Higgs boson couplings to bottom quarks at the ATLAS experiment

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On behalf of the ATLAS Collaboration

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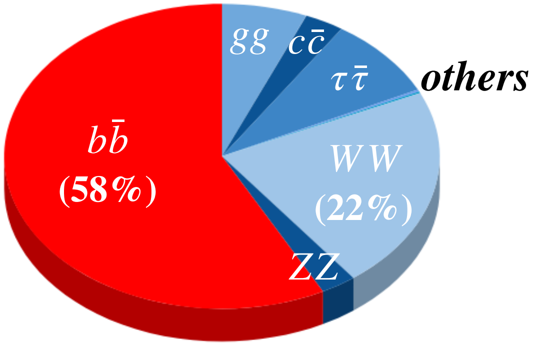
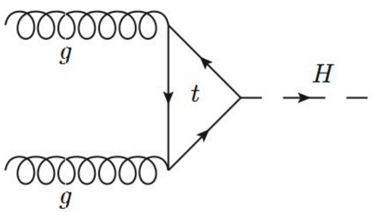
Introduction

- H → $b\bar{b}$ **dominant decay**
  - Measurement of the **b-quark Yukawa coupling** has a **leading impact** on the estimate of **Higgs width** (Γ_H)
  - Provides **enhanced sensitivity** to some **Beyond the SM** (BSM) physics models in the **high p_T regime**



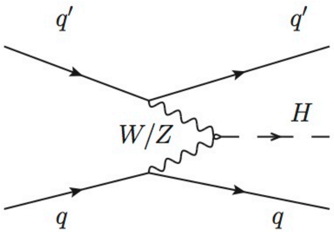
- Different analyses study the H→$b\bar{b}$ decays depending on the Higgs production mode

ggF+ISR boosted H($b\bar{b}$) analysis
ATLAS-CONF-2018-052



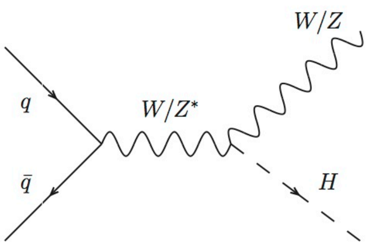
- **Higgs + jet** in the final state
- Highly **boosted jets**

VBF($b\bar{b}$) analysis
Phys.Rev. D 98 (2018) 052003



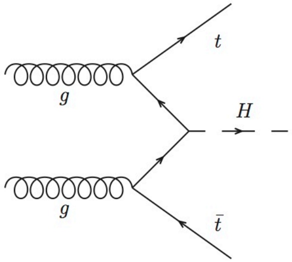
- **All hadronic analysis** with **forward jets**
- **VBF($b\bar{b}$)+γ analysis**

VH($b\bar{b}$) analysis



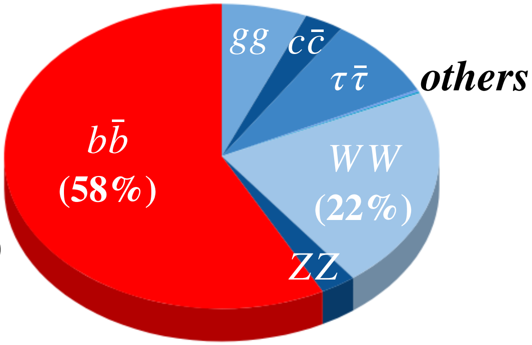
- Triggered by **leptonic decays of the vector boson V(V=Z or W)**
- **Resolved analysis** [ATLAS-CONF-2020-006]
- **New boosted analysis** [ATLAS-CONF-2020-007]

ttH($b\bar{b}$) analysis
Phys.Rev. D 97 (2018) 072016



- **Semileptonic decay** of a least on **top quark**

Introduction



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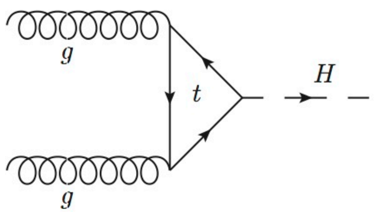

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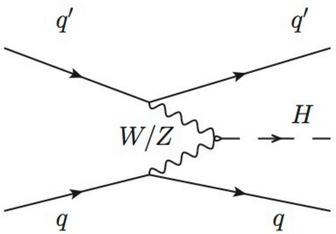

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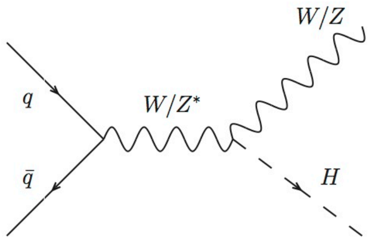
- **VBF($b\bar{b}$)+γ analysis**

VH($b\bar{b}$) analysis



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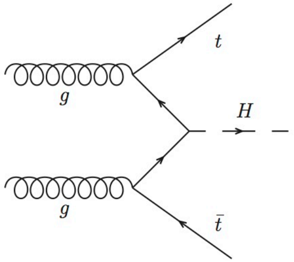
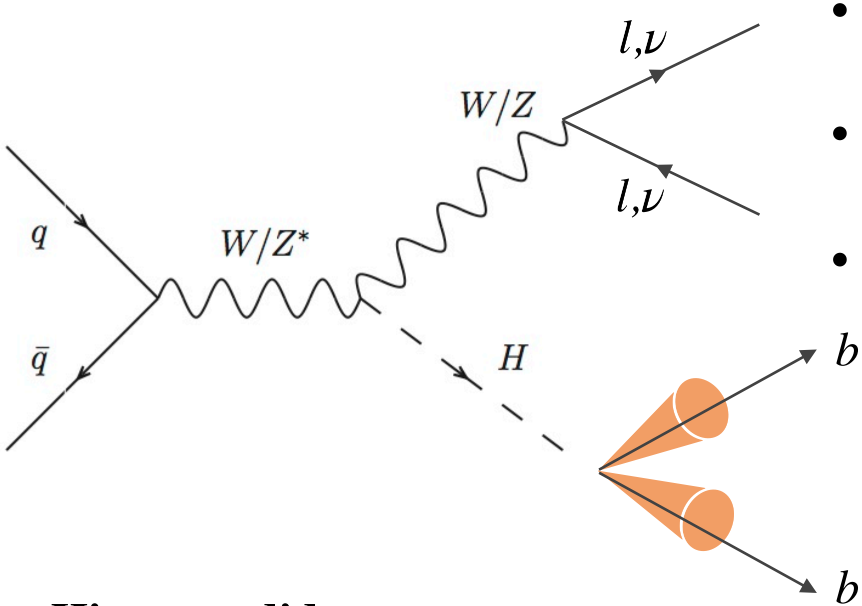


- **Semileptonic decay** of a least on **top quark**

VH($b\bar{b}$) analyses **updated** to the **full Run 2 dataset**

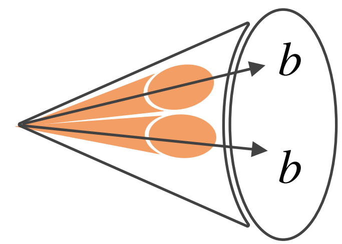
VH($b\bar{b}$) channel



Vector boson candidate reconstruction

- Z $\rightarrow \nu\bar{\nu}$: Missing transverse momentum E_T^{miss}
  ↪ **0-lepton channel (0L)**
- W $\rightarrow l\nu$: 1 charged lepton (e, μ)
  ↪ **1-lepton channel (1L)**
- Z $\rightarrow l\bar{l}$: 2 charged leptons ($ee, \mu\mu$)
  ↪ **2-lepton channel (2L)**

Increase p_T^H



Higgs candidate reconstruction:

Resolved analysis

- Exactly **2 small-R jets** (R=0.4) ***b*-tagged** [70% efficiency for *b*-jets]

Boosted analysis

- **1 large-R jet** (R=1)
- **2 leading track jets *b*-tagged** [70% efficiency for *b*-jets]

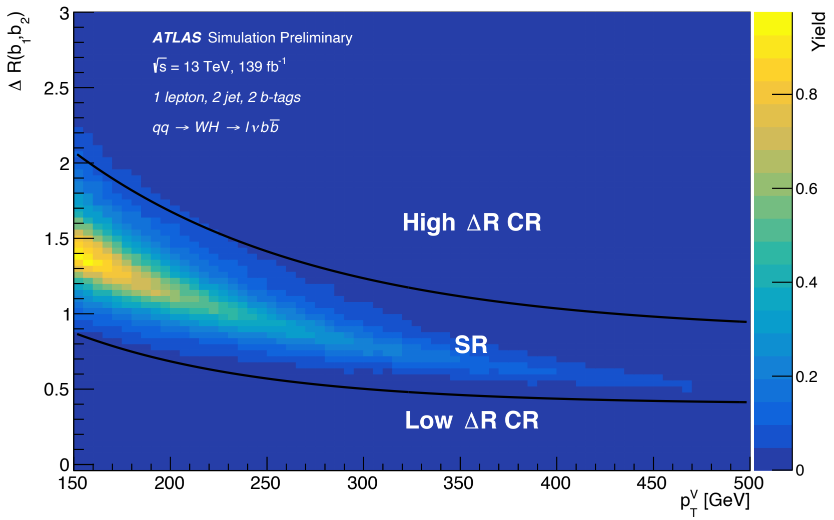
VH($b\bar{b}$) resolved: event categorization

Event categorization:

Channel	0/1-lepton	2-lepton
Number of small-R jets	2/3 jets	2/3+ jets
p_T^V	150-250 GeV >250 GeV	75-150 GeV 150-250 GeV >250 GeV

Signal (SR) and control region (CR) definition:

