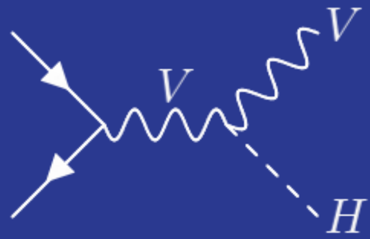
Measurements of Higgs boson associate production with a leptonically decaying vector boson in the $H \rightarrow bb/cc$ decay channel within the ATLAS detector

Gabriele D'Anniballe
on behalf of the ATLAS collaboration



Standard Model at the LHC 2025
07/04/2025

Istituto Nazionale di Fisica Nucleare
UNIVERSITÀ DI PISA
ATLAS EXPERIMENT

Introduction

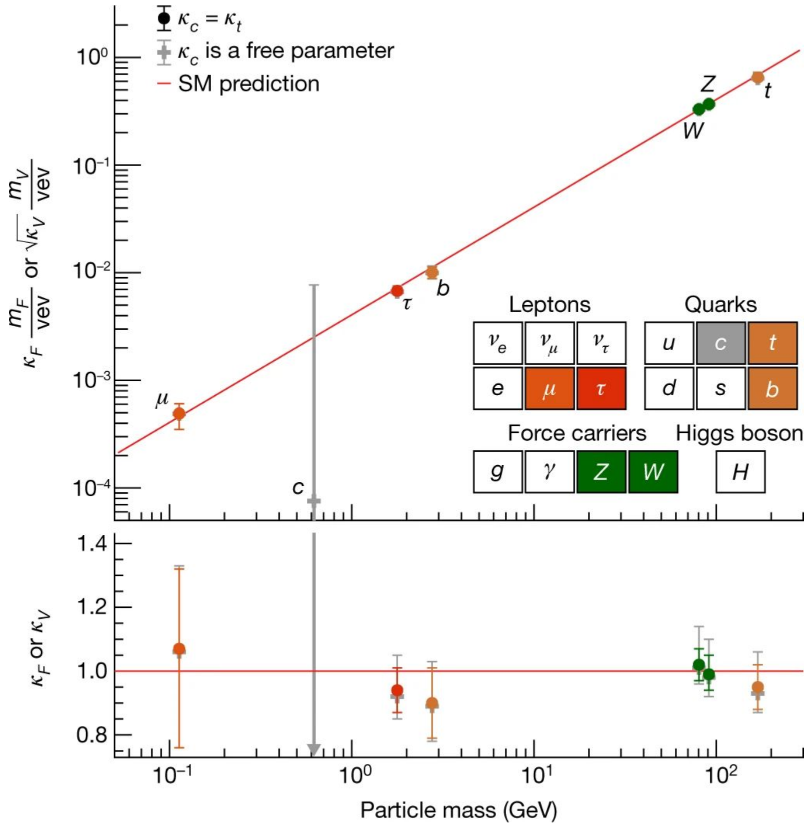
Measurements of Higgs boson Yukawa couplings are stringent tests for the validity of the SM

$$\mathcal{L}_f = \underbrace{-\frac{y_f v}{\sqrt{2}}\bar{\psi}_f\psi_f}_{\text{mass}} \overbrace{-\frac{y_f}{\sqrt{2}}h\bar{\psi}_f\psi_f}^{\text{coupling}}$$

In the quark sector:

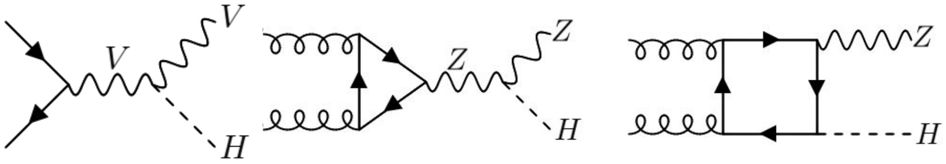
- **H→bb** plays a crucial role in Higgs physics
  - *BR(H→bb) ~58% (the highest)*
  - *y_b has the largest impact on the Higgs boson's width*
  - most sensitive decay channel to study rare Higgs boson processes
  - fundamental in double-Higgs searches

- **H→cc** much more challenging to measure:
  - *BR(H→cc) ~3%*
  - more difficult to identify c-jets, higher backgrounds
  - *BSM phenomena can significantly enhance the BR*

