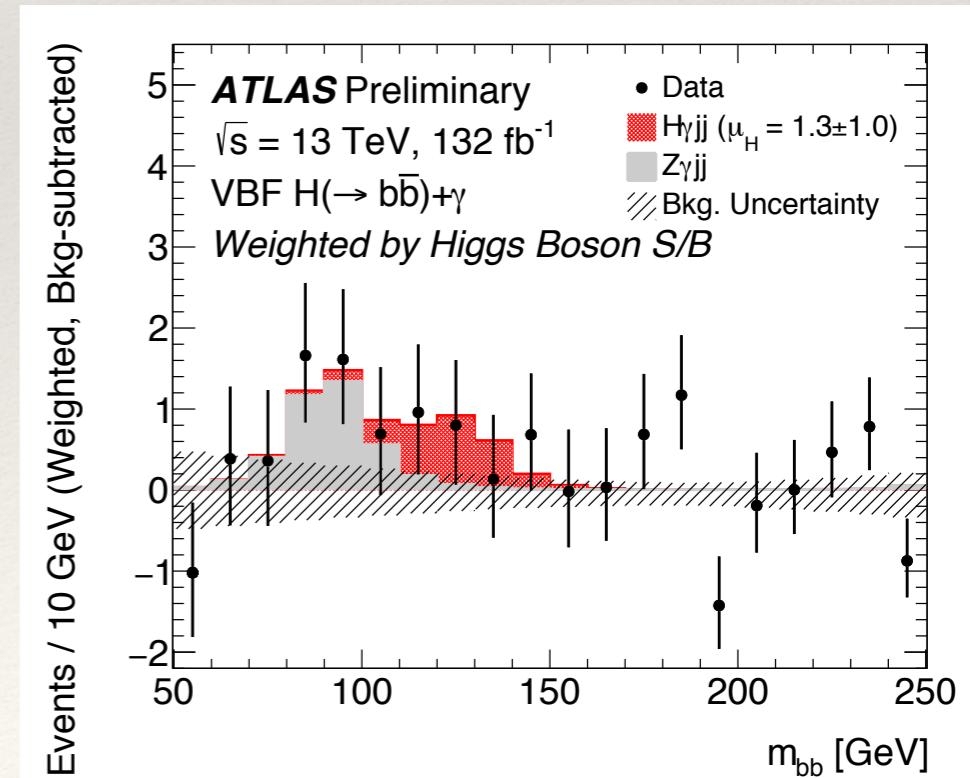
Analysis stat. limited, dominant exp. systematic contributions due to jet energy scale and flavour tagging uncertainties;

$$\mu_H = 1.28^{+1.02}_{-1.00}$$

Observed Higgs signal significance of 1.3σ .



High, Medium, Low BDT
 $\mu_Z = 1.89^{+1.16}_{-1.18}, 1.46^{+1.08}_{-1.13}$ and $-1.25^{+1.19}_{-1.59}$
 $\mu_H = 0.66^{+1.13}_{-1.10}, 3.84^{+2.46}_{-2.43}$, and $3.82^{+7.03}_{-8.33}$



Boosted Higgs Production

Higgs boson candidate reconstructed as leading p_T large-R jet (J), at least two VR track jets associated, the two leading b-tagged VR jets.

Boosted ggF

ATLAS-CONF-2018-052

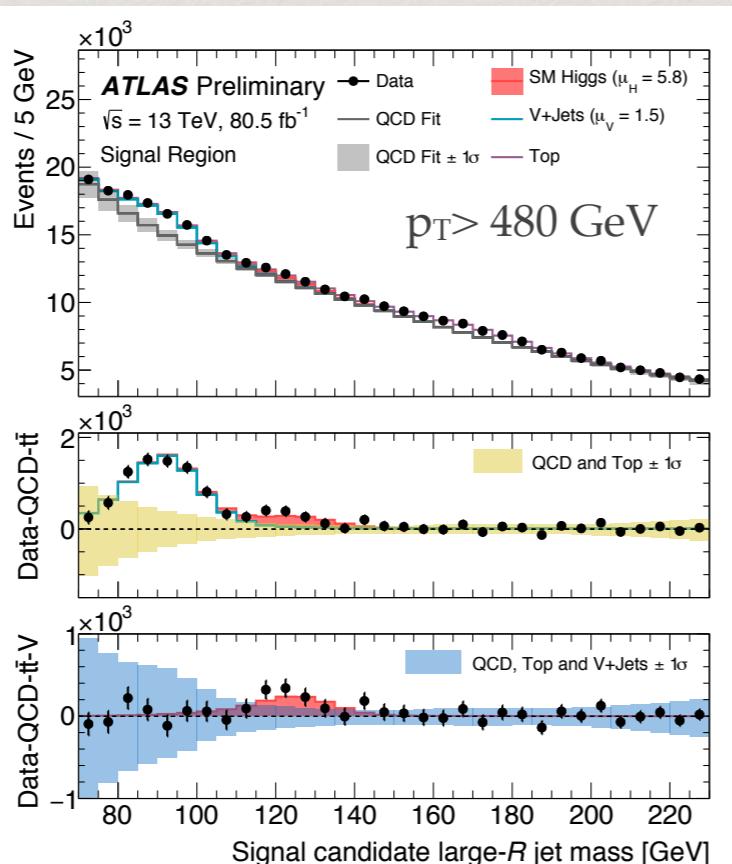
Leading p^{FJ}_T > 480 GeV, sub-leading p^{FJ}_T > 250 GeV
 $2M^{FJ}/p^{FJ}_T < 1$,

QCD contribution modelled with 4th-order polynomial exponential function tested on anti-b tagged Validation Region;
ttbar contribution constrained on ttbar Control Region;

$$\mu_V = 1.5 \pm 0.22 \text{ (stat.)} {}^{+0.29}_{-0.25} \text{ (syst.)} \pm 0.18 \text{ (th.)}$$

$$\mu_H = 5.8 \pm 3.1 \text{ (stat.)} \pm 1.9 \text{ (syst.)} \pm 1.7 \text{ (th.)}$$

Main sources of systematics are large-R jet mass scale and resolution and b-tagging response;
QCD function uncertainties absorbed in stat error.

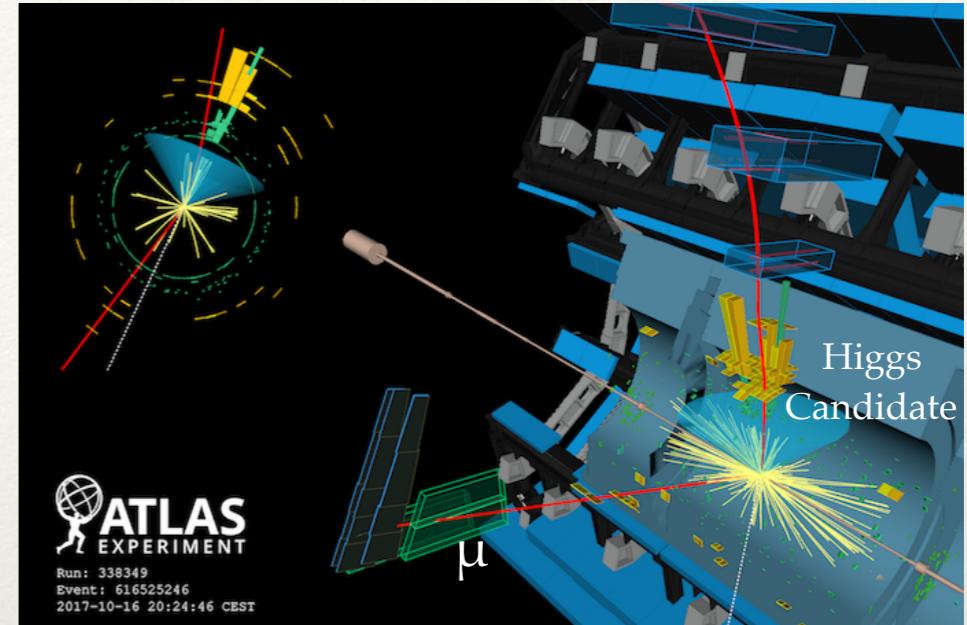


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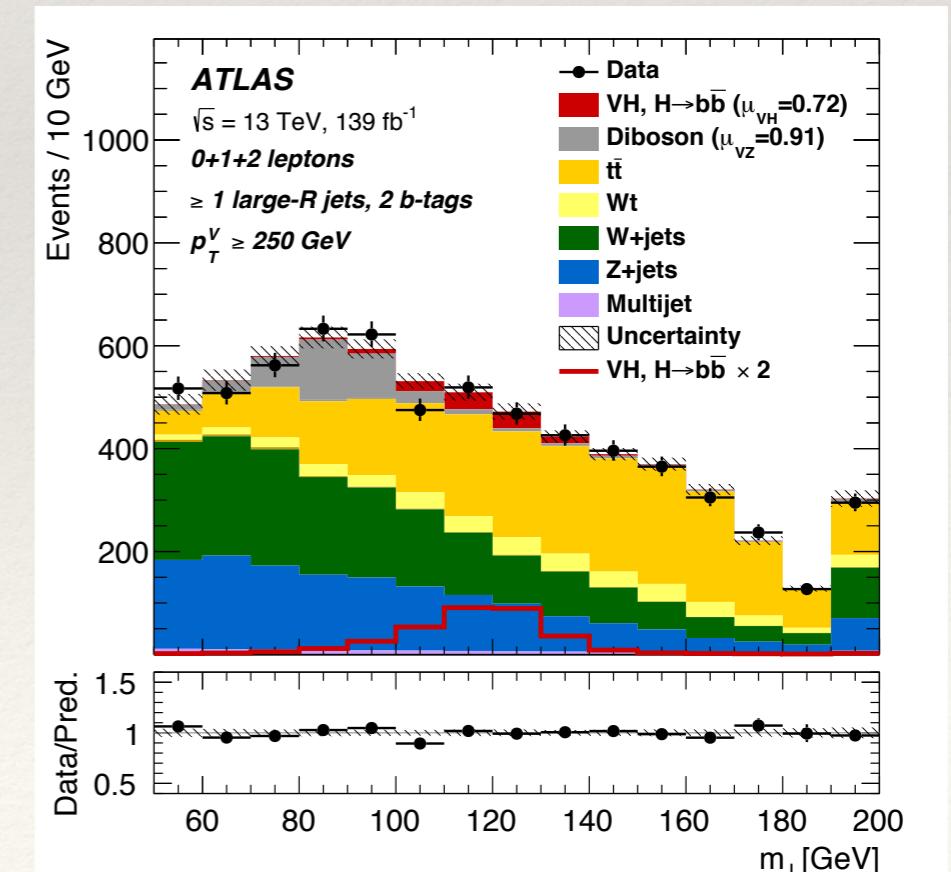
Boosted VH