- Continuous cuts on $\Delta R(b_1, b_2)$ as a function of p_T^V



High ΔR CR: enriched in $t\bar{t}$

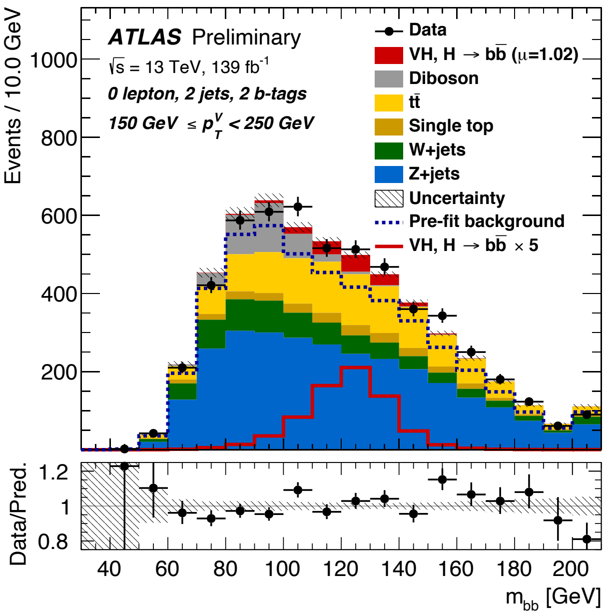
SR: contains > 80% signal events

Low ΔR CR: enriched in V+jets

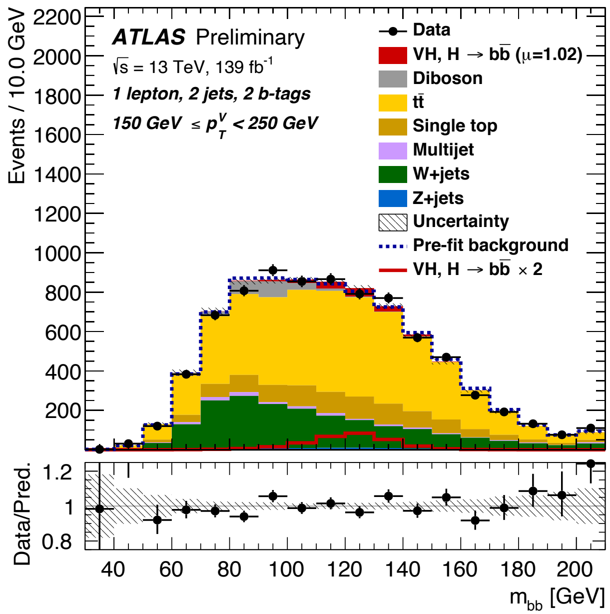
Total:
14 SRs + 28 CRs

VH($b\bar{b}$) resolved: main backgrounds

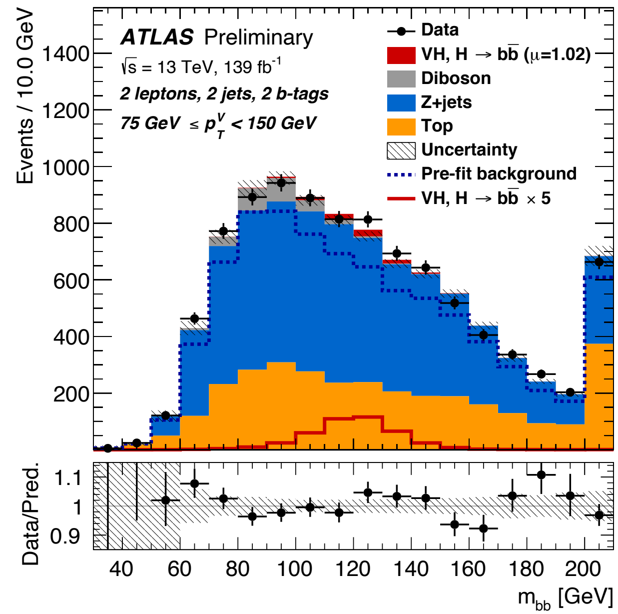
0-lepton



1-lepton



2-lepton



Main backgrounds:

- **Z+jets** and **W+jets**
- **$t\bar{t}$** and **single top**

} Dominant backgrounds, constrained with CR

- **top** ($t\bar{t}$, single-top)→ only in 2L, contribution studied using data-driven method from e-μ events
- **Diboson** (**WZ, ZZ**) → final state similar to VH when $Z \to b\bar{b}$, used to validate the analysis (diboson analysis)
- **Multijets** → suppressed to negligible levels in 0L/2L by dedicated criteria, evaluated in 1L using data-driven method

VH($b\bar{b}$) resolved: Multivariate analysis

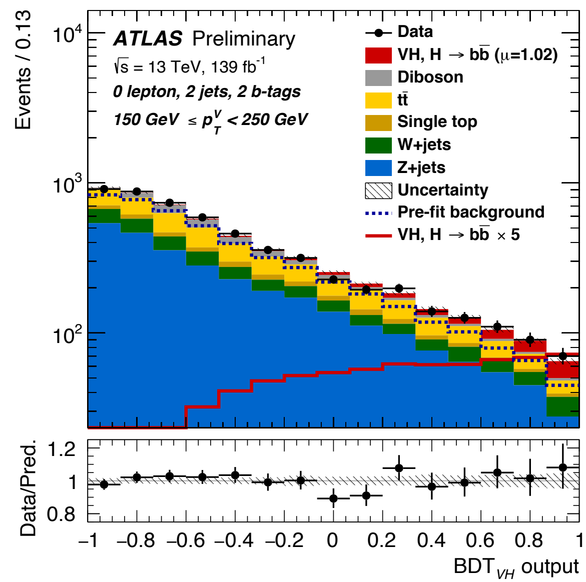
Most powerful

Variable	0-lepton	1-lepton	2-lepton
m_{bb}	×	×	×
$\Delta R(\vec{b_1}, \vec{b_2})$	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
p_T^V	$\equiv E_T^{miss}$	×	×
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
MV2(b_1)	×	×	
MV2(b_2)	×	×	
$\lvert\Delta\eta(\vec{b_1}, \vec{b_2})\rvert$	×		
m_{eff}	×		
$p_T^{miss,st}$	×		
E_T^{miss}	×	×	
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
m_T^W		×	
$\lvert\Delta y(\vec{V}, \vec{bb})\rvert$		×	
m_{top}		×	
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			×
$E_T^{miss}/\sqrt{S_T}$			×
$m_{\ell\ell}$			×
$\cos\theta(\vec{\ell^-}, \vec{Z})$			×
Only in 3-jet events			
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

Boosted Decision Tree (BDT):

- Input: **kinematics variables** and ***b*-tagging info**
- Output: BDT variable

→ discriminate between signal and bkg events

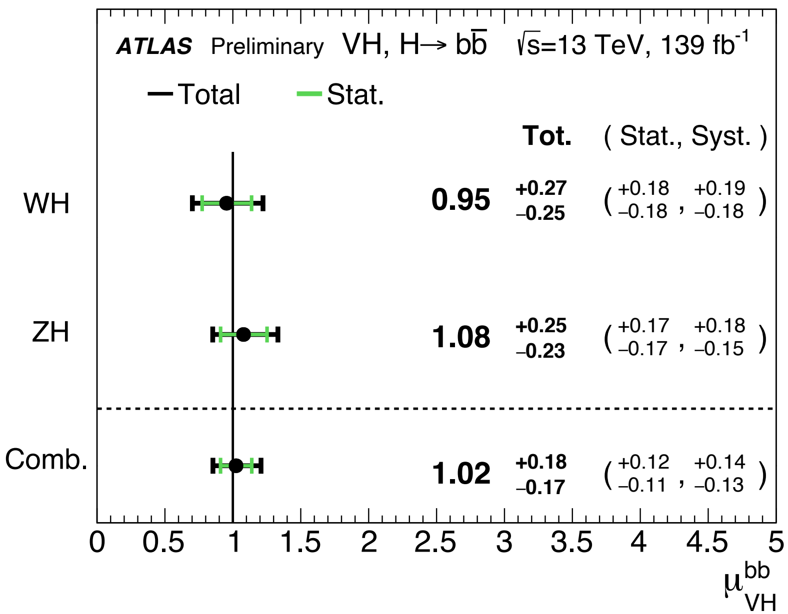


Simultaneous **profile likelihood fit to the BDT outputs** in the **SRs** and to **the event yields** in the **CRs**

→ to extract the signal strength μ

$$\mu_{VH}^{bb} = \frac{(\sigma(VH) \times BR(H \to b\bar{b}))_{measured}}{(\sigma(VH) \times BR(H \to b\bar{b}))_{SM}}$$

VH($b\bar{b}$) resolved: Results

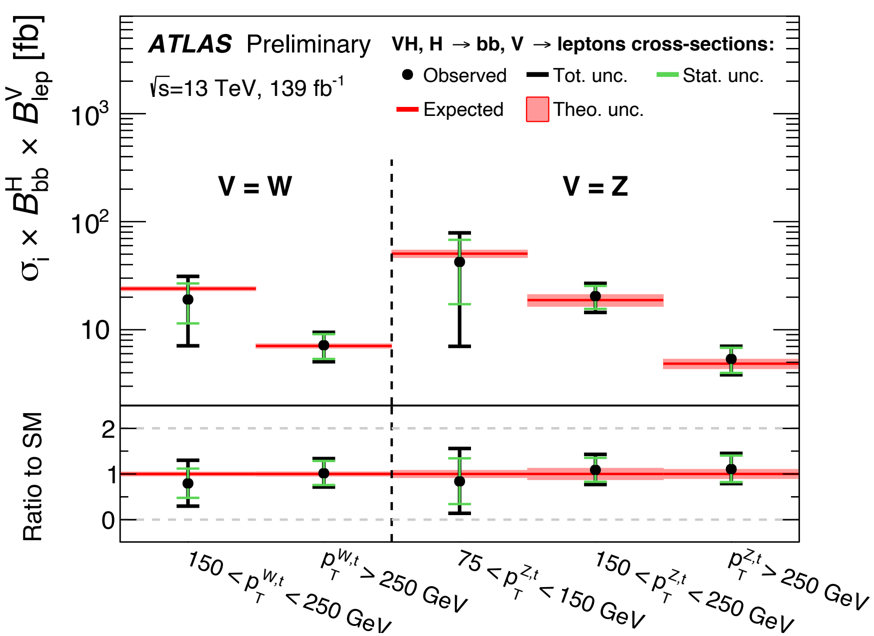


<u>Observed (expected) significance</u>:

- **VH:** 6.7 (6.7) σ
- **WH**: 4.0 (4.1) σ
  - → **strong evidence of WH($b\bar{b}$) production**
- **ZH**: 5.3 (5.1) σ
  - → **observation of ZH($b\bar{b}$) production**

Dijet-mass analysis and **diboson analysis** used to validate the multivariate analysis