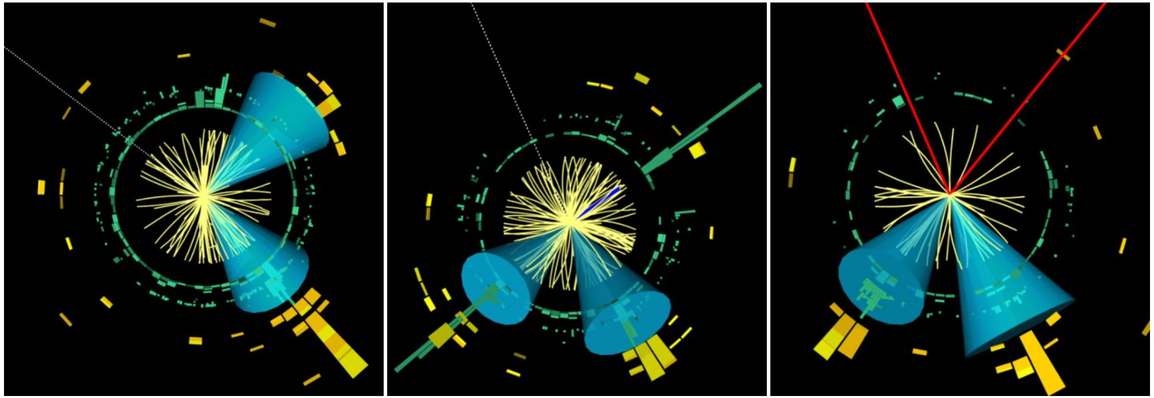


Nature 607, 52–59 (2022)

The V(lep)H process



- The VH (qq/gg-induced) production channel is the most sensitive mode to access the H→bb and H→cc decays
  - Significant reduction of overwhelming multijet background obtained by requiring the *leptonic decay of the vector boson*
  - Cleaner signatures with *2 b/c-jets, charged leptons and/or E_T^{miss}*



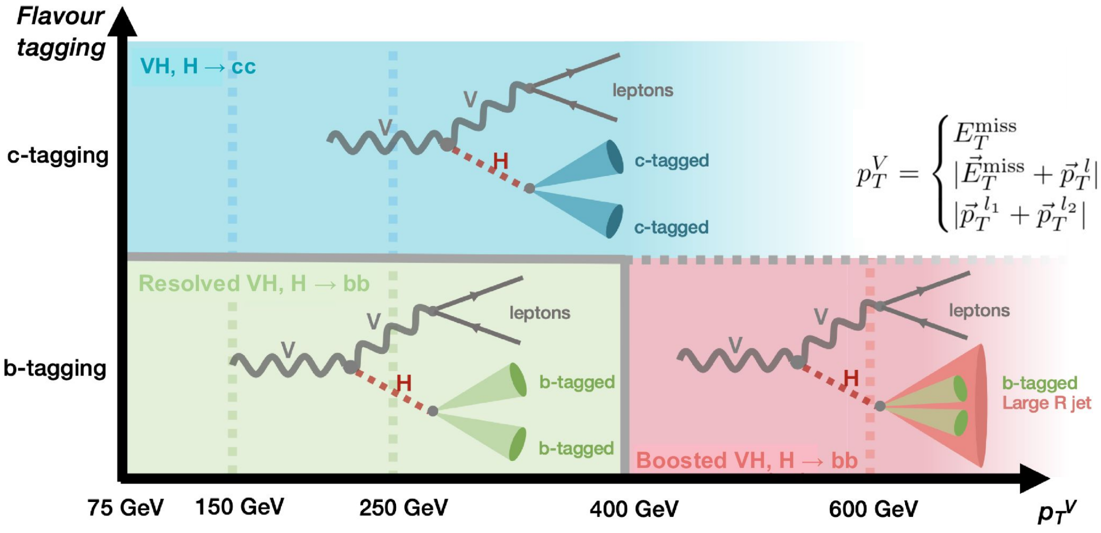
pp→Z(νν)H | pp→W(lν)H | pp→Z(ll)H

cds.cern.ch/record/2771693

The ATLAS VH(bb/cc) analysis

The ATLAS VH(bb/cc) Run2 analysis

- Idea: *exploit similarities between VH(bb) and VH(cc) topologies* to re-analyze the full Run2 dataset with a single harmonized strategy
  - previous results: resolved VH(bb), boosted VH(bb),VH(cc)
- Orthogonal regions in flavour-tagging / p_T^V:



$$p_T^V = \begin{cases} E_T^{\text{miss}} & \text{0 lepton} \\ |\vec{E}_T^{\text{miss}} + \vec{p}_T^{\,l}| & \text{1 lepton} \\ |\vec{p}_T^{\,l_1} + \vec{p}_T^{\,l_2}| & \text{2 lepton} \end{cases}$$