CERN-EP-2020-093

p^{FJ}_T > 250 GeV; p^V_T = E_{miss}_T in 0-lepton channel,
E_{miss}_T+charged-lepton p_T in 1-lepton channel,
2-lepton p_T in 2-lepton channel.



tt main bkg in 0- and 1-lepton channels
Z+jets in 2-leptons channel:



Boosted VH

CERN-EP-2020-093

Results obtained from binned maximum-likelihood

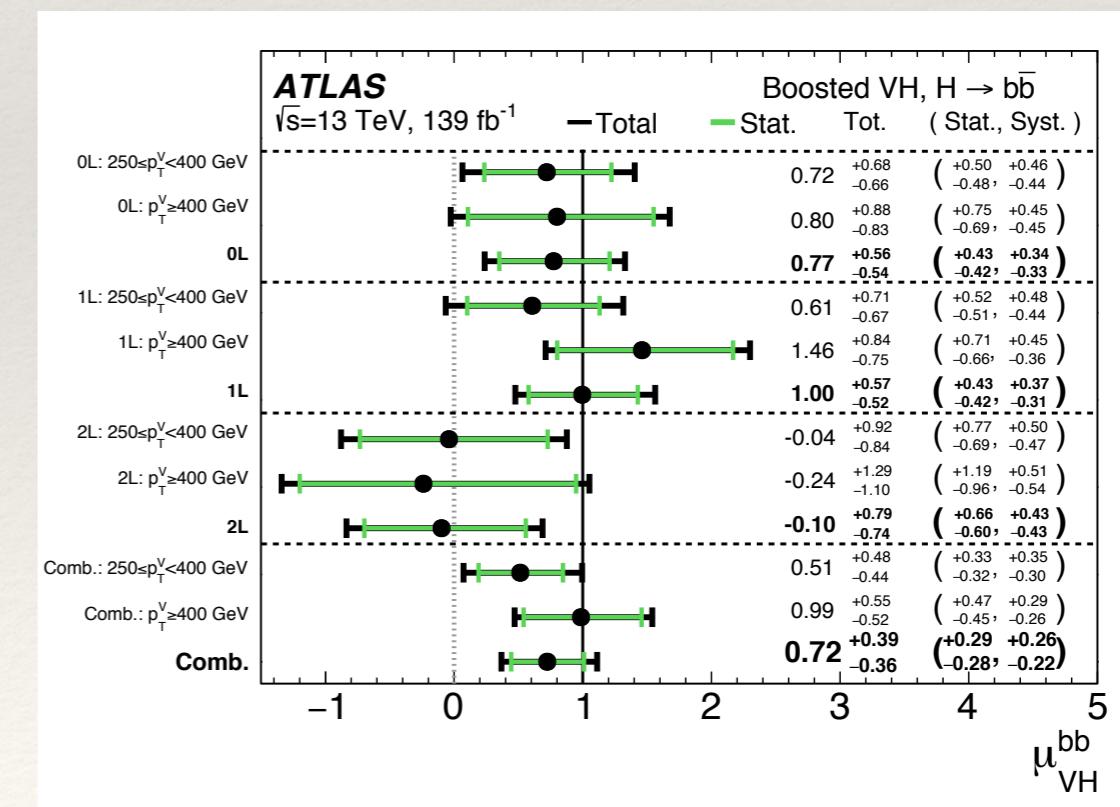
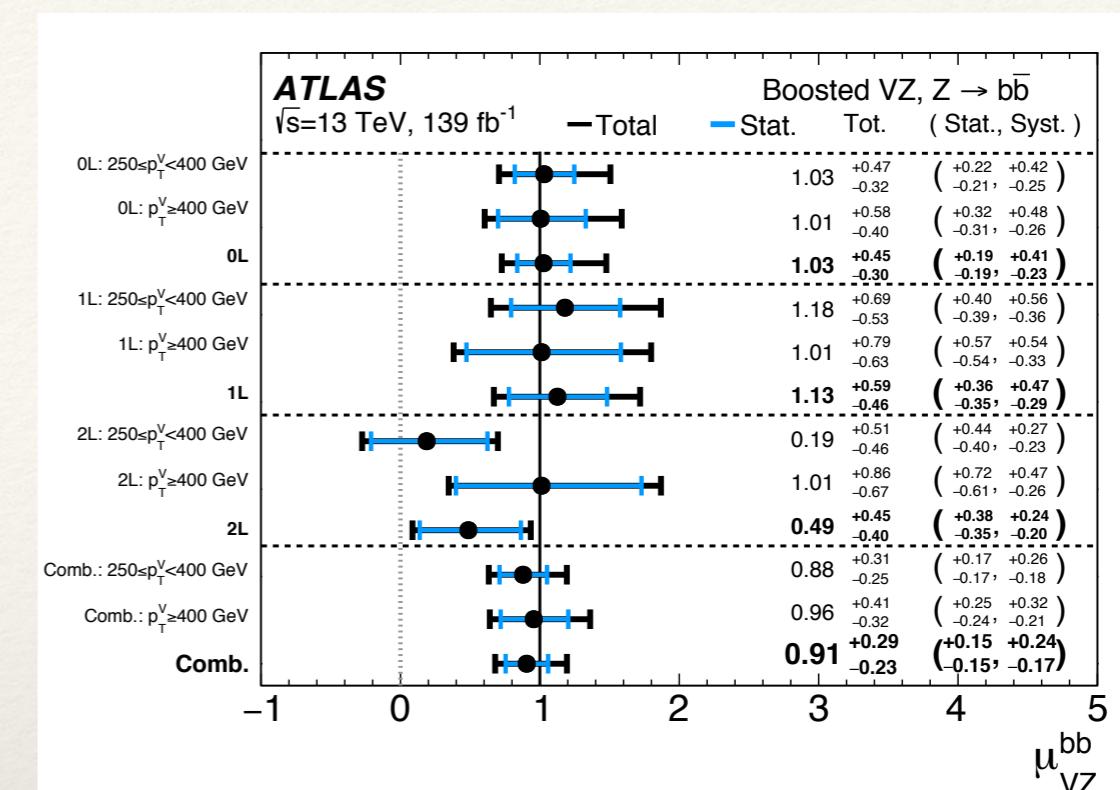
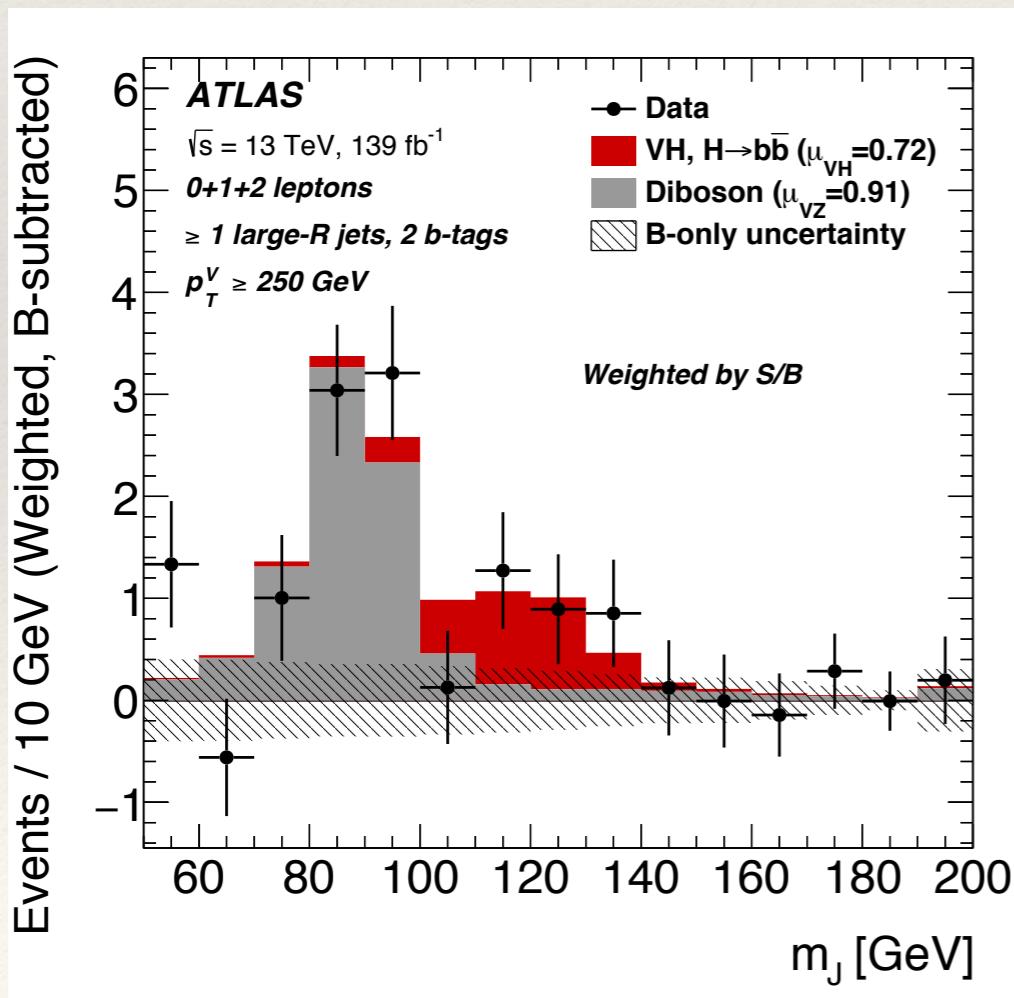
fit to the data of the M_J distribution,
on 10 signal and 4 top control regions,
VZ(bb) and VH(bb) extracted simultaneously;

Main sources of systematics are large-R jet calibration,
in particular mass resolution and background modelling

$$\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.25}_{-0.17}(\text{syst.})$$

$$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$$

Observed VH(bb) significance of 2.1σ , VZ(bb) of 5.7σ .