- **5σ observation** of **VH($b\bar{b}$)** from the **dijet-mass analysis**

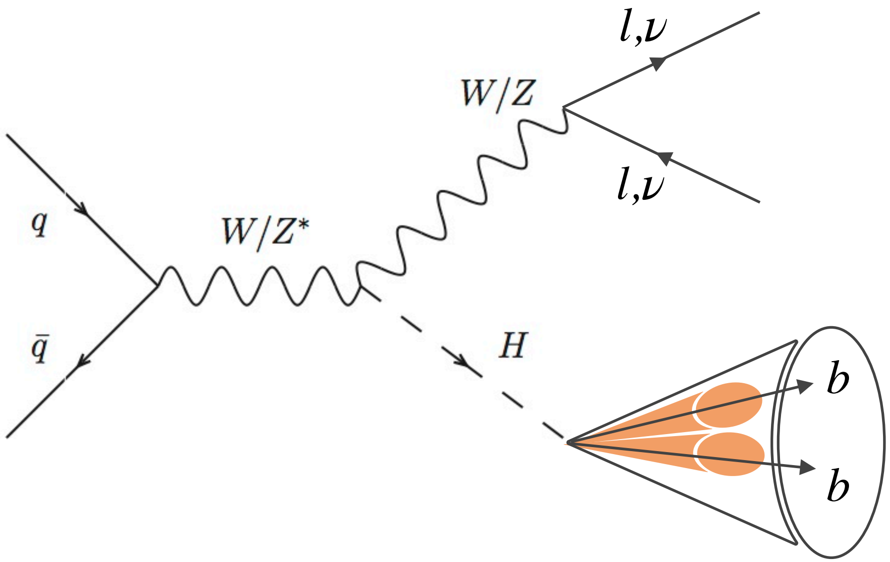


Differential cross-section measurement

- Performed using **Simplified Template Cross Section (STXS) framework in 5 bins**
- **Good agreement with SM predictions**

VH($b\bar{b}$) boosted

- **Aim:**
  - To study high p_T VH production → **focus on p_T^V > 250 GeV**
  - To establish boosted H($b\bar{b}$) reconstruction techniques for Higgs measurements → **robust & standalone analysis**



Higgs-candidate reconstruction:

- Leading large-R jet
  - $p_T > 250$ GeV, $|\eta| < 2.0$;
  - ≥ 2 associated variable-radius track jets
    - Leading 2 b-tagged

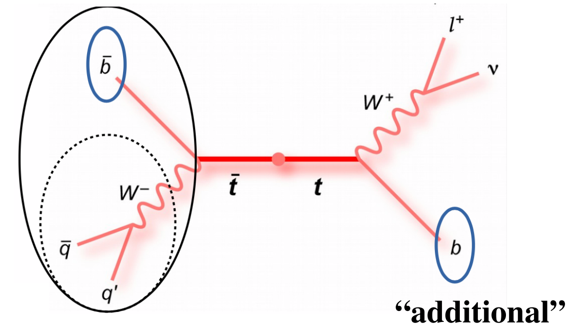
Event selection:

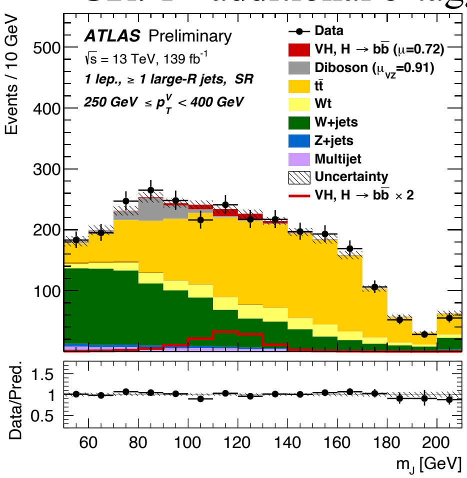
- Built up on "resolved" VH($b\bar{b}$) analysis

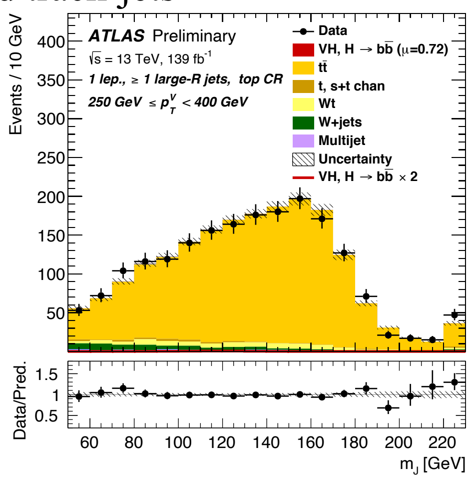
Final discriminant: **large-R jet mass m_J**

VH($b\bar{b}$) boosted: event categorization

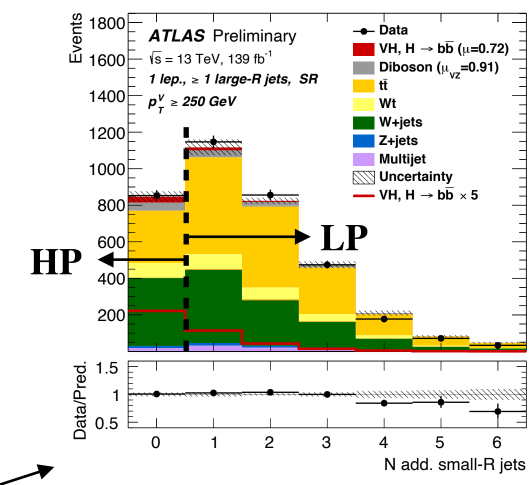
- **Channel:** 0-lepton, 1-lepton and 2-lepton channel
- **p_T^V split**:
    - 250 GeV < p_T^V < 400 GeV,
    - p_T^V > 400 GeV;
- **SR/CR definition** (only in 0L/1L): # additional b-tagged track-jets
    - **SR**: 0 additional b-tagged track-jets
    - **CR**: 1+ additional b-tagged track-jets







- **SR splitting** (only in 0L/1L): # additional small-R jets
    - **High Purity (HP) SR**: 0 additional small-R jets
    - **Low Purity (LP) SR**: 1+ additional small-R jets



Total:
10 SRs + 4 CRs

VH($b\bar{b}$) boosted: Results

- **Binned profile likelihood fit** in m_J in 14 regions:
  - *simultaneously* extracting **VH($b\bar{b}$) and VZ($b\bar{b}$) signal strengths (μ_{VH}, μ_{VZ})**

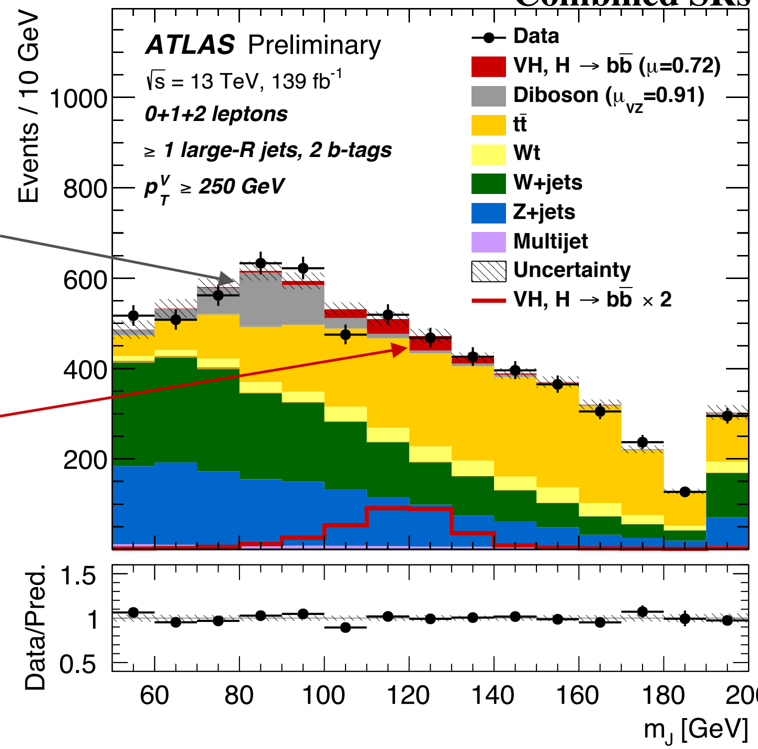
$$\mu_{VZ} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(stat.)^{+0.25}_{-0.17}(syst.)$$

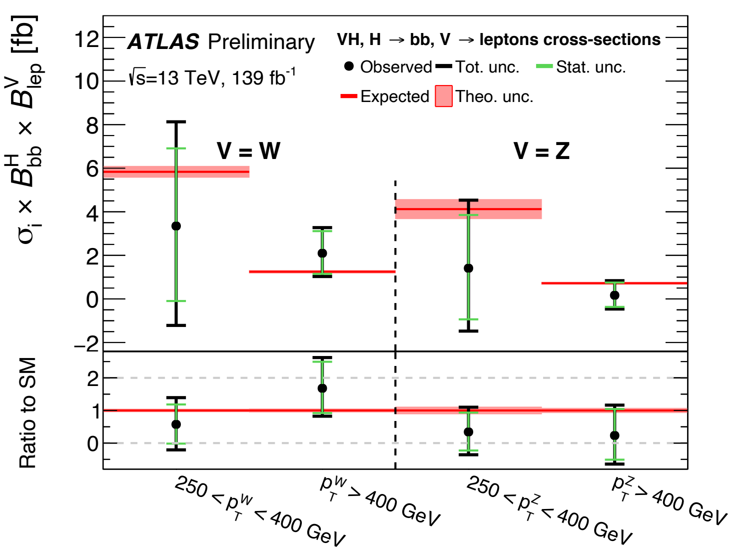
Obs.(exp) significance: 5.2 (5.7) σ

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

Obs.(exp) significance: 2.1 (2.7) σ

Combined SRs





Differential cross-section measurement

- Performed using **STXS framework in 4 bins**
- **First measurement of $p_T^V > 400$ GeV**
- **Good agreement** with **SM prediction**

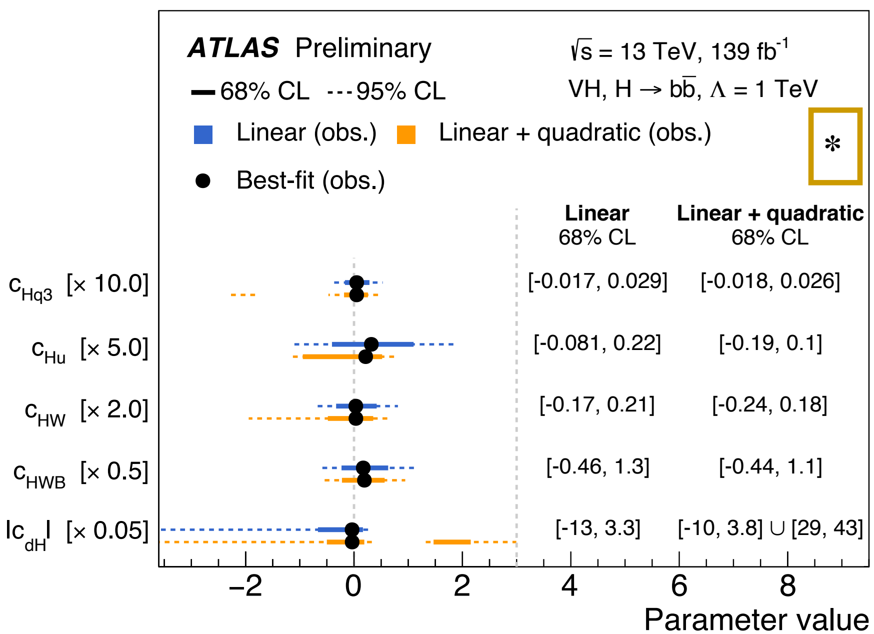
Constraints on BSM parameters

- Parameterization of BSM effects using **effective Lagrangian** with **dimension-6 operators** in the Warsaw basis: $\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i c_i^{(6)} \cdot \mathcal{O}_i^{(6)}/\Lambda^2$
  - $c_i^{(6)}$ = Wilson coefficient
  - $\mathcal{O}_i^{(6)}$ = dimension-6 operator
  - Λ = BSM scale