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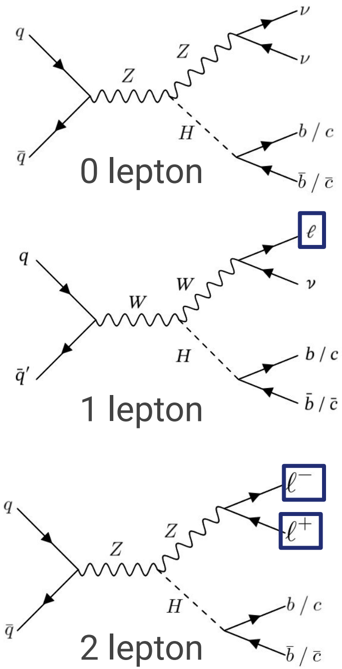
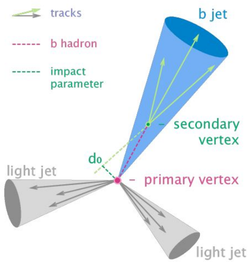
- Three analysis channels:



ℓ=e,μ,τ(had)

ℓ=e,μ

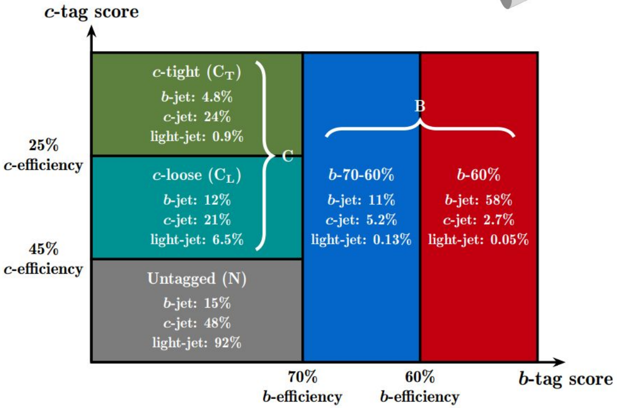
Jet flavour-tagging: PCFT approach

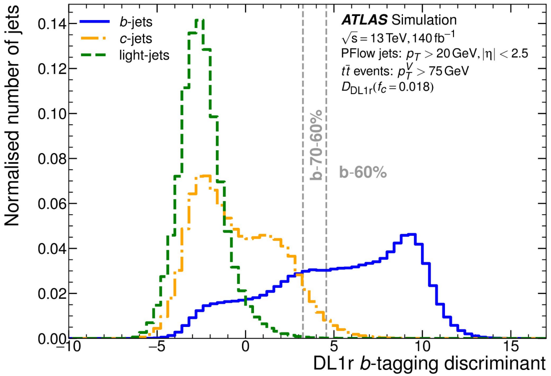


- Key experimental ingredient: to be able to efficiently distinguish b/c-jets from light-jets (u/d/s- or gluon-initiated)

- *Jet flavour tagging* performed employing DL1r algorithm
  - DNN architecture, output $[p_b, p_c, p_u]$
  - b-tag and c-tag scores:

$$D_b = \log\left[\frac{p_b}{f_c \cdot p_c + (1-f_c)\cdot p_u}\right] \quad D_c = \log\left[\frac{p_c}{f_b \cdot p_b + (1-f_b)\cdot p_u}\right]$$





- *Pseudo-Continous-Flavour-Tagging* approach (PCFT):
  - orthogonal regions defined in the (D_b, D_c) plane for fixed efficiency working points (*PCFT bins*)
  - dedicated calibrations for each PCFT bin derived on ttbar samples