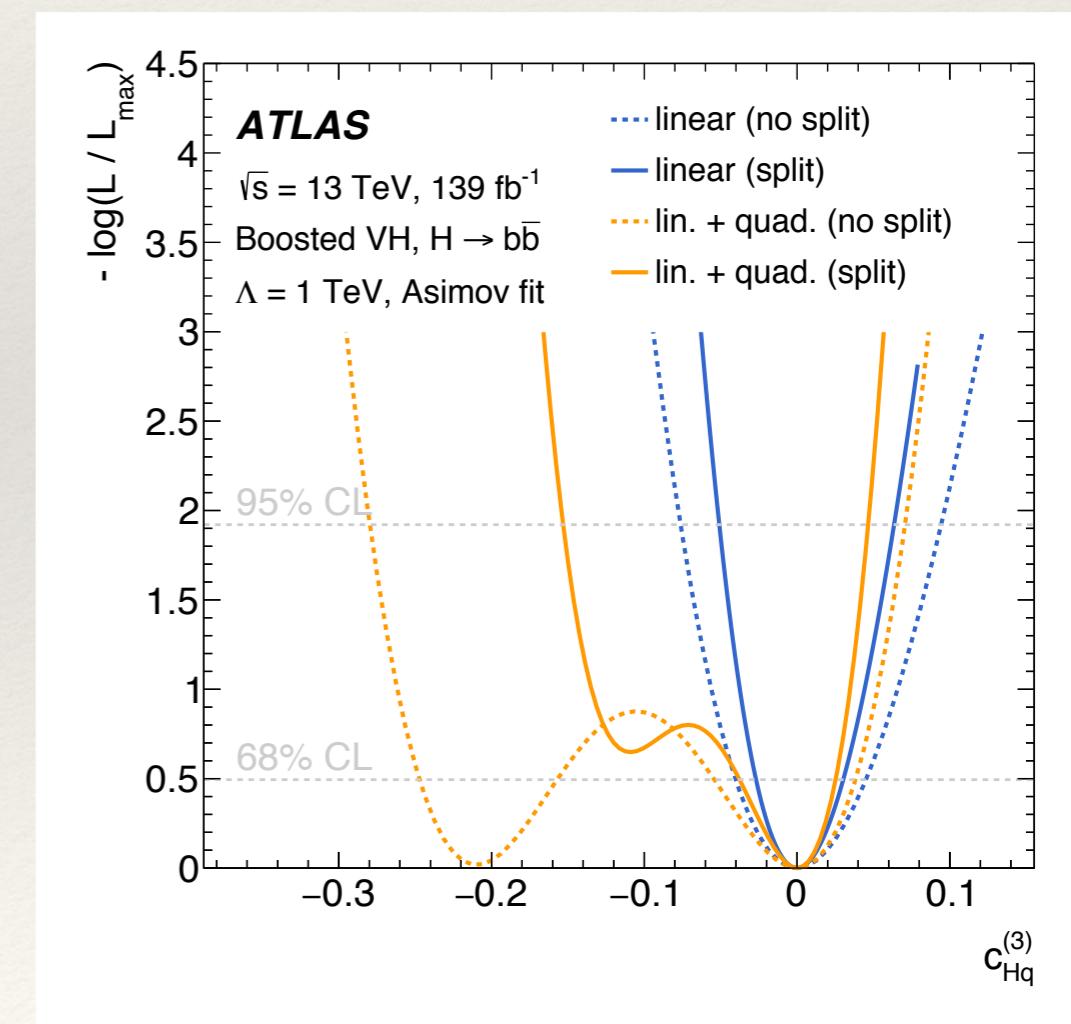
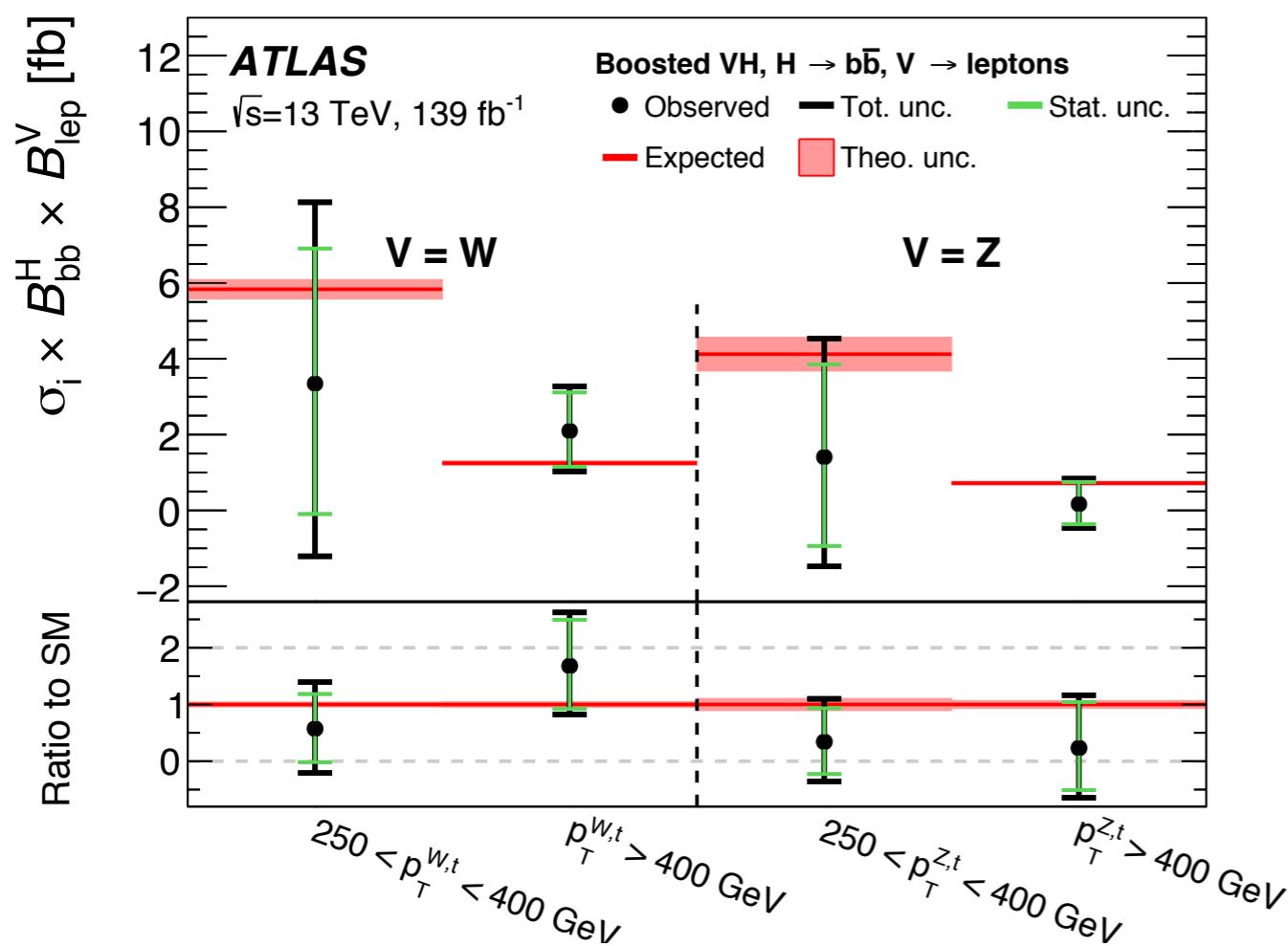
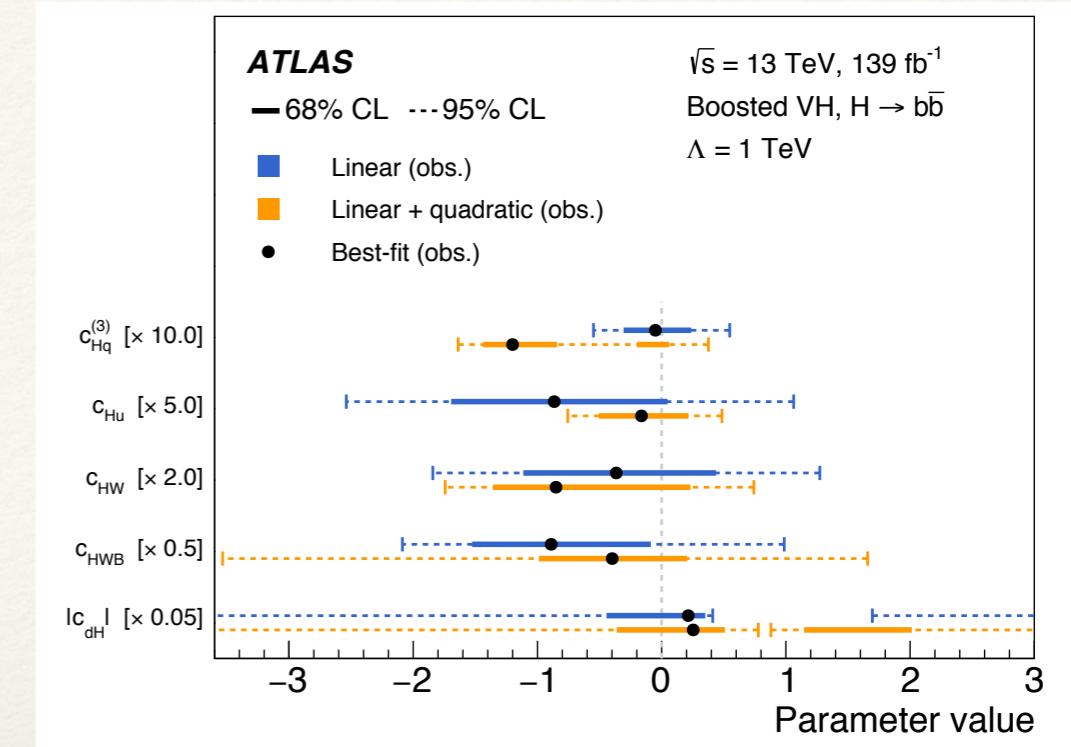
See also Brian Moser's poster at today Poster Session

STXS framework cross sections measured for ZH and WH

CERN-EP-2020-093

S/B increase with p^H_T justifies events to be split
split into two bins: $250 < p^V_T < 400 \text{ GeV}$ and $p^V_T \geq 400 \text{ GeV}$