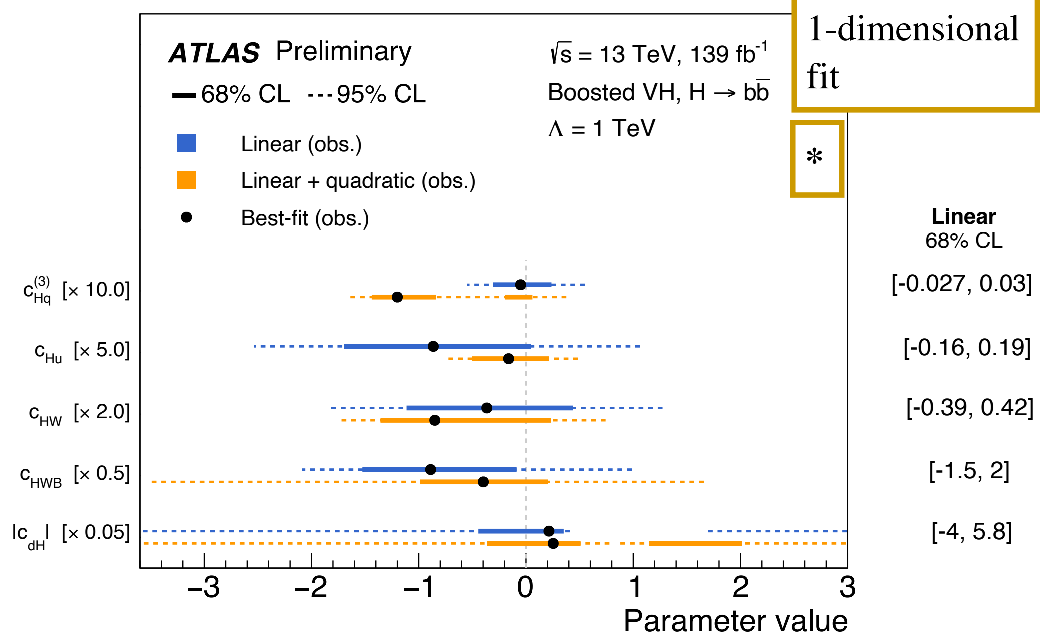
Coefficient	Operator
c_{HWB}	$O_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$
c_{HW}	$O_{HW} = H^\dagger H W^I_{\mu\nu} W^{\mu\nu}_I$
c_{Hq3}	$O^{(3)}_{Hq} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
c_{Hu}	$O_{Hu} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
c_{dH}	$O_{dH} = (H^\dagger H)(\bar{q} d H)$

- **Same set** of **Wilson coefficients** studied by both VH($b\bar{b}$) analyses

Resolved analysis



Boosted analysis



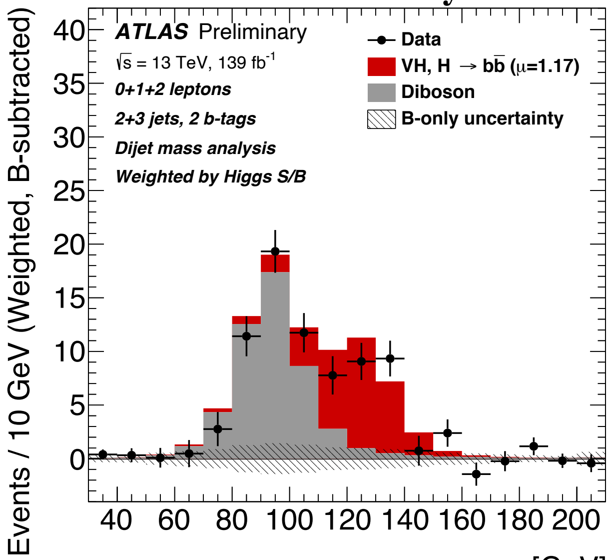
* results from 1-dimensional fit

- Results are all **consistent with the SM expectations**

Conclusions

- **Measurement of VH($b\bar{b}$) process** from ATLAS using the **full Run 2** dataset
- **<u>Resolved VH($b\bar{b}$):</u>**
    - Observation of ZH($b\bar{b}$)
    - Strong evidence of WH($b\bar{b}$)
    - Observation of VH($b\bar{b}$) from dijet-mass analysis
- **<u>Boosted VH($b\bar{b}$):</u>**
    - Establish boosted H($b\bar{b}$) reconstruction techniques for Higgs measurements
    - Extend STXS bin $p_T^V > 400$ GeV
- All the measurements are in **good agreement with SM prediction**
    - Extracted **EFT limits** from VH STXS measurements

Resolved analysis



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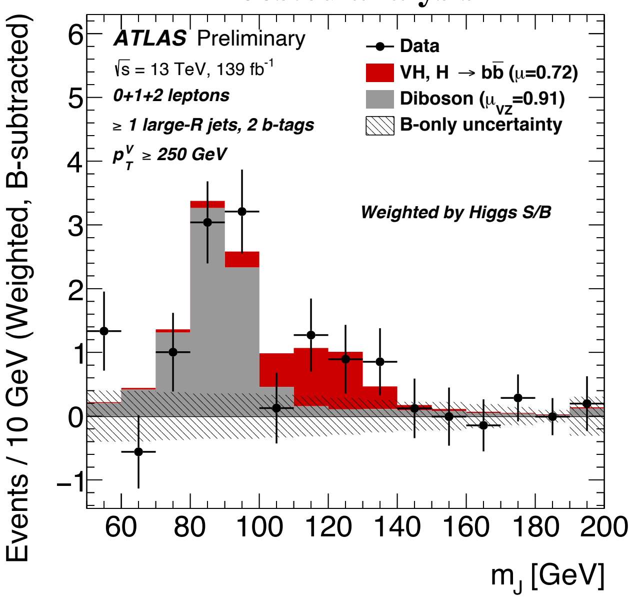

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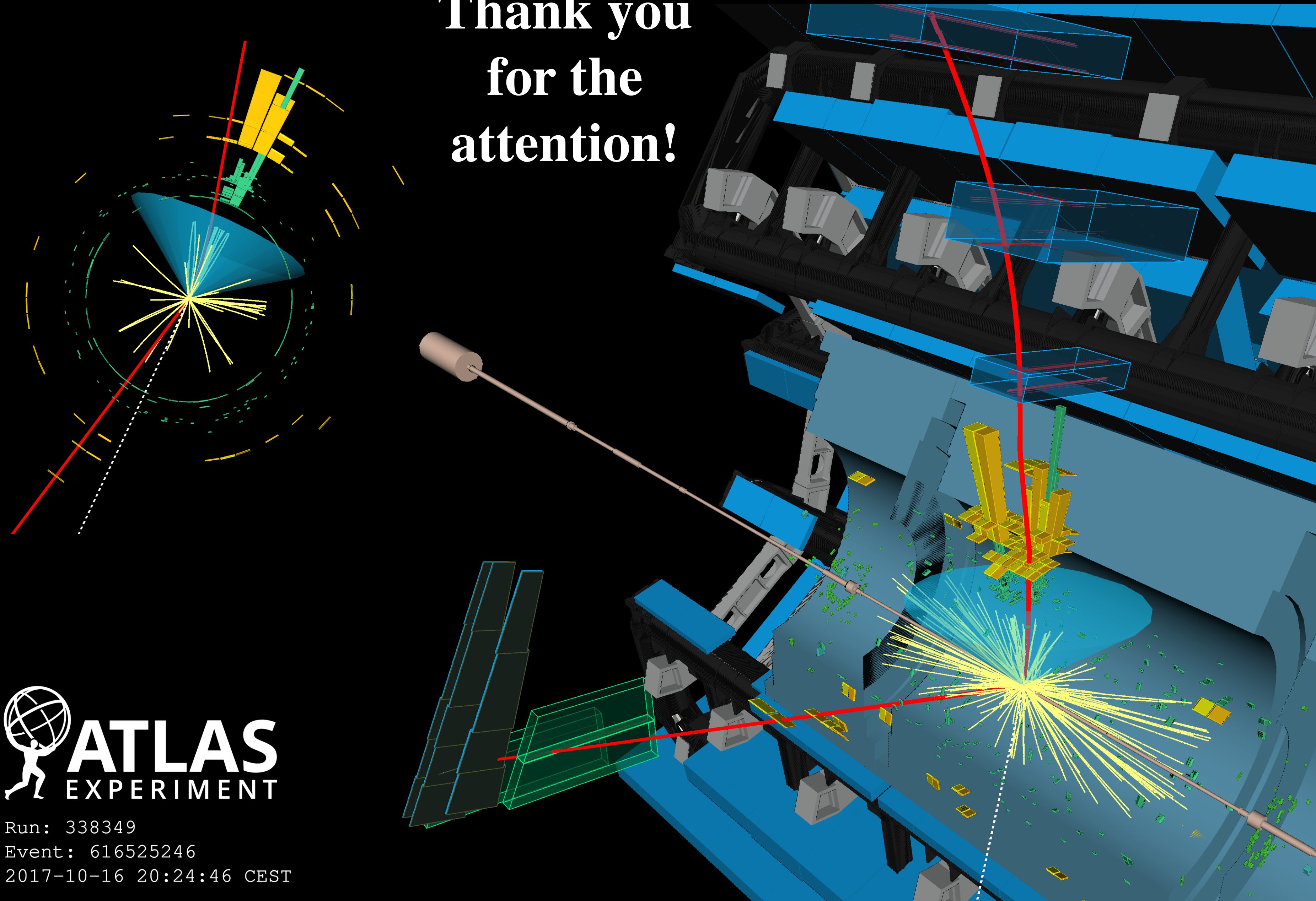
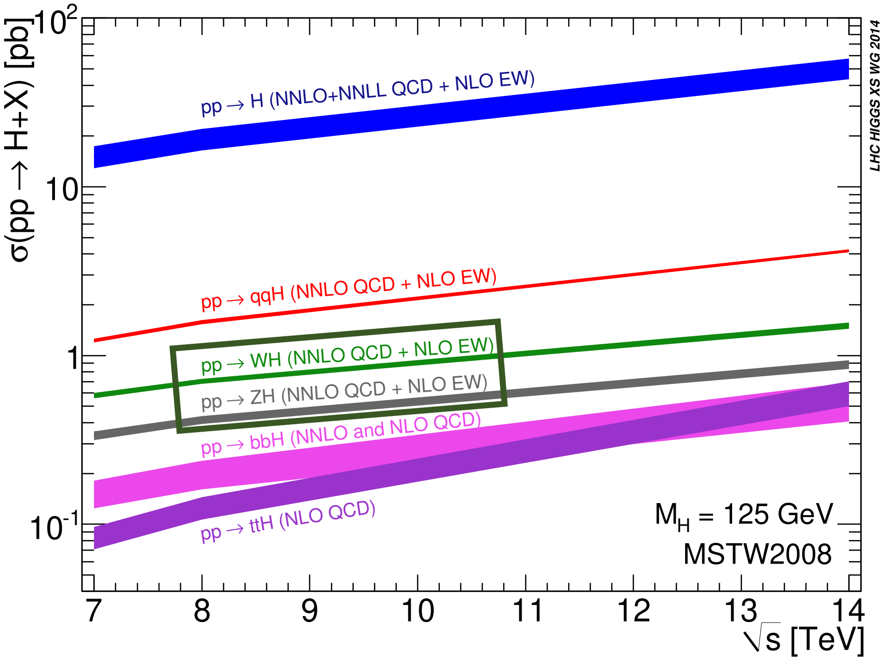
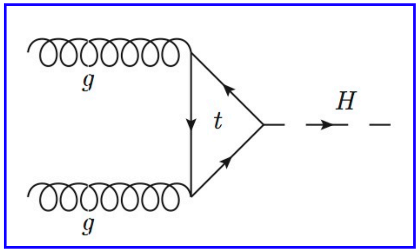