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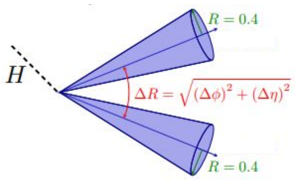
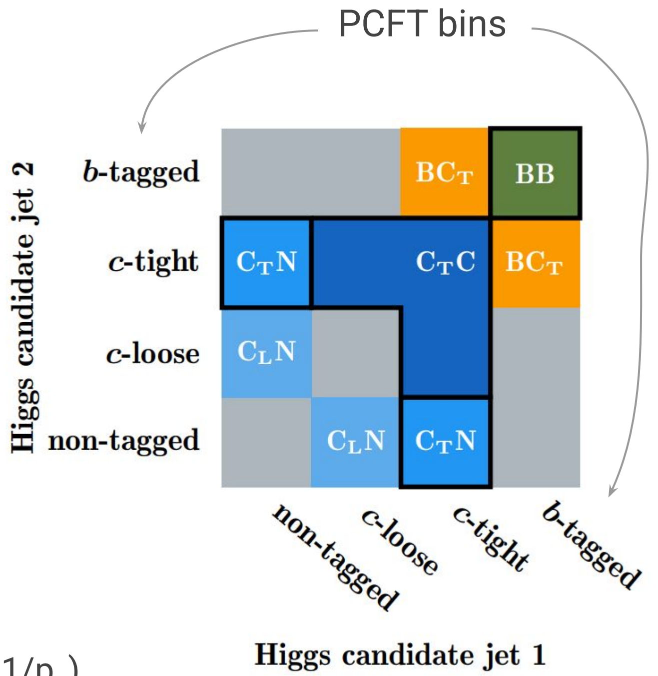
Higgs candidate selection

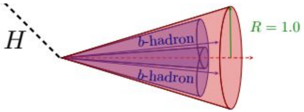
Resolved (p_T^V < 400 GeV):



- Reconstructed jets ordered in p_T, first two are the Higgs candidate jets (j_1, j_2)
  - **VH(bb)**: exactly *two b-tagged jets (BB)*
  - **VH(cc)**: *at least one c-tagged jet, no b-tagged jets*:
    - $C_TC = C_TC_T + C_TC_L$
    - C_TC_N
  - BC_T and C_LN used as control-regions



Boosted VH(bb) (p_T^V > 400 GeV):



Higgs candidate: leading large-R jet with m_J > 50 GeV

- At least two matched track-jets (anti-k_T with $R \propto 1/p_T$)
  - exactly two b-tagged

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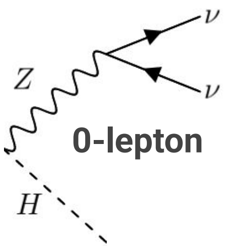
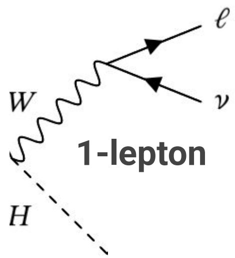
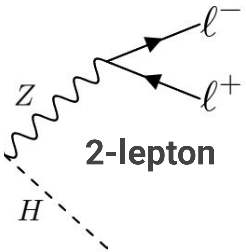
Vector boson candidate (main) selections



ℓ=e,μ,τ(had)



ℓ=e,μ



$Z \rightarrow \nu\nu$ selection

- E_T^{miss} trigger
- **No μ, e, $\tau_{had\text{-}vis}$**
- E_T^{miss} > 150 GeV
- Anti-QCD topological cuts

$W \rightarrow \ell\nu$ selection

- Single lepton / E_T^{miss} trigger
- **Exactly one μ or e or $\tau_{had\text{-}vis}$**
- E_T^{miss} > 30 GeV (e channel)

$Z \rightarrow \ell\ell$ selection

- Single lepton / E_T^{miss} trigger
- **Exactly 2μ or 2e**
  - OS (μ-channel)
- 81 GeV < m_{ll}< 101 GeV

(large E_T^{miss} values can be produced by unreconstructed QCD radiation)

Requirements on min[$\Delta\varphi$(E_T^{miss}, jets)],
$\Delta\varphi$(E_T^{miss}, Higgs candidate),
$\Delta\varphi$(Higgs candidate jet 1, Higgs candidate jet 2)

The detailed event selection is in the backup.