Sensitivity gain in determination of
EFT Wilson coefficients by splitting p^V_T range:



Conclusion and Perspectives

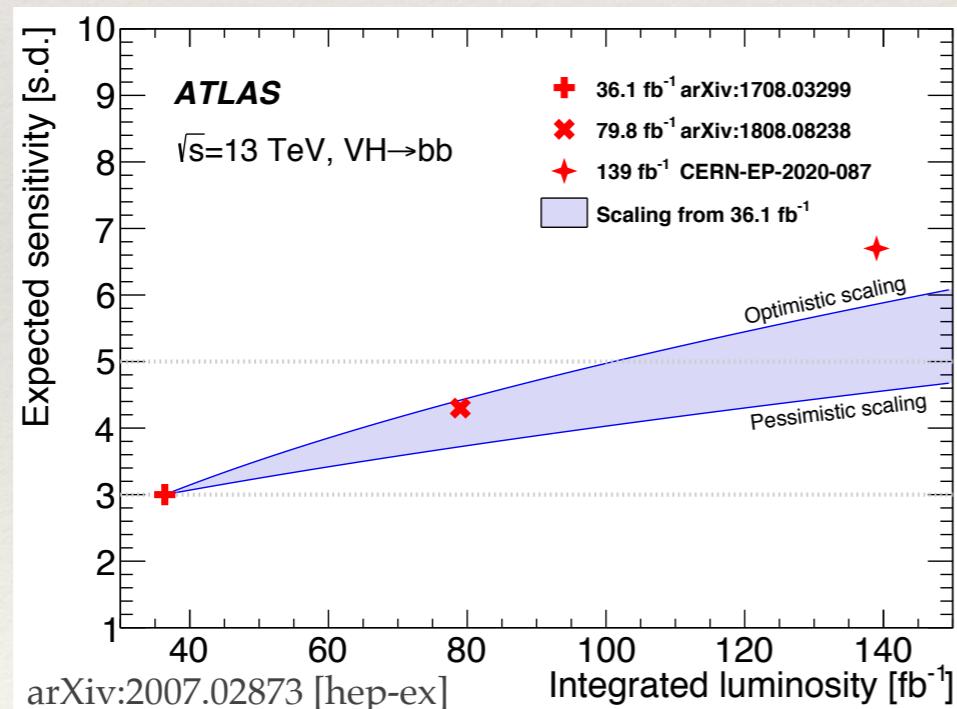
Studies of $H \rightarrow bb$ decays performed in all main production modes: VH (resolved and boosted), VBF and VBF+ γ , ggH boosted: measurements in combination of production modes important for interpretation and sensitivity to new phenomena ;

Most results reported on full Run 2 statistics, more analyses in progress and expected to be completed by the end of the year;

First p_T differential cross section results extracted for VH boosted analysis used in conjunction to resolved VH to constrain Wilson coefficients in EFTs;

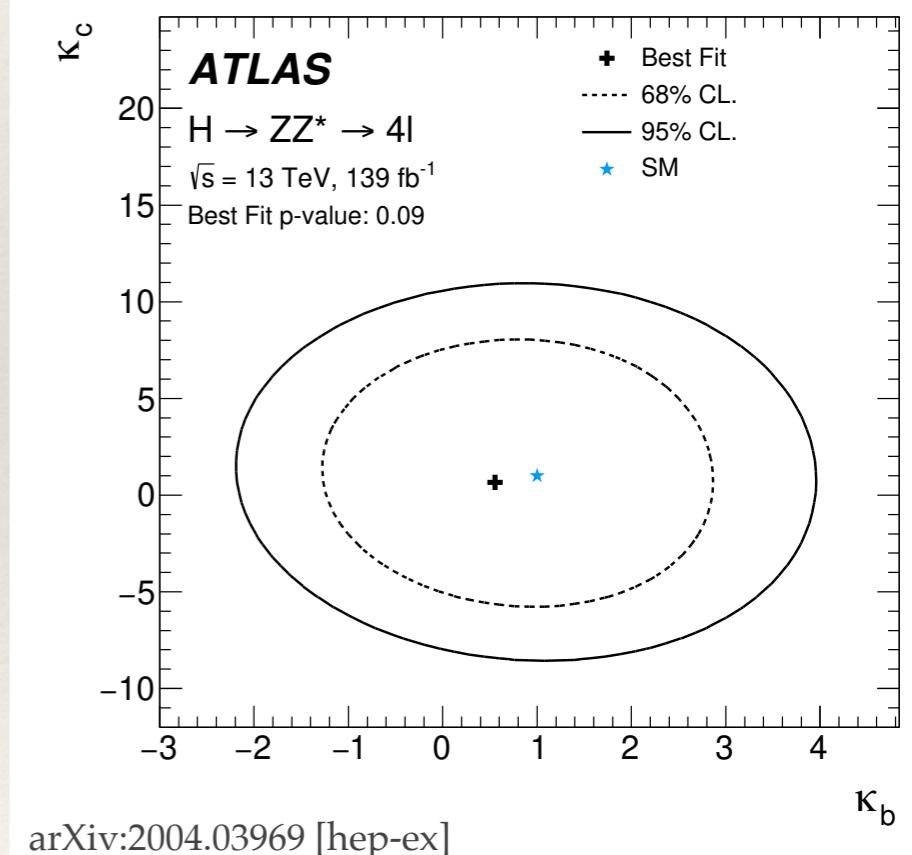
p^H_T spectrum (+ Hbb coupling) puts indirect constraint on Hcc coupling:

Results compatible with SM expectations but New Physics effects may still be much smaller than current accuracy (see, for example, MSSM, ...);

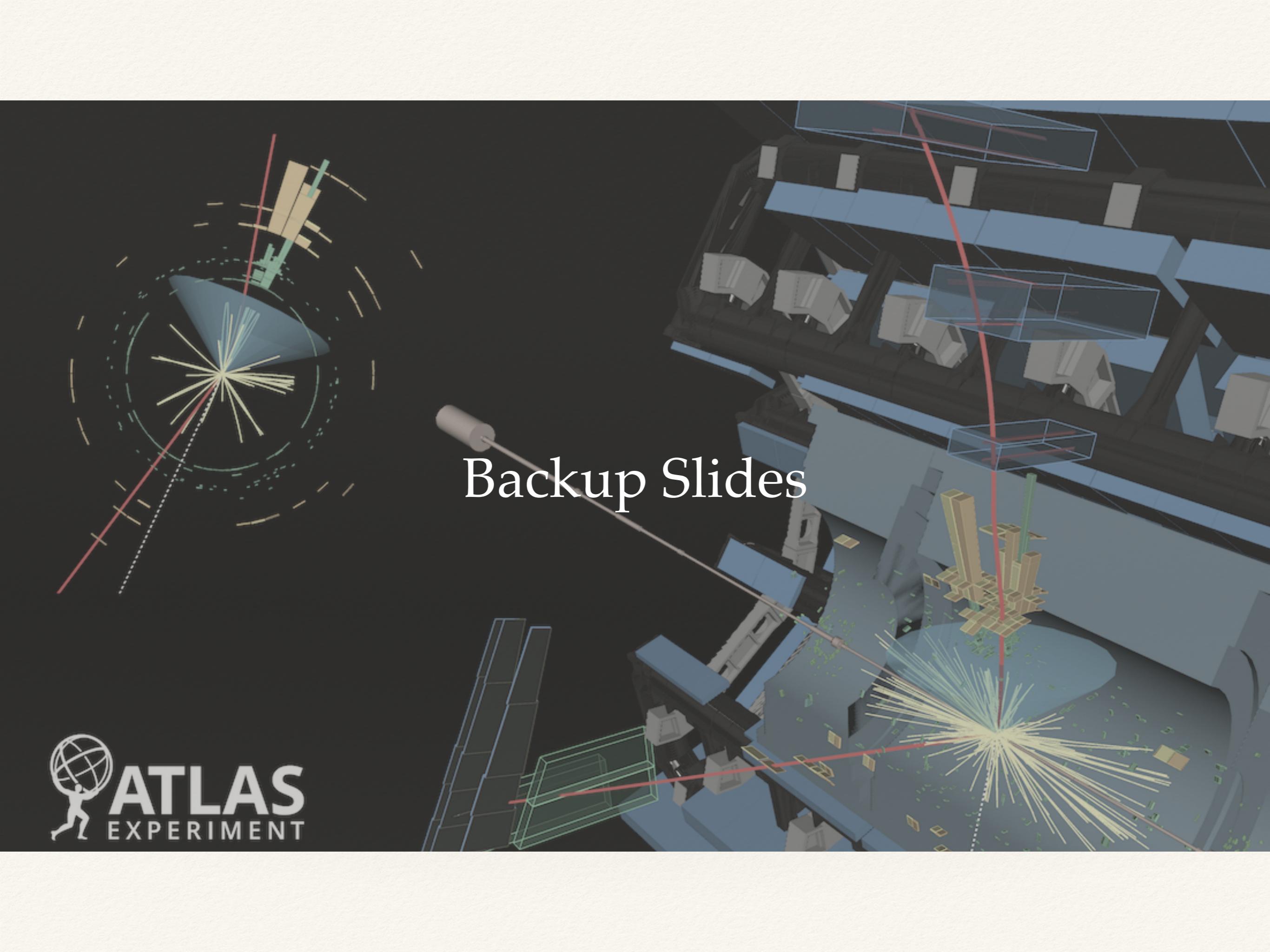


Parameter	(a) $B_{\text{inv}} = B_{\text{undet}} = 0$	(b) B_{inv} free, $B_{\text{undet}} \geq 0, \kappa_{W,Z} \leq 1$
κ_Z	1.02 ± 0.06	> 0.88 at 95% CL
κ_W	1.06 ± 0.07	> 0.89 at 95% CL
κ_b	$0.98^{+0.14}_{-0.13}$	0.92 ± 0.10
κ_t	1.00 ± 0.12	0.97 ± 0.12
κ_τ	$1.05^{+0.15}_{-0.14}$	$1.02^{+0.13}_{-0.14}$
κ_γ	$1.06^{+0.08}_{-0.07}$	$1.04^{+0.06}_{-0.07}$
κ_g	$0.96^{+0.09}_{-0.08}$	$0.93^{+0.08}_{-0.07}$
B_{inv}	-	< 0.09 at 95% CL
B_{undet}	-	< 0.19 at 95% CL

ATLAS-CONF-2020-027



$H \rightarrow bb$ remains very active and constantly improving, as size of stat. and syst. uncertainties in measurements with largest sensitivity already comparable, efforts to reduce systematics foreseen for Run 3 and HL-LHC analyses.