Backup slides

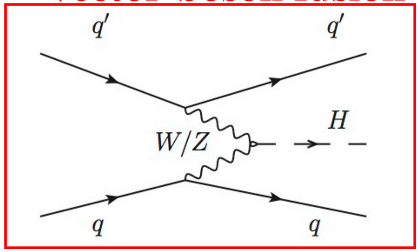
Higgs production mode



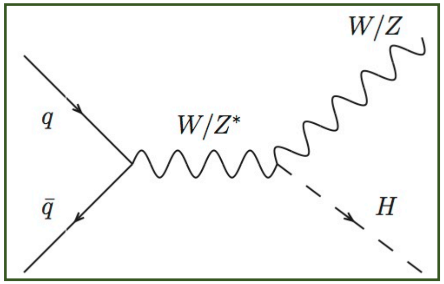
Gluon-gluon fusion



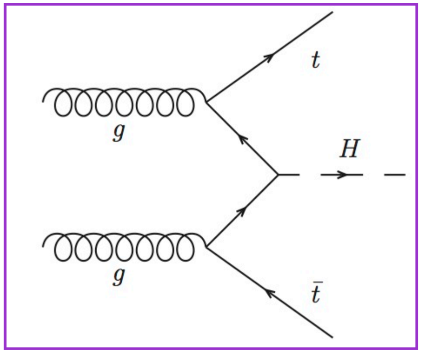
Vector-boson fusion



Associated production with a vector boson V (V=Z or W)



Associated production top quarks



VH($b\bar{b}$) resolved: 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	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			

VH($b\bar{b}$) boosted: event selection

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

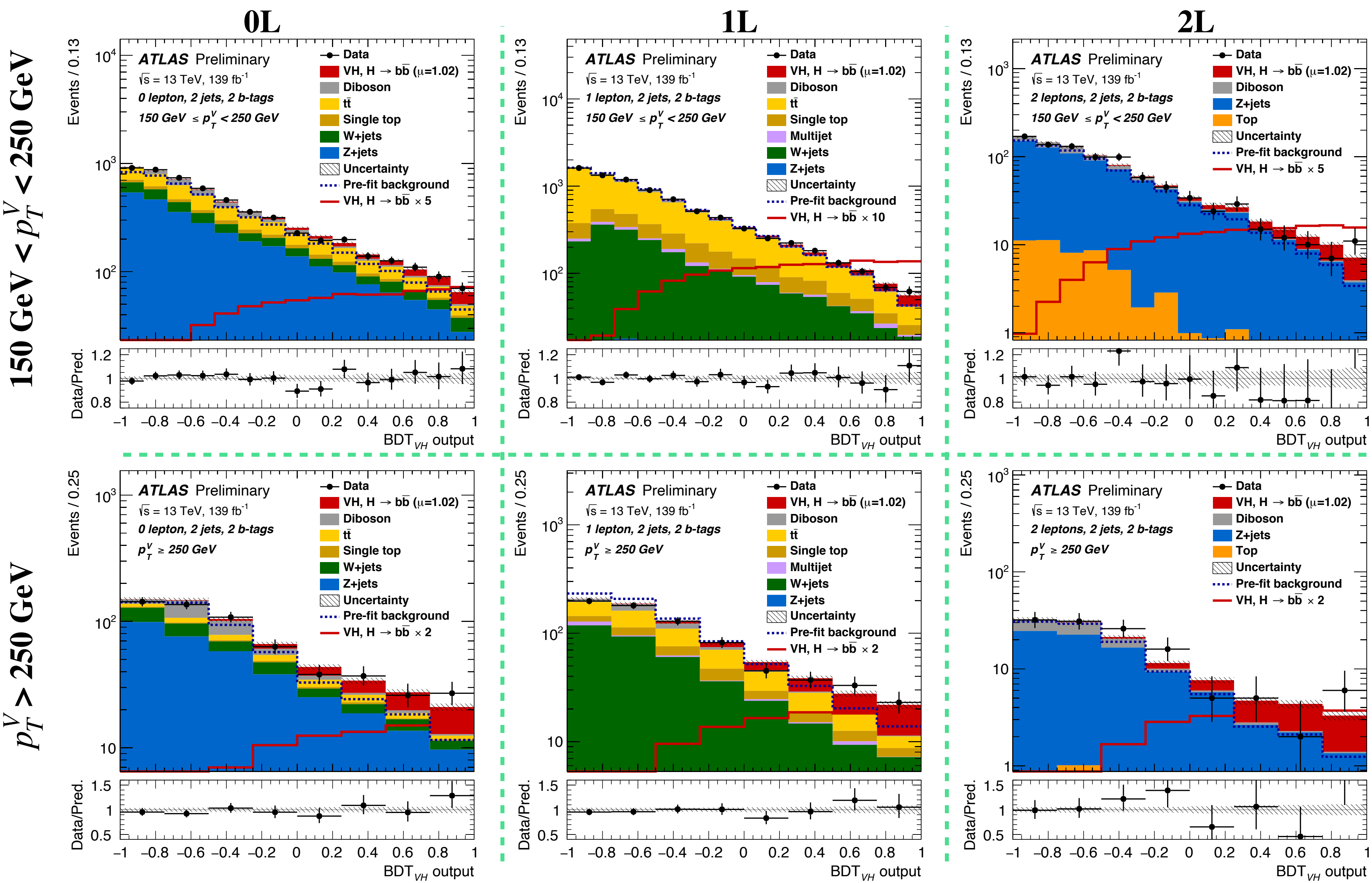
VH($b\bar{b}$) resolved: event categorization

Channel	Region	Categories					
		75 GeV$< p_{\mathrm{T}}^{V} <$ 150 GeV		150 GeV$< p_{\mathrm{T}}^{V} <$ 250 GeV		$p_{\mathrm{T}}^{V} >$ 250 GeV	
		2-jets	3-jets	2-jets	3-jets	2-jets	3-jets
0-lepton	Low ΔR CR	–	–	Yield	Yield	Yield	Yield
	Signal region	–	–	BDT	BDT	BDT	BDT
	High ΔR CR	–	–	Yield	Yield	Yield	Yield
1-lepton	Low ΔR CR	–	–	Yield	Yield	Yield	Yield
	Signal region	–	–	BDT	BDT	BDT	BDT
	High ΔR CR	–	–	Yield	Yield	Yield	Yield
2-lepton	Low ΔR CR	Yield	Yield	Yield	Yield	Yield	Yield
	Signal region	BDT	BDT	BDT	BDT	BDT	BDT
	High ΔR CR	Yield	Yield	Yield	Yield	Yield	Yield

VH($b\bar{b}$) boosted: event categorization

Channel	Categories					
	$250 < p_T^V < 400$ GeV			$p_T^V \geq 400$ GeV		
	0 add. b-track-jets		≥ 1 add. b-track-jets	0 add. b-track-jets		≥ 1 add. b-track-jets
	0 add. small-R jets	≥ 1 add. small-R jets		0 add. small-R jets	≥ 1 add. small-R 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		