Main backgrounds

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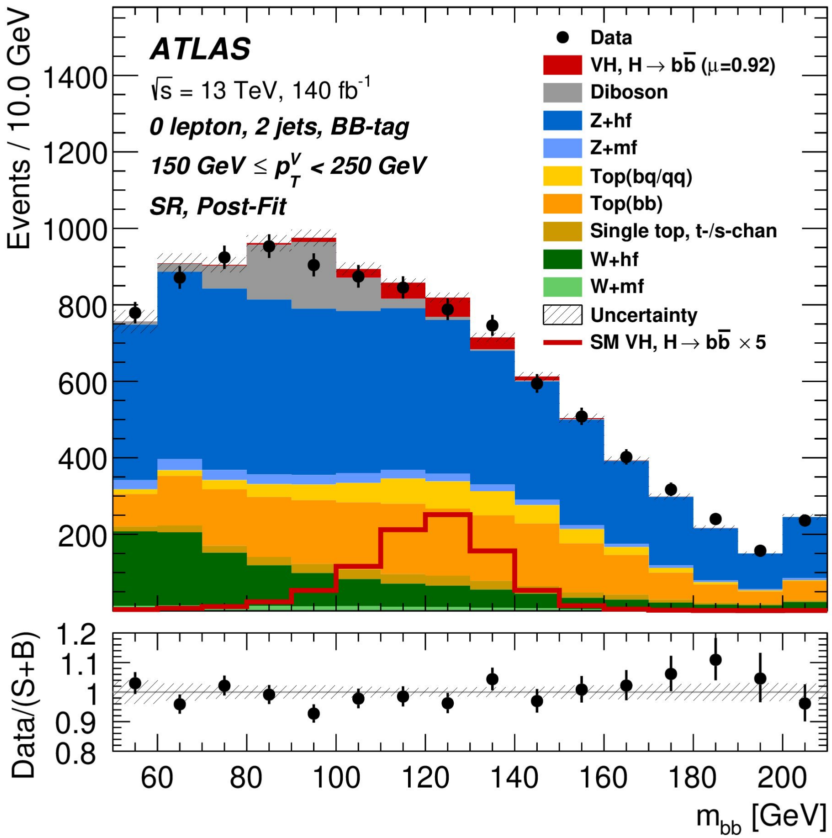
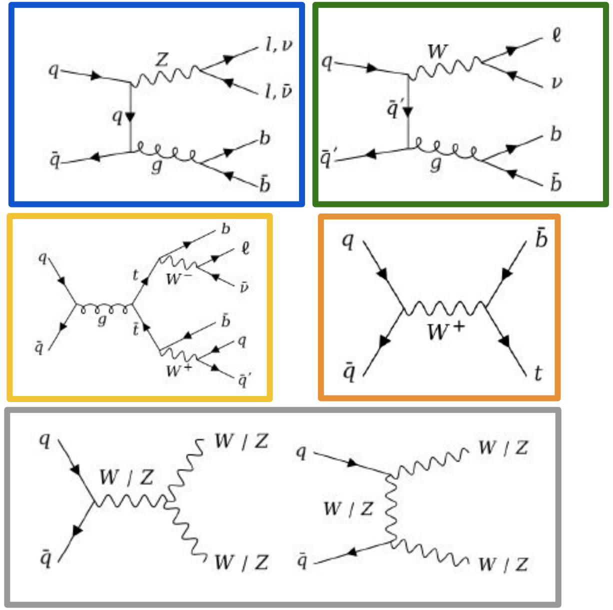


Main:

- Z+jets
- W+jets
- tt production

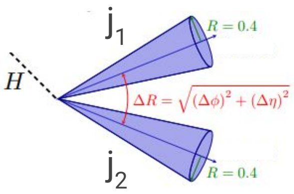
Minor:

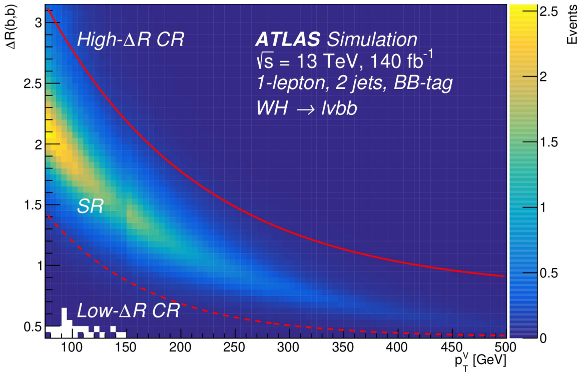
- single top
- diboson
- multijet (data-driven in 1-lepton)