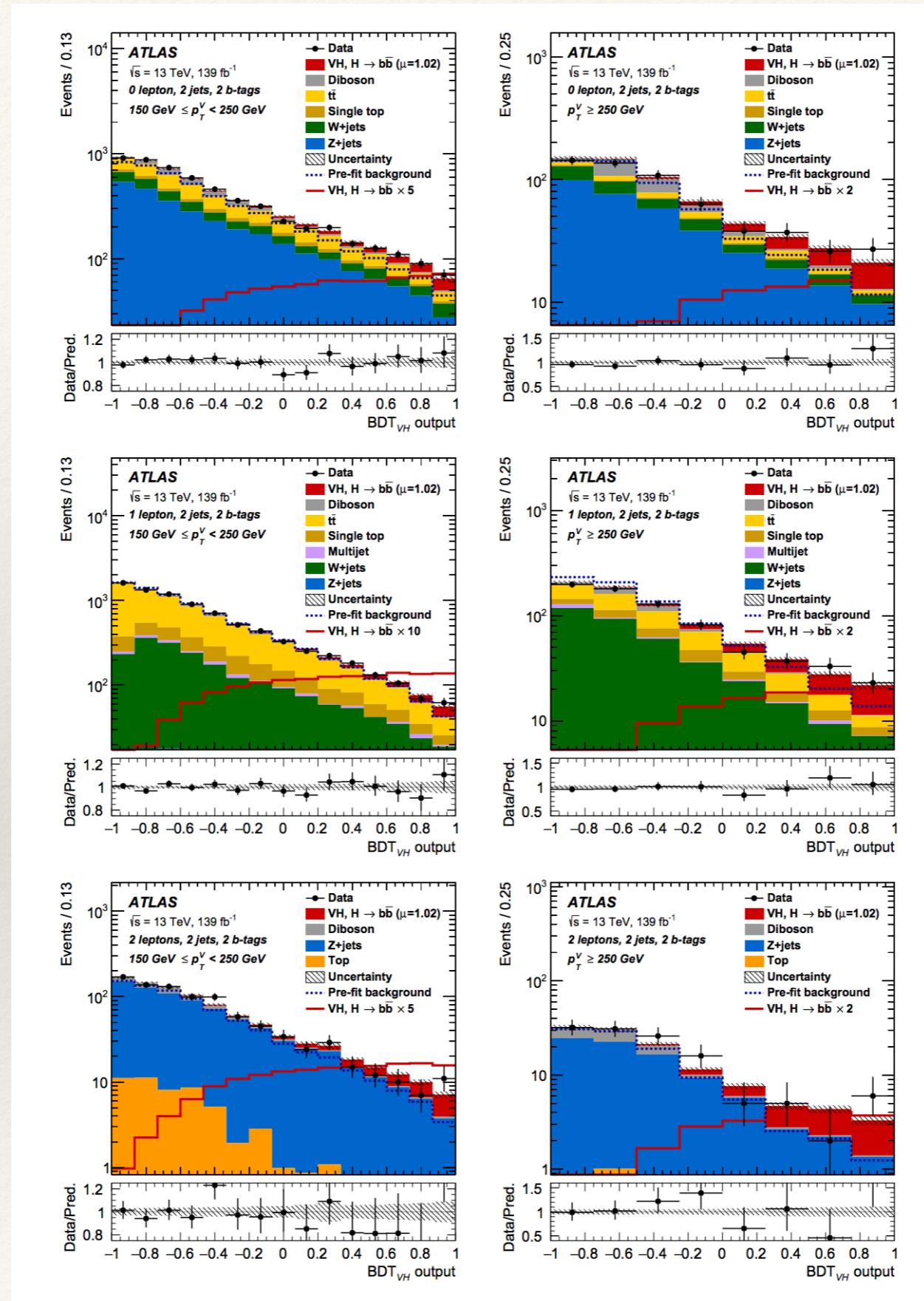


Backup Slides



WH and ZH production in the H \rightarrow bb channel

arXiv:2007.02873 [hep-ex]



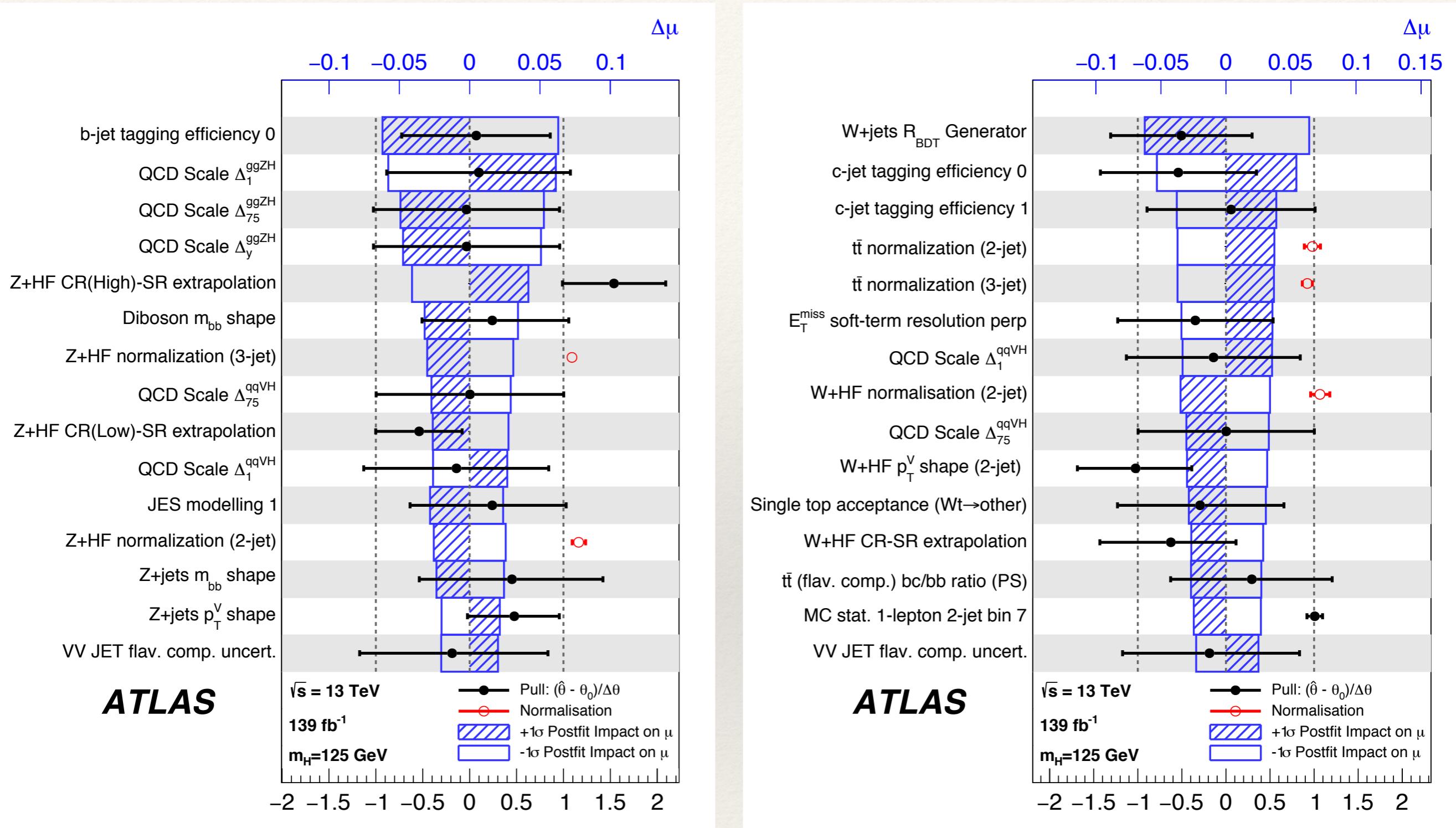
WH and ZH production in the H \rightarrow bb channel

arXiv:2007.02873 [hep-ex]

Source of uncertainty	VH	σ_μ	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_T^{miss}	0.015		0.045	0.013											
Leptons	0.004		0.015	0.005											
b -tagging	<table border="0"> <tr> <td>b-jets</td> <td>0.045</td> <td>0.025</td> <td>0.064</td> </tr> <tr> <td>c-jets</td> <td>0.035</td> <td>0.068</td> <td>0.010</td> </tr> <tr> <td>light-flavour jets</td> <td>0.009</td> <td>0.004</td> <td>0.014</td> </tr> </table>	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		
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											
$Z + \text{jets}$	0.032		0.013	0.059											
$W + \text{jets}$	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											