VH($b\bar{b}$) resolved: BDT distribution

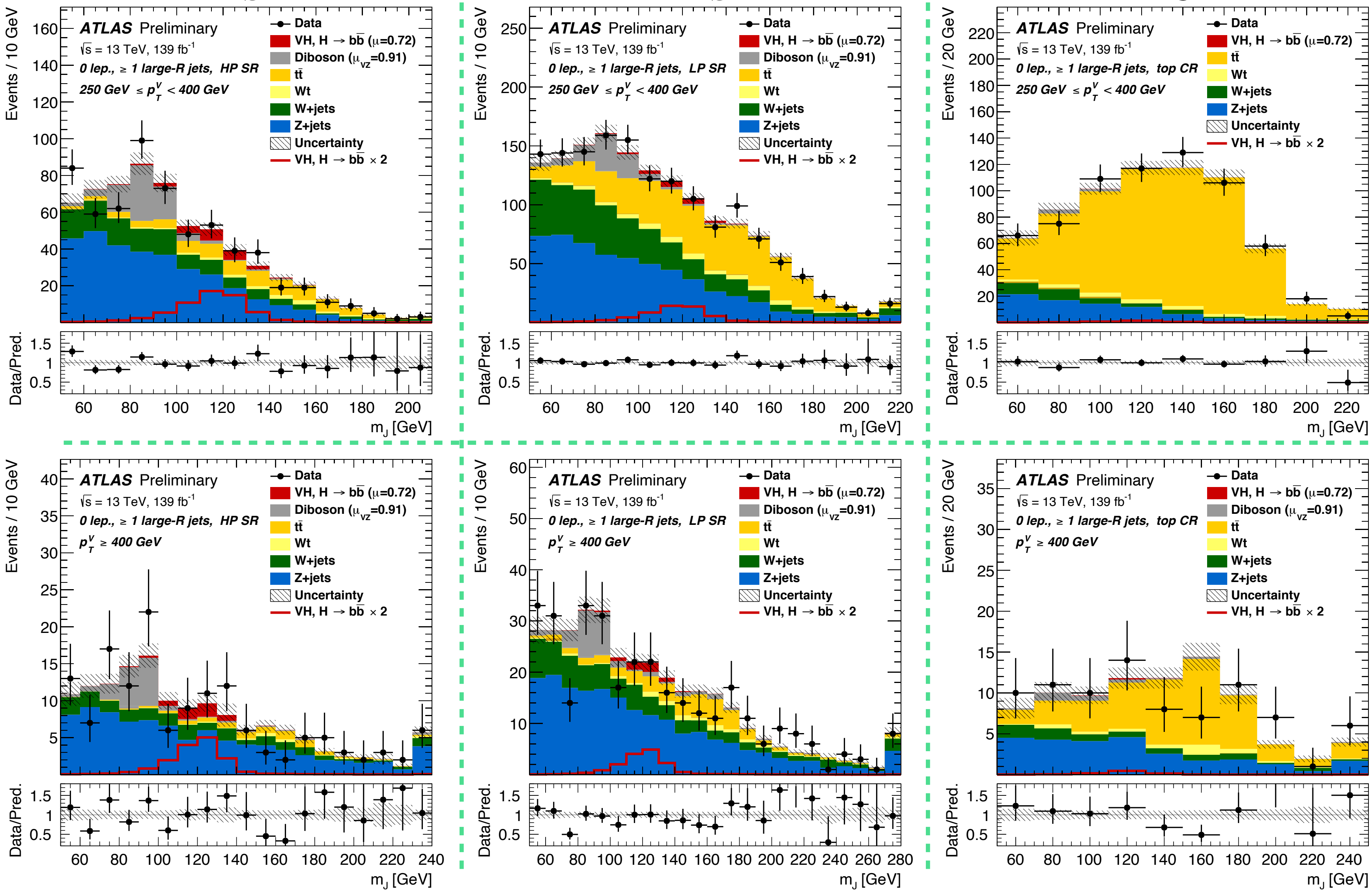


VH($b\bar{b}$) boosted: mJ distribution (0L)

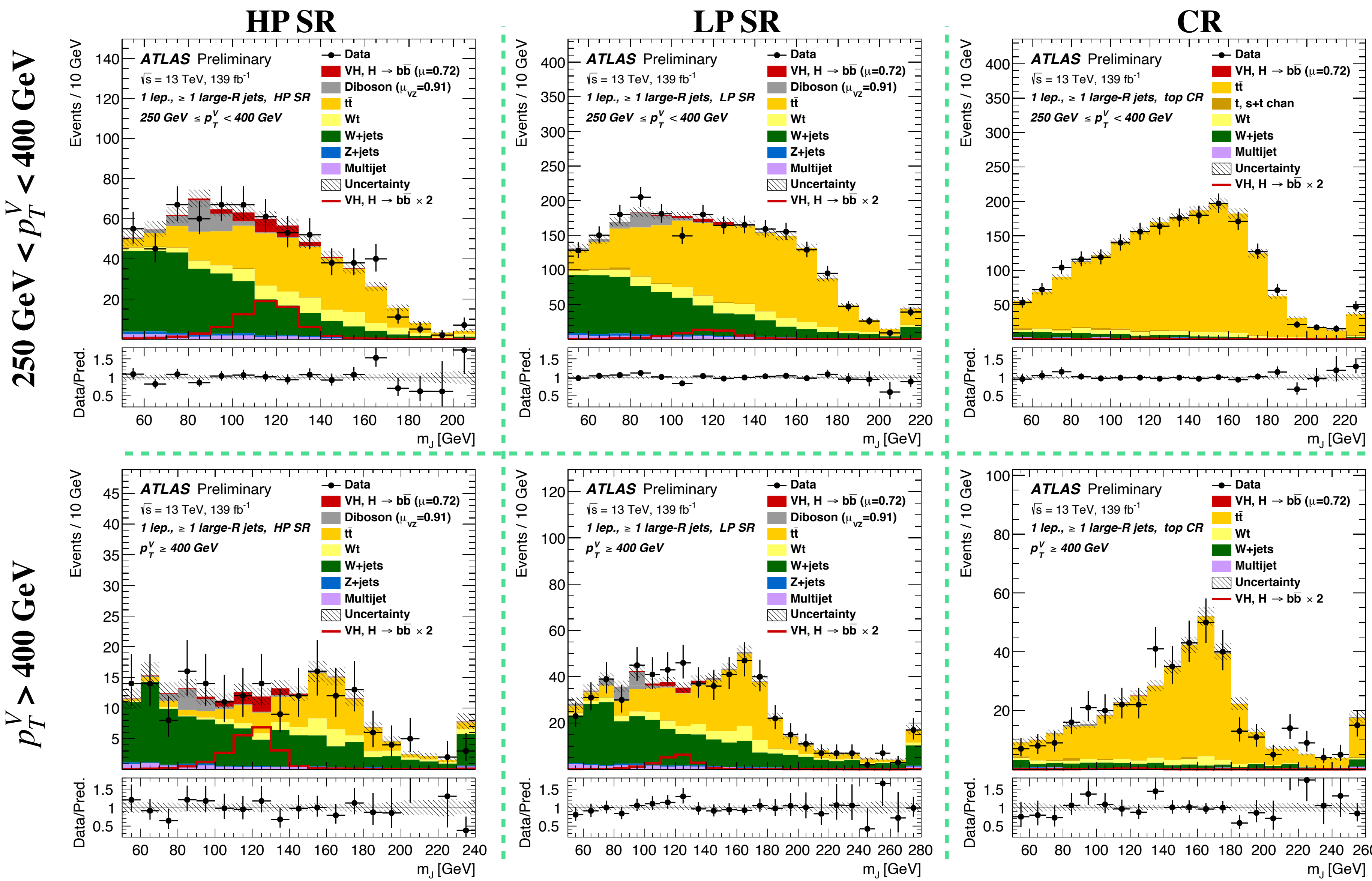
HP SR | LP SR | CR

250 GeV < p_T^V < 400 GeV

p_T^V > 400 GeV



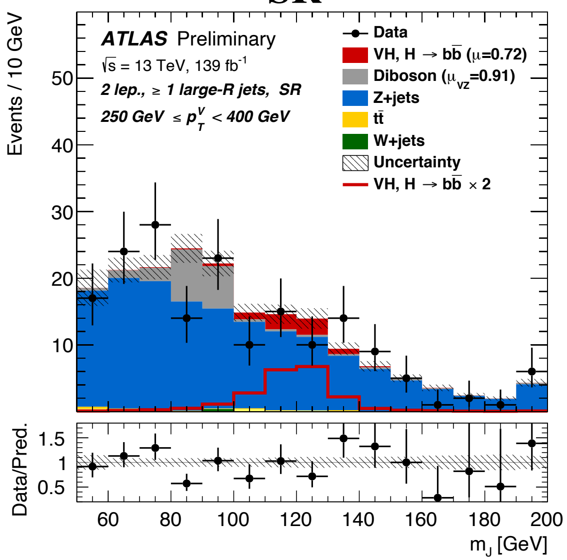
VH($b\bar{b}$) boosted: mJ distribution (1L)



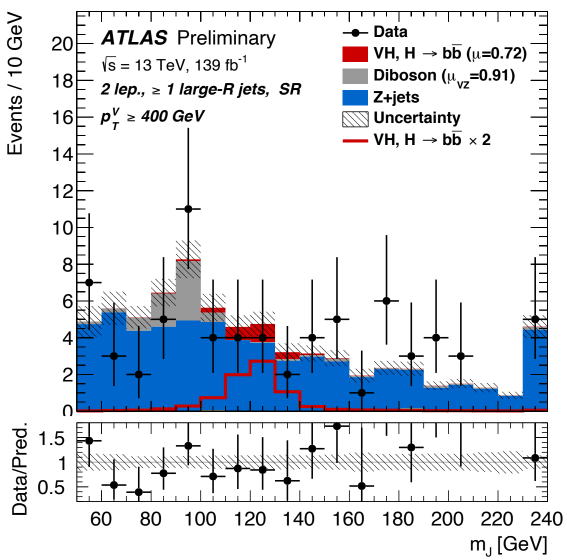
VH($b\bar{b}$) boosted: mJ distribution (2L)

SR

250 GeV < p_T^V < 400 GeV



p_T^V > 400 GeV



VH($b\bar{b}$) resolved: systematic uncertainties

Z + jets	
$Z+ll$ normalisation	18%
$Z+cl$ normalisation	23%
Z + HF normalisation	Floating (2-jet, 3-jet) × ($75\,GeV < p_T^V < 150\,GeV, p_T^V > 150\,GeV$)
$Z+bc$-to-$Z+bb$ ratio	30 – 40%
$Z+cc$-to-$Z+bb$ ratio	13 – 16%
$Z+bl$-to-$Z+bb$ ratio	20 – 28%
SR-to-low ΔR CR ratio	3.8 – 9.9% ($75\,GeV < p_T^V < 150\,GeV, p_T^V > 150\,GeV$)
SR-to-high ΔR CR	2.7 – 4.1% ($75\,GeV < p_T^V < 150\,GeV, p_T^V > 150\,GeV$)
0-to-2 lepton ratio	7%
p_T^V	M+S ($75\,GeV < p_T^V < 150\,GeV, p_T^V > 150\,GeV$)
m_{bb}	S ($75\,GeV < p_T^V < 150\,GeV, p_T^V > 150\,GeV$)

W + jets	
$W+ll$ normalisation	32%
$W+cl$ normalisation	37%
W + HF normalisation	Floating (2-jet, 3-jet)
$W+bc$-to-$W+bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W+cc$-to-$W+bb$ ratio	10% (0-lepton) and 30% (1-lepton)
$W+bl$-to-$W+bb$ ratio	26% (0-lepton) and 23% (1-lepton)
SR-to-CR ratio	3.6-15%
0-to-1 lepton ratio	5%
p_T^V	M+S (2-jet, 3-jet)
R_{BDT}	S