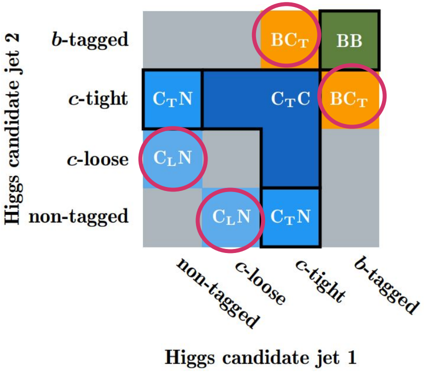


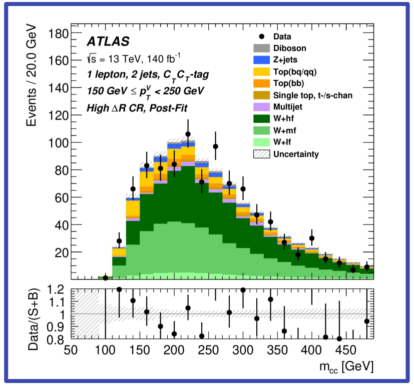
Event categorization

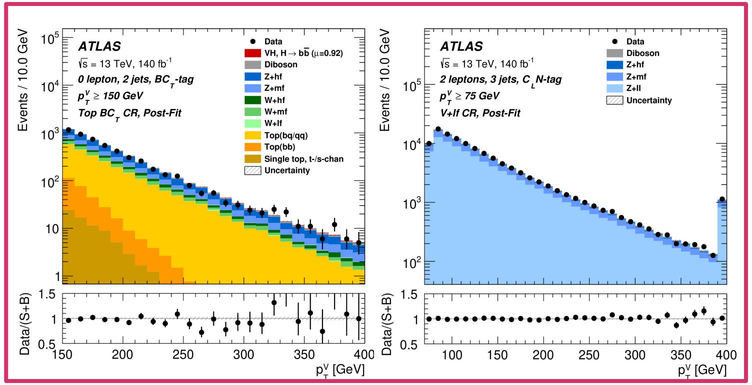
- Categorization based on
  - the number of *b*- and *c*-tagged jets,
  - the value p_T^V ,
  - the number of additional jets
- ***Signal regions*** (SRs)
  - (resolved) continuous cut in $\Delta R(j_1,j_2)$ - p_T^V
  - (boosted) no additional *b*-tagged track-jet outside the large-R jet
- ***Control regions*** (CRs)
  - needed to have a handle on V+jets and Top production
  - *$\Delta R(j_1j_2)$-based*: j_1j_2 with the same flavours as in the signal
  - *Tag based CRs*: j_1j_2 with the different flavours











In total: 59 SRs, 97 CRs. Full event categorization in backup.

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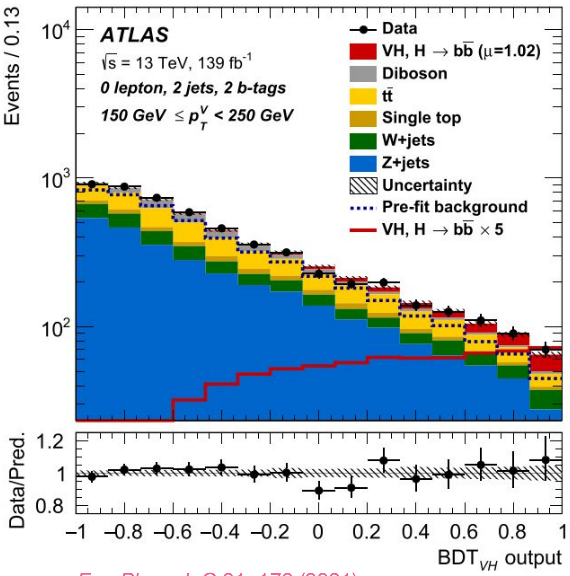
Analysis strategy

1. MVA based on a set of *boosted decision trees (BDTs)*
   - ***innovative approach for VH(cc) and boosted VH(bb)*** - previously based on m_H
2. *Global (binned) maximum likelihood fit* used to extract parameters of interests (POIs).
   - Complex likelihood structure due to large number of regions and variables.



[Eur. Phys. J. C 81, 178 (2021)]

$$\mathcal{L}(\mu;\alpha,\gamma,\tau) = \mathcal{L}_{\text{Pois}}(\mu;\alpha,\gamma,\tau)\cdot\mathcal{L}_{\text{syst}}(\alpha)\cdot\mathcal{L}_{\text{stat}}(\gamma)$$

- τ: Floating normalizations
- γ: Stat. unc. on MC predictions
- α: Modelling and experimental unc.

(the three above: **Nuisance Parameters**)

- μ: **POIs**

3. Targeted measurements:
   - global signal strengths for VH(bb) and VH(cc)
     - WH(bb), ZH(bb) signal strengths
   - STXS differential measurements of ZH(bb) and WH(bb)
   - κ-framework reinterpretation: κ_b, κ_c, $|\kappa_b/\kappa_c|$

Results

Diboson cross-check

$$\mu \equiv \frac{(\sigma \times BR)_{meas}}{(\sigma \times BR)_{SM}}$$

Alternative set of BDTs trained to *extract **V(lep)Z(bb/cc)** diboson processes from background*.