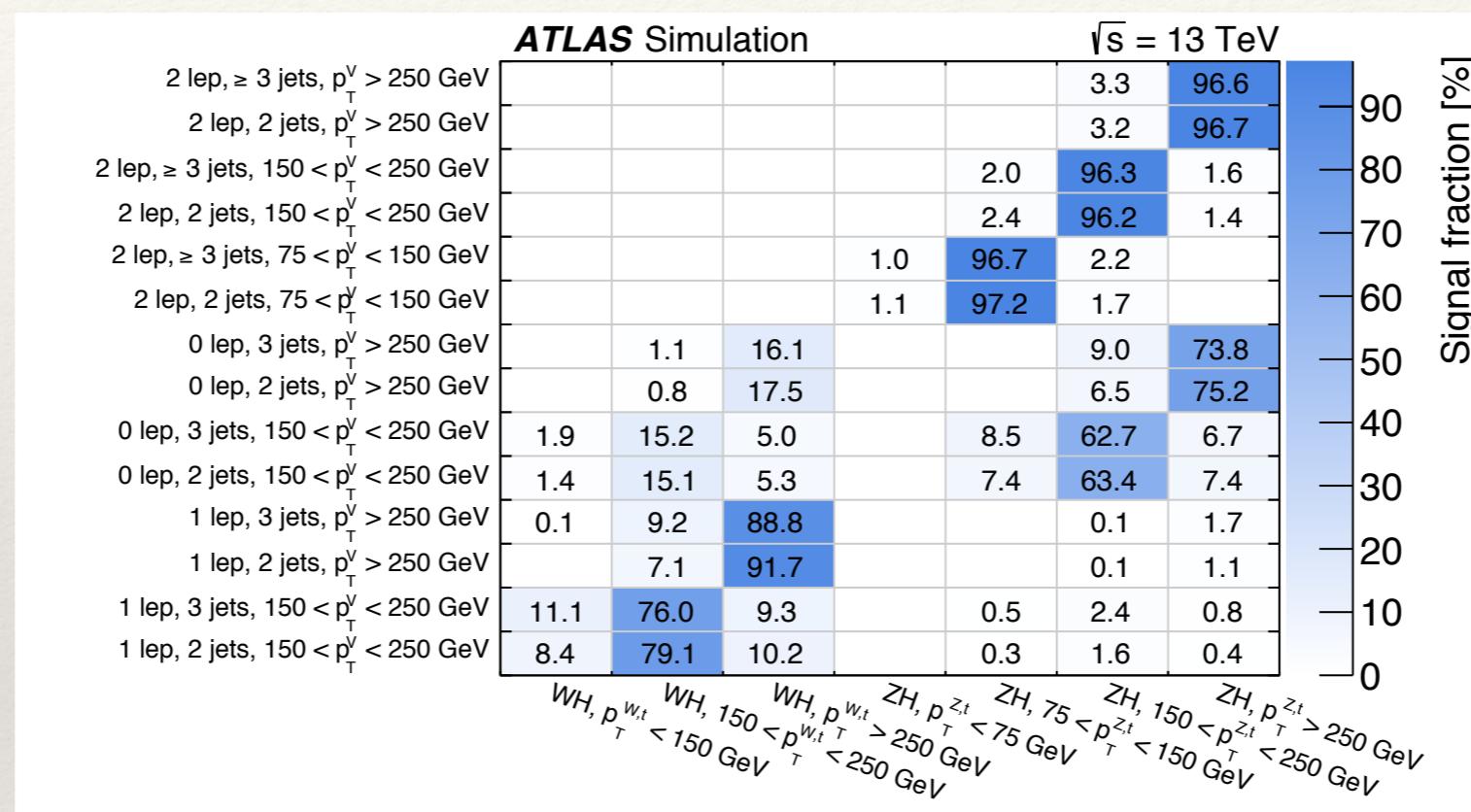
WH and ZH production in the H \rightarrow bb channel

arXiv:2007.02873 [hep-ex]



WH and ZH production in the H \rightarrow bb channel

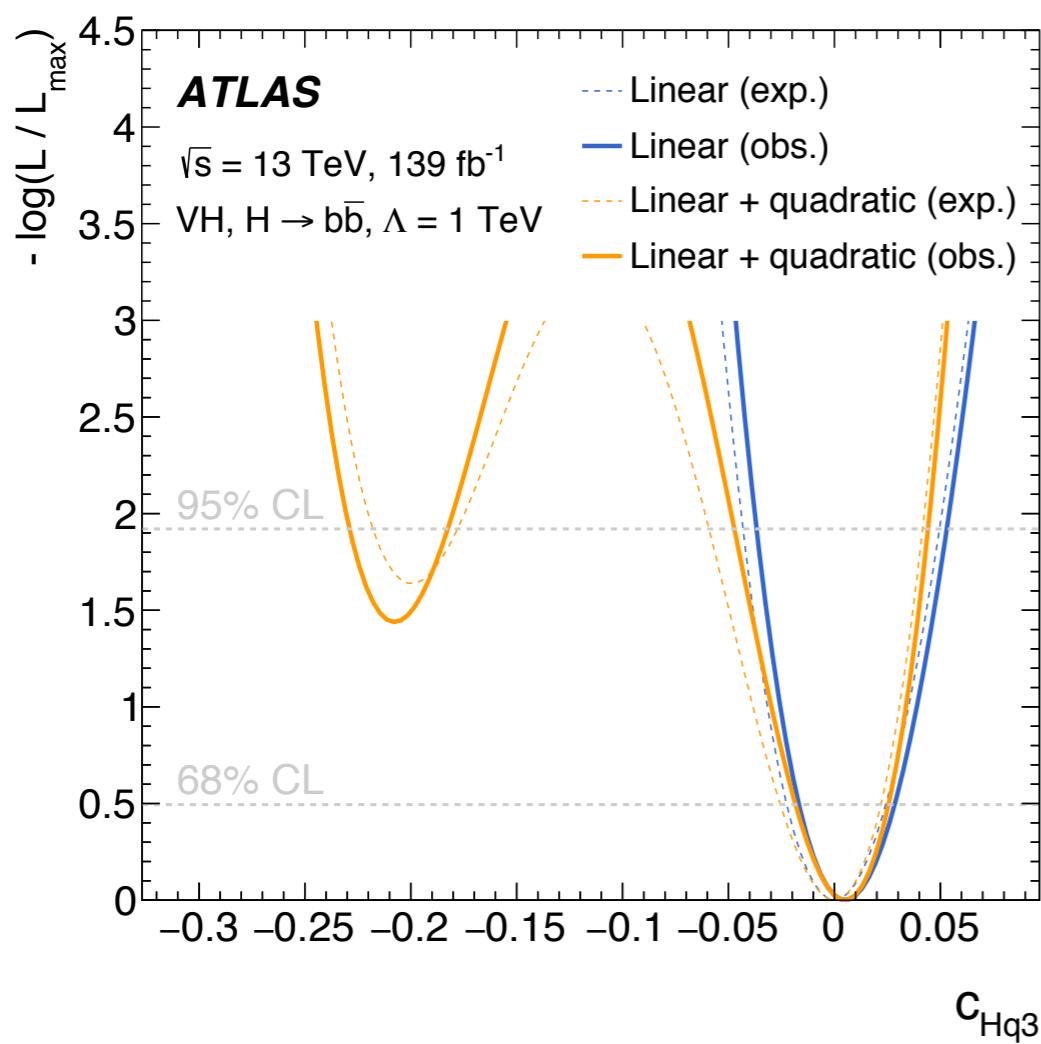
arXiv:2007.02873 [hep-ex]



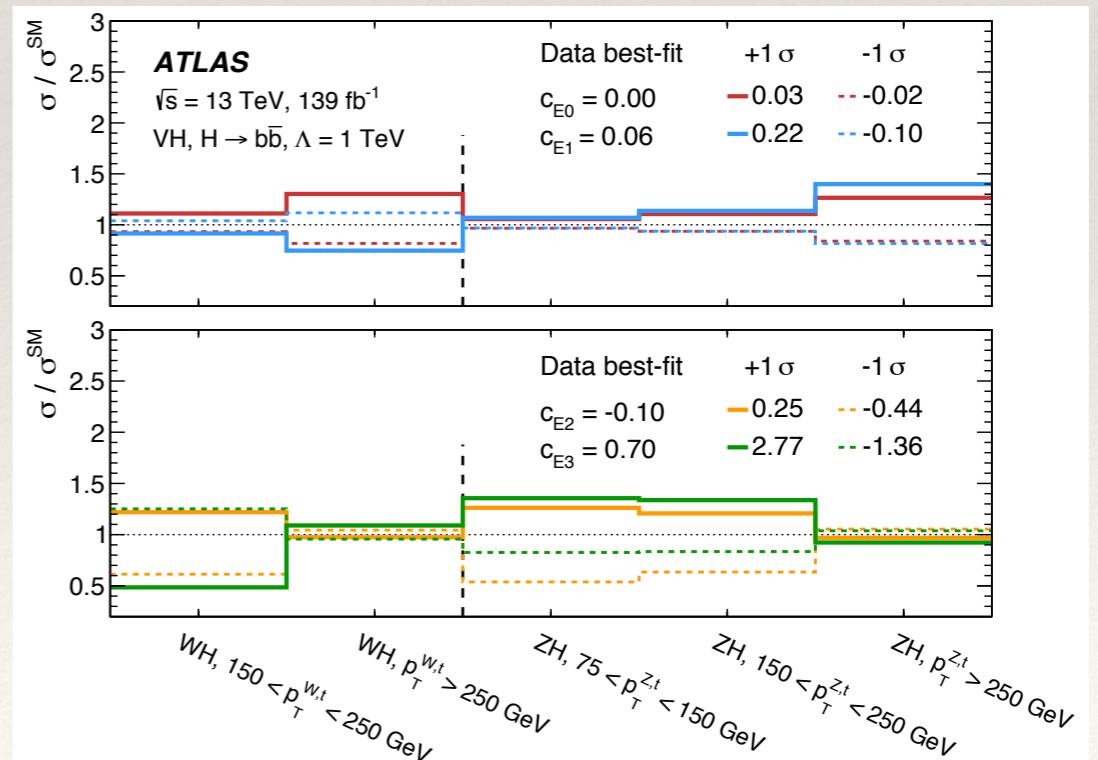
WH and ZH production in the $H \rightarrow b\bar{b}$ channel

arXiv:2007.02873 [hep-ex]

Wilson coefficient	Operator	Impacted vertex	
		Production	Decay
c_{HWB}	$\mathcal{O}_{HWB} = H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	HZZ	
c_{HW}	$\mathcal{O}_{HW} = H^\dagger H W_{\mu\nu}^I W_I^{\mu\nu}$	HZZ, HWW	
c_{Hq3}	$\mathcal{O}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$qqZH, qq'WH$	
c_{Hq1}	$\mathcal{O}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$qqZH$	
c_{Hu}	$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	$qqZH$	
c_{Hd}	$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	$qqZH$	
c_{dH}	$\mathcal{O}_{dH} = (H^\dagger H)(\bar{q}dH)$		Hbb