$t\bar{t}$ (0+1-lepton channels only)	
$t\bar{t}$ normalisation	Floating (2-jet, 3-jet)
0-to-1 lepton ratio	8%
$t\bar{t}$ (flavour composition) bc-to-bb ratio (ME)	7.6 – 8.2% (0-lepton), 1.3 – 3.8% (1-lepton)
$t\bar{t}$ (flavour composition) bc-to-bb ratio (PS)	2.1 – 3.2% (0-lepton), 1.5 – 7.1% (1-lepton)
$t\bar{t}$ (flavour composition) other-to-bb ratio (ME)	2.8 – 6.4% (0-lepton), 3.3 – 5.7% (1-lepton)
$t\bar{t}$ (flavour composition) other-to-bb ratio (PS)	5.6 – 13% (0-lepton), 0.3 – 2.1% (1-lepton)
p_T^V	M+S (2-jet, 3-jet)
R_{BDT} ME variation	M+S (2-jet, 3-jet)
R_{BDT} PS variation	M+S (0-lepton, 1-lepton)

Single top-quark	
Cross-section	4.6% (s-channel), 4.4% (t-channel), 6.2% (Wt)
Acceptance 2-jet	17% (t-channel), 55% ($Wt(bb)$), 24% (Wt(other))
Acceptance 3-jet	20% (t-channel), 51% ($Wt(bb)$), 21% (Wt(other))
m_{bb}	M+S (t-channel, $Wt(bb)$, Wt(other))
p_T^V	M+S (t-channel, $Wt(bb)$, Wt(other))

Multi-jet (1-lepton)	
Normalisation	30 – 200% (2-jet), 100% (3-jet)
BDT template	M+S

ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations	10 – 18%
Acceptance from PS/UE variations for 2 or more jets	6%
Acceptance from PS/UE variations for 3 jets	7% (0-lepton), 3% (2-lepton)
m_{bb} from scale variations	M+S (correlated with WZ uncertainties)
p_T^V from scale variations	M+S (correlated with WZ uncertainties)
m_{bb} from PS/UE variations	M+S (correlated with WZ uncertainties)
p_T^V from PS/UE variations	M+S (correlated with WZ uncertainties)
m_{bb} from matrix-element variations	M+S (correlated with WZ uncertainties)

WZ	
Normalisation	26%
0-to-1 lepton ratio	11%
Acceptance from scale variations	13 – 21%
Acceptance from PS/UE variations for 2 or more jets	4%
Acceptance from PS/UE variations for 3 jets	11%
m_{bb} from scale variations	M+S (correlated with ZZ uncertainties)
p_T^V from scale variations	M+S (correlated with ZZ uncertainties)
m_{bb} from PS/UE variations	M+S (correlated with ZZ uncertainties)
p_T^V from PS/UE variations	M+S (correlated with ZZ uncertainties)
m_{bb} from matrix-element variations	M+S (correlated with ZZ uncertainties)

WW	
Normalisation	25%

Signal	
Cross-section (scale)	0.7% (qq), 25% (gg)
$H \to b\bar{b}$ branching fraction	1.7%
Scale variations in STXS bins	3.0 – 3.9% ($qq \to WH$), 6.7 – 12% ($qq \to ZH$), 37 – 100% ($gg \to ZH$)
PS/UE variations in STXS bins	1 – 5% for $qq \to VH$, 5 – 20% for $gg \to ZH$
PDF+α_S variations in STXS bins	1.8 – 2.2% ($qq \to WH$), 1.4 – 1.7% ($qq \to ZH$), 2.9 – 3.3% ($gg \to ZH$)
m_{bb} from scale variations	M+S ($qq \to VH$, $gg \to ZH$)
m_{bb} from PS/UE variations	M+S
m_{bb} from PDF+α_S variations	M+S
p_T^V from NLO EW correction	M+S

VH($b\bar{b}$): systematic breakdown

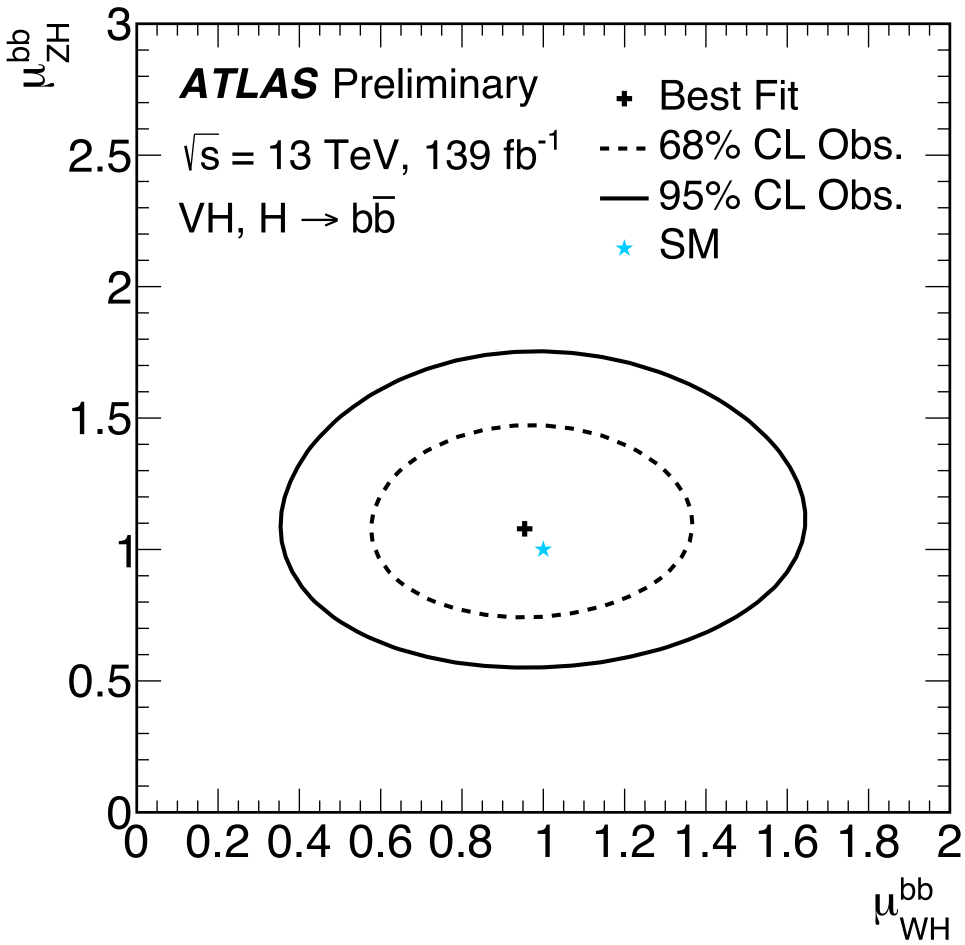
Resolved analysis

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

Boosted analysis

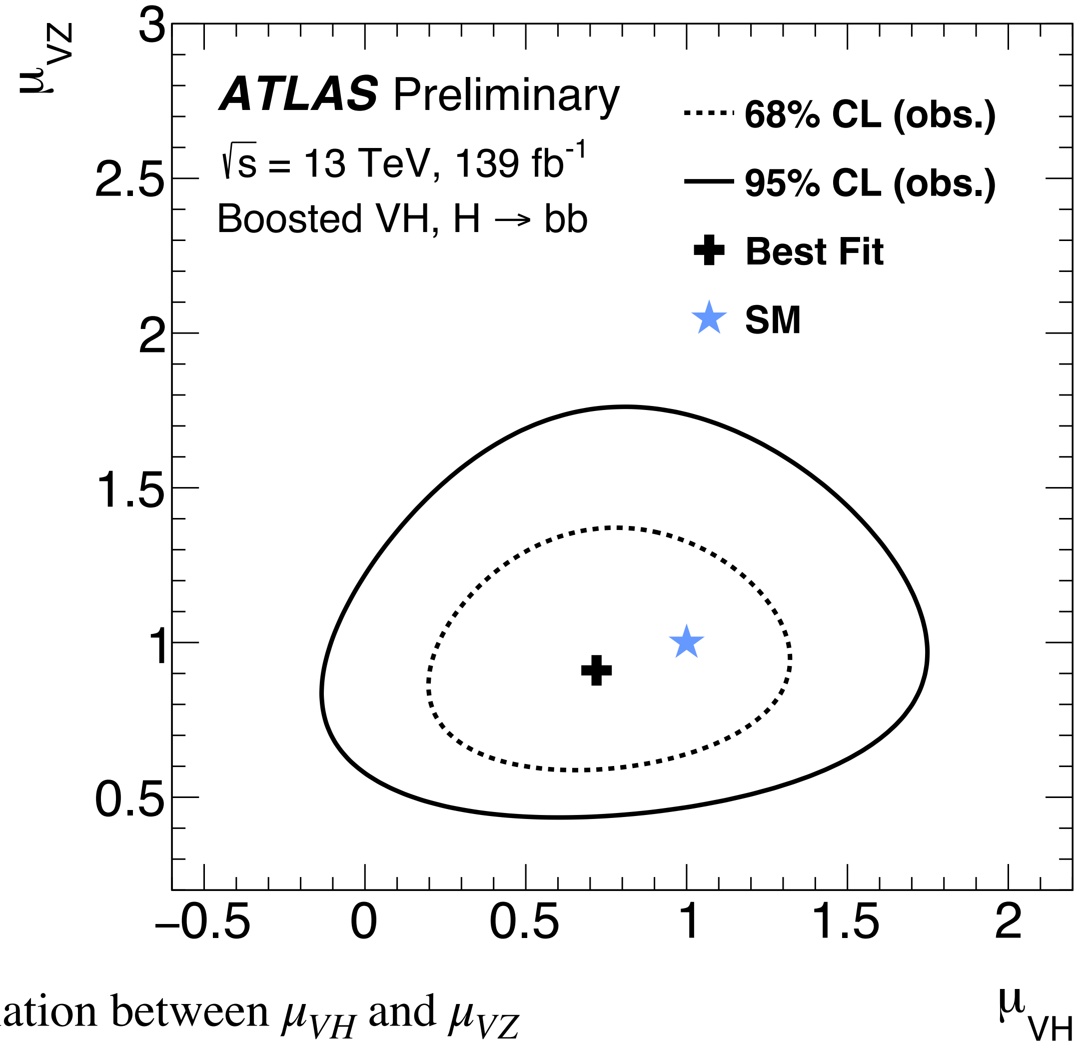
Source of uncertainty		Avg. impact
Total		0.372
Statistical		0.283
Systematic		0.240
Experimental uncertainties		
small-R jets		0.038
large-R jets		0.133
E_T^{miss}		0.007
Leptons		0.010
b-tagging	b-jets	0.016
	c-jets	0.011
	light-flavour jets	0.008
	extrapolation	0.004
Pile-up		0.001
Luminosity		0.013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