- BDTs evaluated on the *same events categorized in the SRs*
- Powerful test to validate the V(lep)H(bb/cc) analysis

Compatible results with SM expectations.

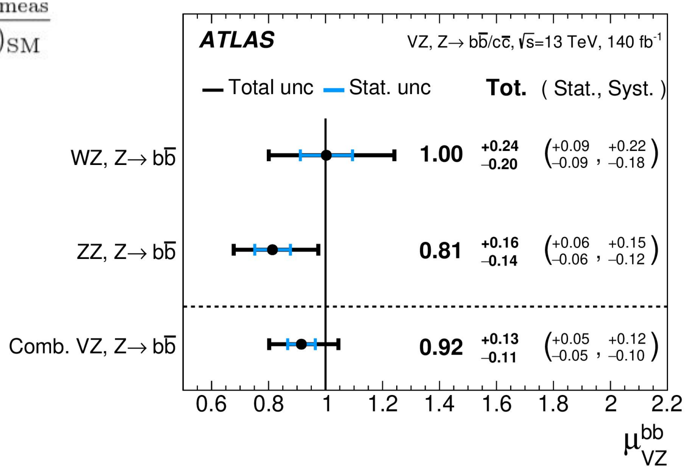
VZ(bb):

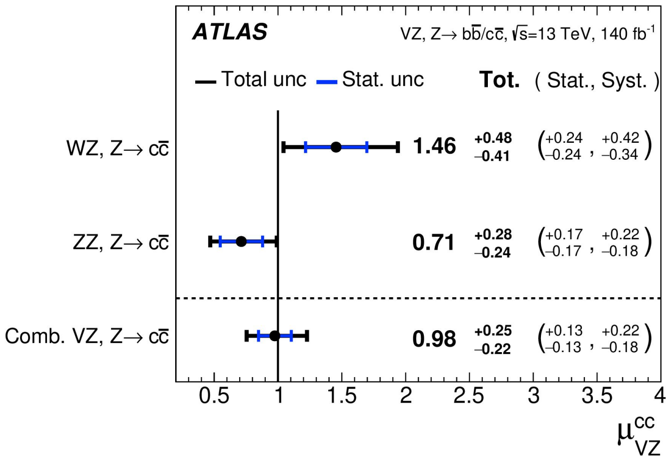
- **WZ(bb): 6.4σ (6.5σ) obs. (exp.) → First observation**
- ZZ(bb): more than 10σ

VZ(cc):

- WZ(cc): 3.9σ (2.7σ) obs. (exp.)
- ZZ(cc): 3.1σ (4.3σ) obs. (exp.)

Combination: 5.2σ (5.3σ) obs. (exp.) → First observation





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VH signal strength results

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

Simultaneous extraction of VH(bb) and VH(cc) signal strengths. VH(bb) also decorrelated in WH(bb) and ZH(bb).

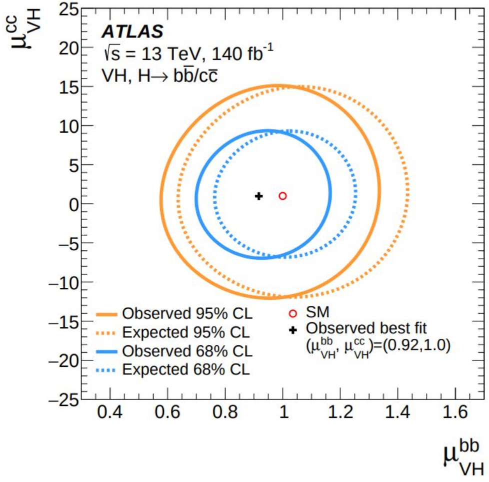
VH signal strength results

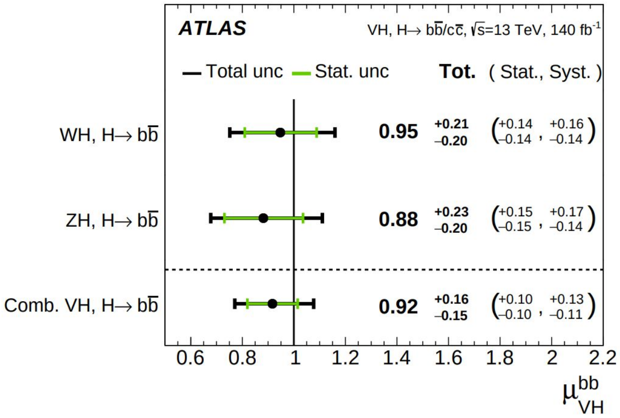
$$\mu \equiv \frac{(\sigma \times \text{BR})_{\text{meas}}}{(\sigma \times \text{BR})_{\text{SM}}}$$

Simultaneous extraction of VH(bb) and VH(cc) signal strengths. VH(bb) also decorrelated in WH(bb) and ZH(bb).