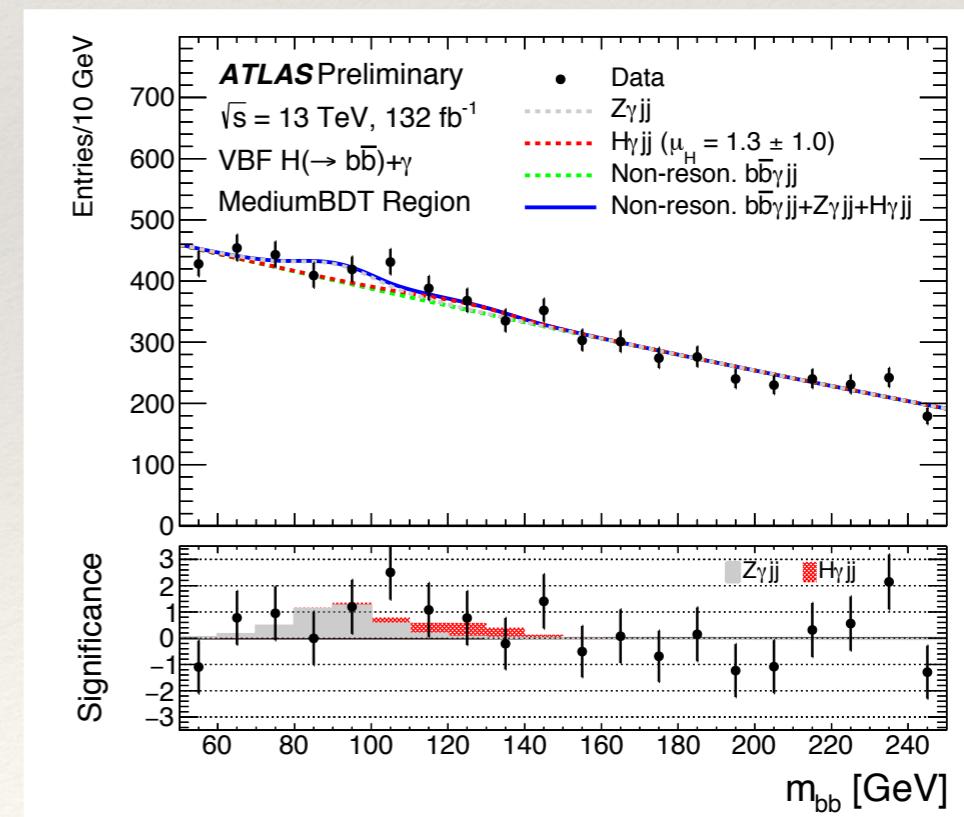
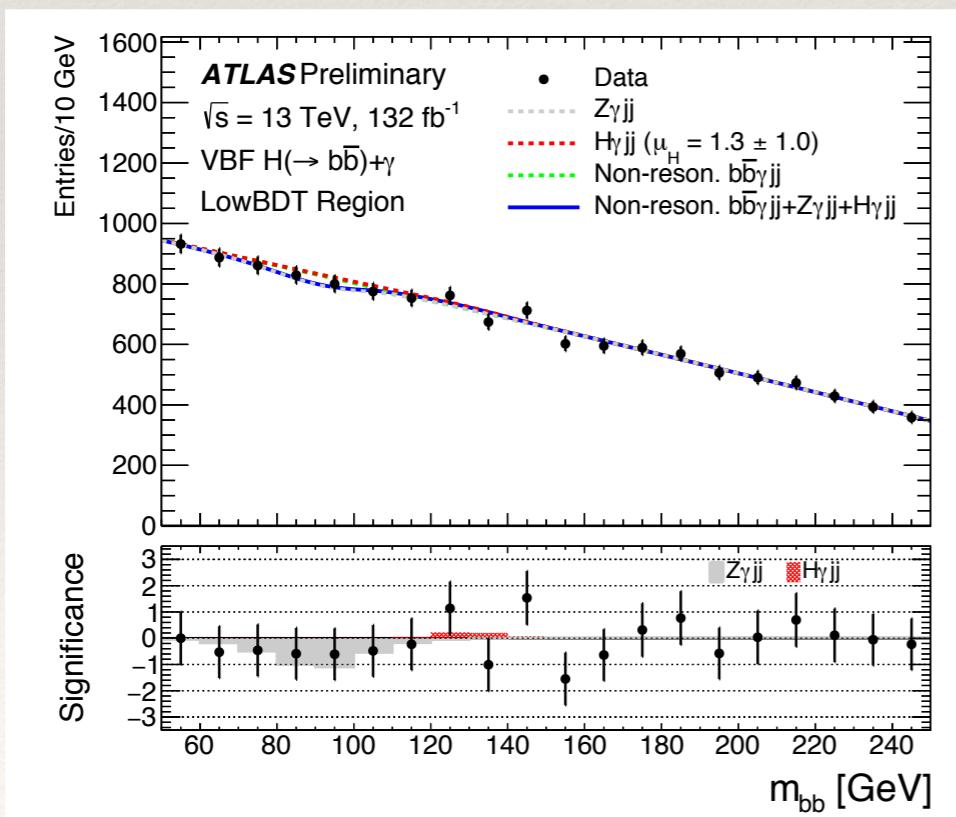
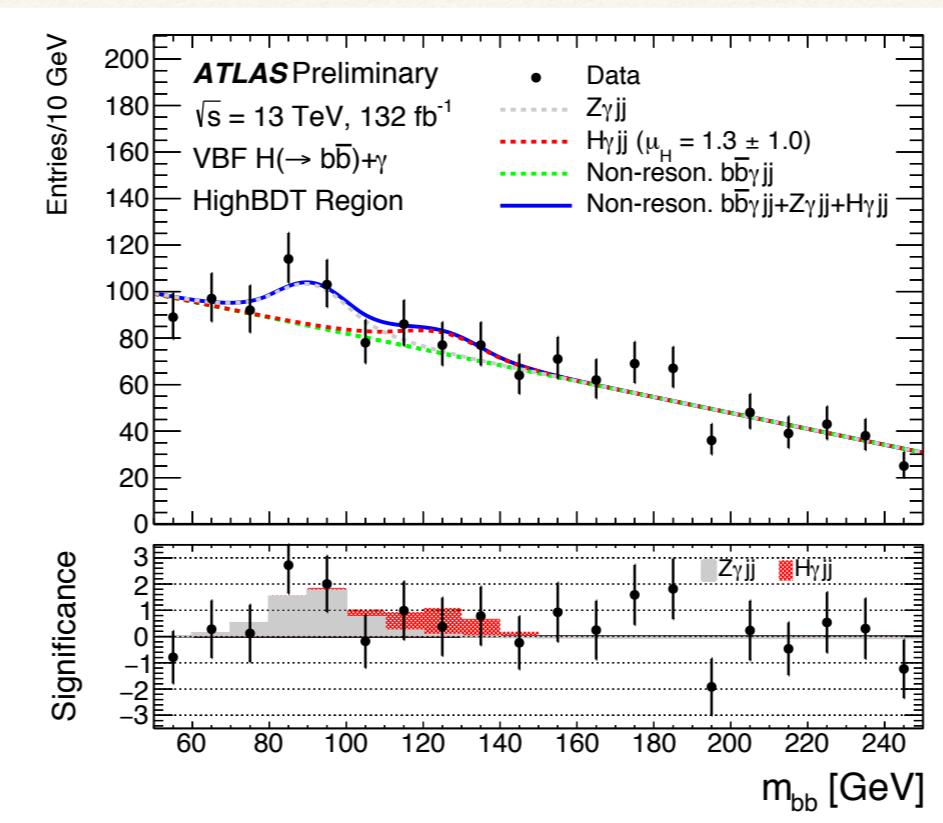


Wilson coefficient	Eigenvalue	Eigenvector
c_{E0}	2000	$0.98 \cdot c_{Hq3}$
c_{E1}	38	$0.85 \cdot c_{Hu} - 0.39 \cdot c_{Hq1} - 0.27 \cdot c_{Hd}$
c_{E2}	8.3	$0.70 \cdot \Delta BR/BR_{SM} + 0.62 \cdot c_{HW}$
c_{E3}	0.2	$0.74 \cdot c_{HWB} + 0.53 \cdot c_{Hq1} - 0.32 \cdot c_{HW}$
c_{E4}	$6.4 \cdot 10^{-3}$	$0.65 \cdot c_{HW} - 0.60 \cdot \Delta BR/BR_{SM} + 0.35 \cdot c_{Hq1}$



VBF + γ Production

ATLAS-CONF-2020-044



Uncertainty	$\sigma(\mu_H)$
Total Statistical Uncertainty	-0.96 +0.99
Data Statistical Uncertainty	-0.78 +0.80
Bkg. Fit Shape	-0.19 +0.22
Bkg. Fit Normalization	-0.51 +0.52
Z Boson Normalization	-0.15 +0.14
Total Systematic Uncertainty	-0.25 +0.32
Spurious Signal	-0.24 +0.21
Theoretical Uncertainty	-0.01 +0.08
Photon	-0.01 +0.03
Jet	-0.06 +0.20
<i>b</i> -tagging	-0.02 +0.11
Auxiliary Uncertainty	-0.01 +0.04
Total Uncertainty	-0.99 +1.04

Boosted VH

CERN-EP-2020-093

Selection	0 lepton channel	1 lepton channel		2 leptons channel	
		e sub-channel	μ sub-channel	e sub-channel	μ sub-channel
Trigger	E_T^{miss}	Single electron	E_T^{miss}	Single electron	E_T^{miss}
Leptons	0 <i>baseline</i> leptons	1 <i>signal</i> lepton $p_T > 27 \text{ GeV}$ $p_T > 25 \text{ GeV}$ no second <i>baseline</i> lepton		2 <i>baseline</i> leptons among which ≥ 1 <i>signal</i> lepton, $p_T > 27 \text{ GeV}$ both leptons of the same flavour - opposite sign muons	
E_T^{miss}	$> 250 \text{ GeV}$	$> 50 \text{ GeV}$	-		-
p_T^V			$p_T^V > 250 \text{ GeV}$		
Large- R jets		at least one large- R jet, $p_T > 250 \text{ GeV}$, $ \eta < 2.0$			
Track-jets		at least two track-jets, $p_T > 10 \text{ GeV}$, $ \eta < 2.5$, matched to the leading large- R jet			
b -jets		leading two track-jets matched to the leading large- R must be b -tagged (MV2c10, 70%)			
m_J		$> 50 \text{ GeV}$			
$\min[\Delta\phi(\vec{E}_T^{\text{miss}}, \text{small-}R \text{ jets})]$	$> 30^\circ$	-			
$\Delta\phi(\vec{E}_T^{\text{miss}}, H_{\text{cand}})$	$> 120^\circ$	-			
$\Delta\phi(\vec{E}_T^{\text{miss}}, E_{T, \text{trk}}^{\text{miss}})$	$< 90^\circ$	-			
$\Delta y(V, H_{\text{cand}})$	-	$ \Delta y(V, H_{\text{cand}}) < 1.4$			
$m_{\ell\ell}$		-		$66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$	
Lepton p_T imbalance		-		$(p_T^{\ell_1} - p_T^{\ell_2})/p_T^Z < 0.8$	