VH($b\bar{b}$) resolved: likelihood contours



2.7% of correlation between $\mu_{ZH}^{b\bar{b}}$ and $\mu_{WH}^{b\bar{b}}$

VH($b\bar{b}$) boosted: likelihood contours



11% of correlation between μ_{VH} and μ_{VZ}

VH($b\bar{b}$): Normalization factors

Resolved analysis

Process and Category	Normalisation factor
$t\bar{t}$ 2-jet	0.98 ± 0.09
$t\bar{t}$ 3-jet	0.93 ± 0.06
$W +$ HF 2-jet	1.06 ± 0.11
$W +$ HF 3-jet	1.15 ± 0.09
$Z +$ HF 2-jet, $75 < p_{\mathrm{T}}^{V} < 150$ GeV	1.28 ± 0.08
$Z +$ HF 3-jet, $75 < p_{\mathrm{T}}^{V} < 150$ GeV	1.17 ± 0.05
$Z +$ HF 2-jet, 150 GeV $< p_{\mathrm{T}}^{V}$	1.16 ± 0.07
$Z +$ HF 3-jet, 150 GeV $< p_{\mathrm{T}}^{V}$	1.09 ± 0.04

Boosted analysis

Process	Floating normalisations
$t\bar{t}$ 0-lepton	0.88 ± 0.10
$t\bar{t}$ 1-lepton	0.83 ± 0.09
W+HF	1.12 ± 0.14
Z+HF	1.32 ± 0.16

EFT effects: parametrizing observables

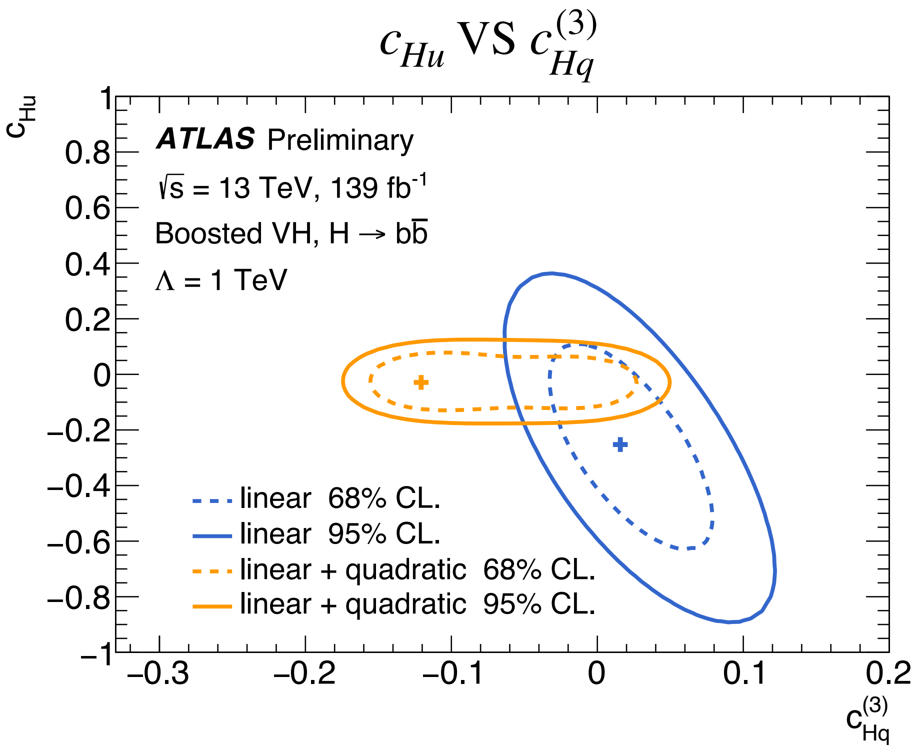
Restricting to leading order BSM contribution, the production cross-section of a process can be expressed as

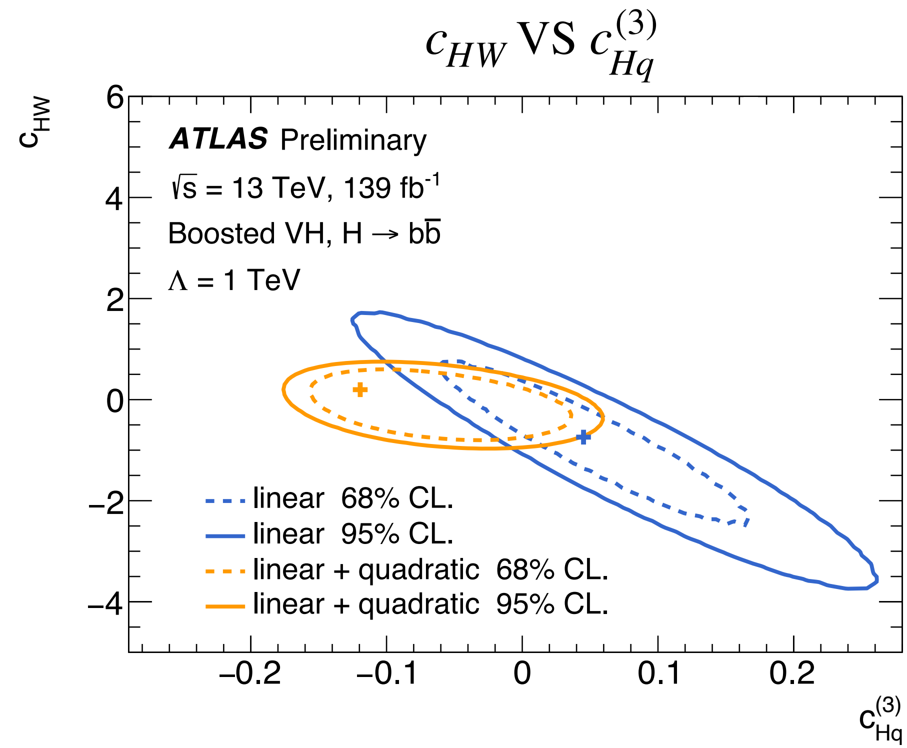
$$\sigma = \sigma_{SM} + \sigma_{int} + \sigma_{BSM}$$

$$\frac{\sigma}{\sigma_{SM}} = 1 + \sum_i A_i \bar{c}_i + \sum_{ij} B_{ij} \bar{c}_i \bar{c}_j$$

Linear term **Quadratic term**

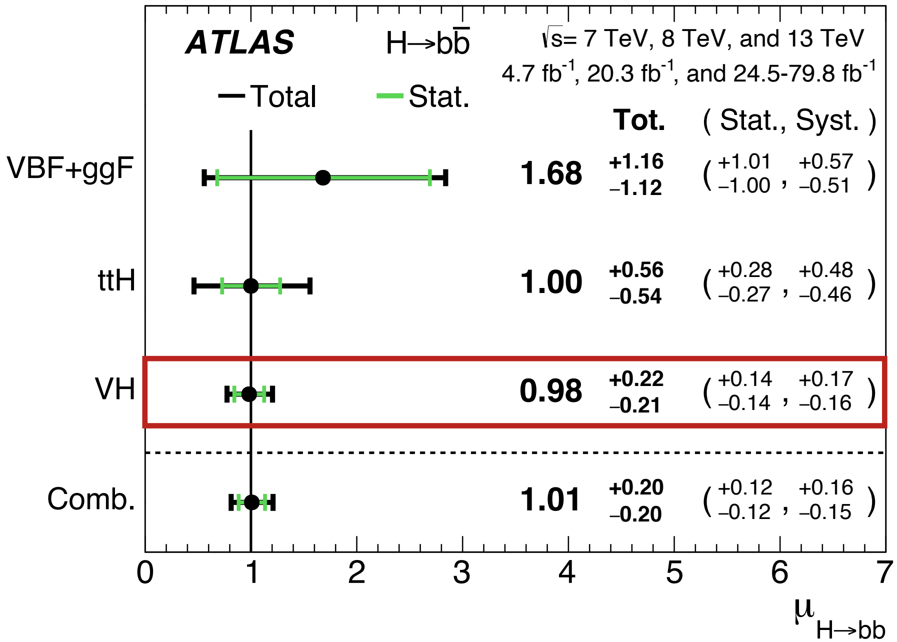
VH($b\bar{b}$) boosted: 2D likelihood scan

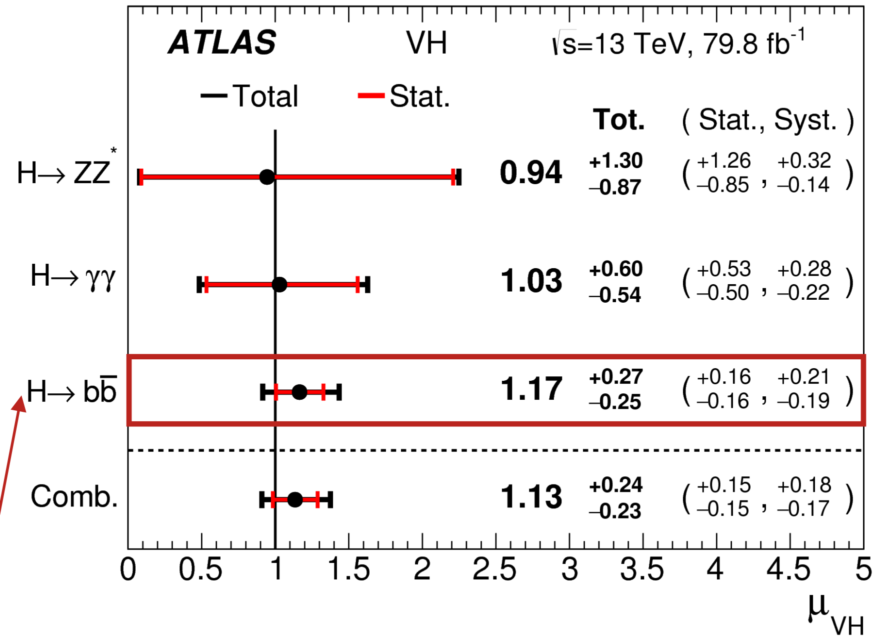




H($b\bar{b}$) and VH combination

Run1+ partial Run2 dataset





Leading sensitivity from VH($b\bar{b}$) resolved analysis