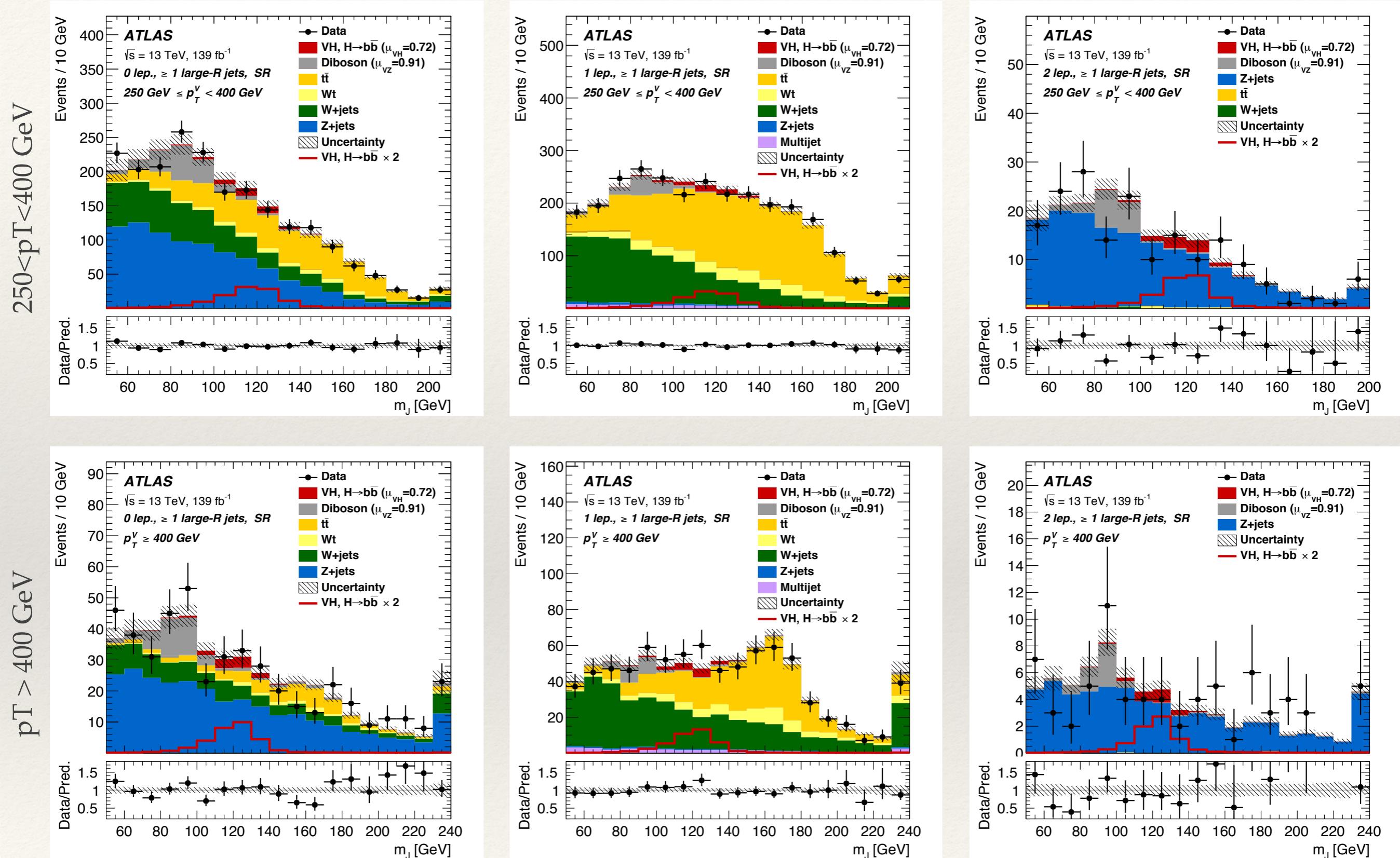
Boosted VH

CERN-EP-2020-093

Channel	Categories					
	250 < p_T^V < 400 GeV			$p_T^V \geq 400$ GeV		
	0 add. small- R jets	≥ 1 add. small- R jets	≥ 1 add. b -track-jets	0 add. small- R jets	≥ 1 add. small- R jets	≥ 1 add. b -track-jets
0-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
1-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
2-lepton	SR			SR		

Boosted VH

CERN-EP-2020-093



Boosted VH

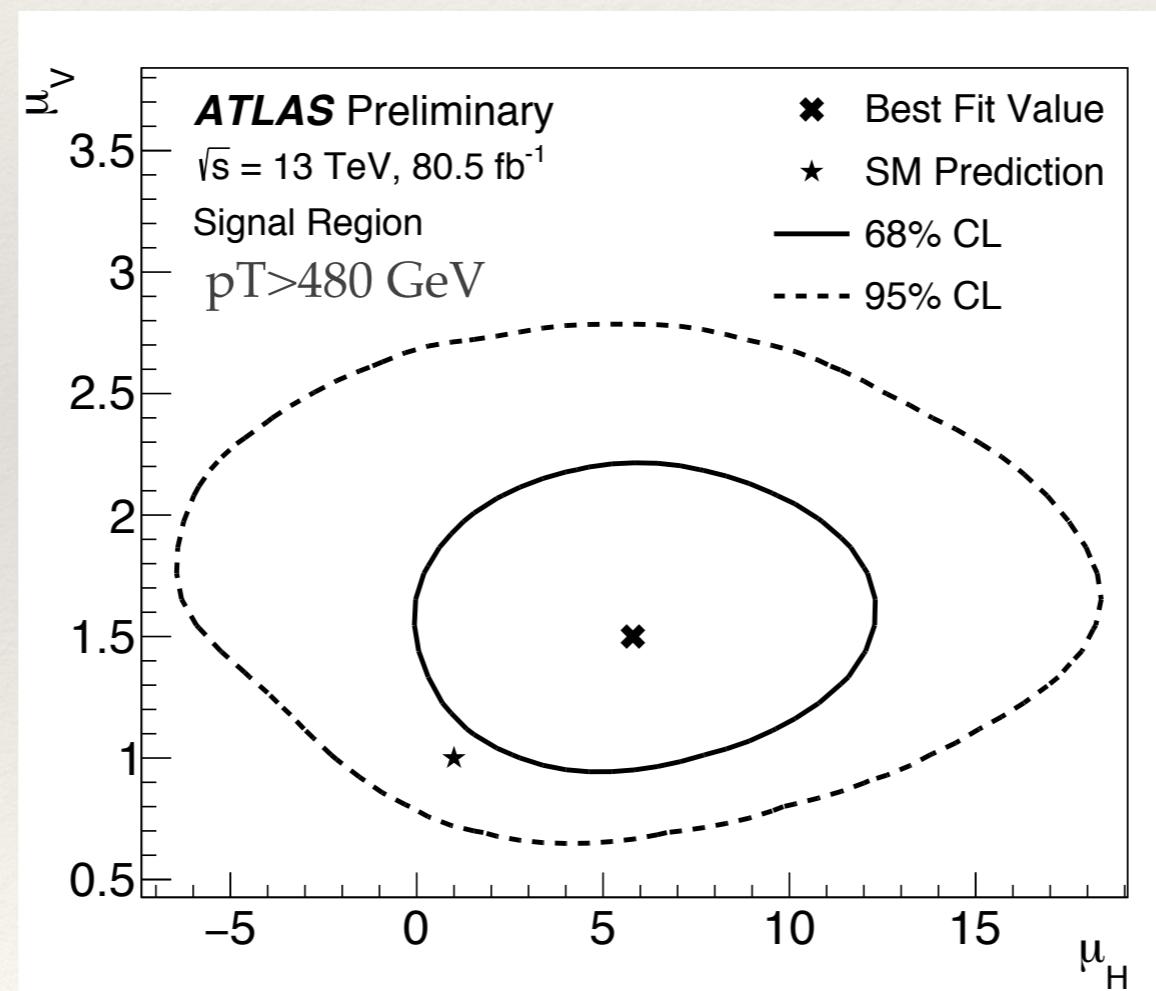
CERN-EP-2020-093

Source of uncertainty	Avg. impact
Total	0.372
Statistical	0.283
Systematic	0.240
Experimental uncertainties	
Small- R jets	0.038
Large- R jets	0.133
E_T^{miss}	0.007
Leptons	0.010
b -tagging	0.016 0.011 0.008 0.004
Pile-up	0.001
Luminosity	0.013
Theoretical and modelling uncertainties	
Signal	0.038
Backgrounds	0.100
$\rightarrow Z + \text{jets}$	0.048
$\rightarrow W + \text{jets}$	0.058
$\rightarrow t\bar{t}$	0.035
\rightarrow Single top quark	0.027
\rightarrow Diboson	0.032
\rightarrow Multijet	0.009
MC statistical	0.092

Boosted ggF

ATLAS-CONF-2018-052

Process	CR _{QCD} Eff. (%)	CR _{QCD} Yield 80.5 fb ⁻¹	CR _{QCD} Yield 1.4 fb ⁻¹	SR Eff. (%)	SR Yield 80.5 fb ⁻¹
$Z \rightarrow q\bar{q} + \text{jets}$	46.2	84400	1470	3.4	6200
$W \rightarrow q\bar{q} + \text{jets}$	51.3	219000	3810	0.4	1500
$t\bar{t}$	25.9	110900	1929	2.5	10550
$H \rightarrow bb \text{ (ggF)}$	23.6	140	2	19.4	115
$H \rightarrow b\bar{b} \text{ (VBF)}$	15.8	41	1	20.7	53
$H \rightarrow b\bar{b} \text{ (WH)}$	32.4	71	1	12.0	26
$H \rightarrow b\bar{b} \text{ (ZH)}$	30.5	40	1	15.8	21
$H \rightarrow bb \text{ (Total)}$	24.3	292	5	17.9	216
Data	38.7	29883000	519710	0.6	484600



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