- *15%-level of precision reached on VH(bb) - obs (exp) 7.4σ (8.0σ)*
  - 4.9σ (5.6σ) on ZH(bb)
  - **5.3σ (5.5σ) on WH(bb) → First observation**

$$\mu_{VH}^{bb} = 0.92^{+0.16}_{-0.15} = 0.92 \pm 0.10\,(\text{stat.})^{+0.13}_{-0.11}\,(\text{syst.})$$
$$\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\,(\text{stat.})^{+3.7}_{-3.5}\,(\text{syst.}).$$





VH signal strength results

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

Simultaneous extraction of VH(bb) and VH(cc) signal strengths. VH(bb) also decorrelated in WH(bb) and ZH(bb).

- *15%-level of precision reached on VH(bb) - obs (exp) 7.4σ (8.0σ)*
  - 4.9σ (5.6σ) on ZH(bb)
  - **5.3σ (5.5σ) on WH(bb) → First observation**
- *obs (exp) 11.5 (10.6) 95% upper limit on VH(cc)*
  - more than a factor 2x better wrt previous VH(cc) round
  - **most stringent upper limit on $\mu_{VH(cc)}$ to date**

$$\mu_{VH}^{bb} = 0.92^{+0.16}_{-0.15} = 0.92 \pm 0.10\,(\mathrm{stat.})^{+0.13}_{-0.11}\,(\mathrm{syst.})$$
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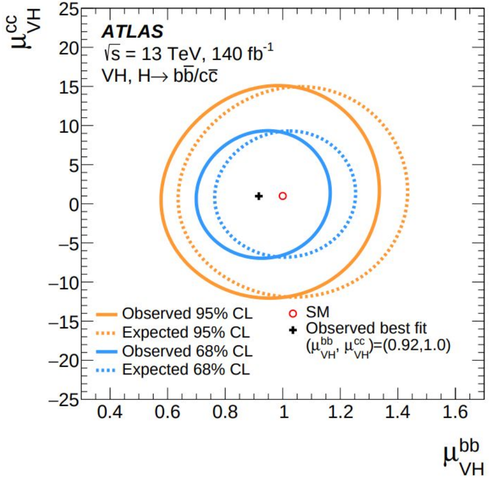

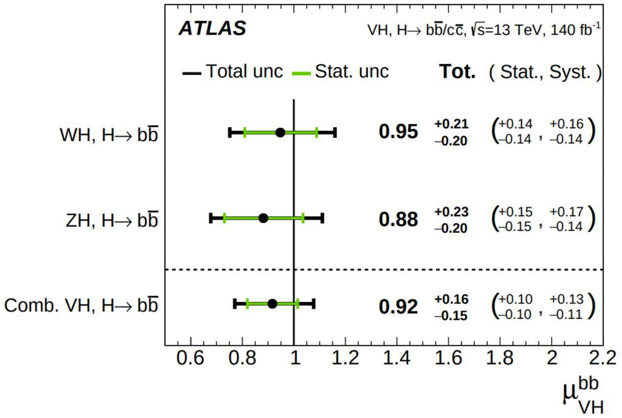

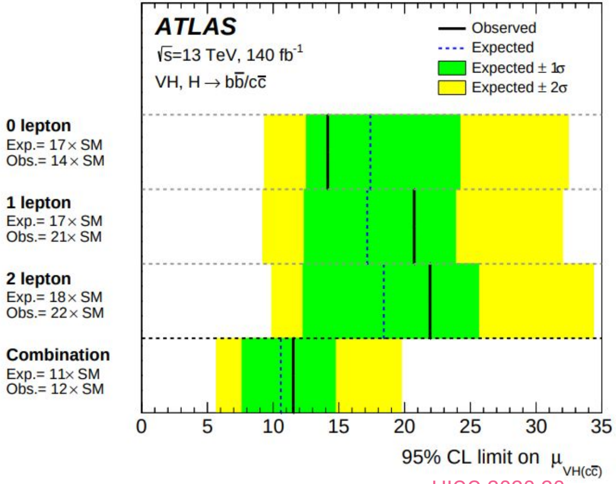

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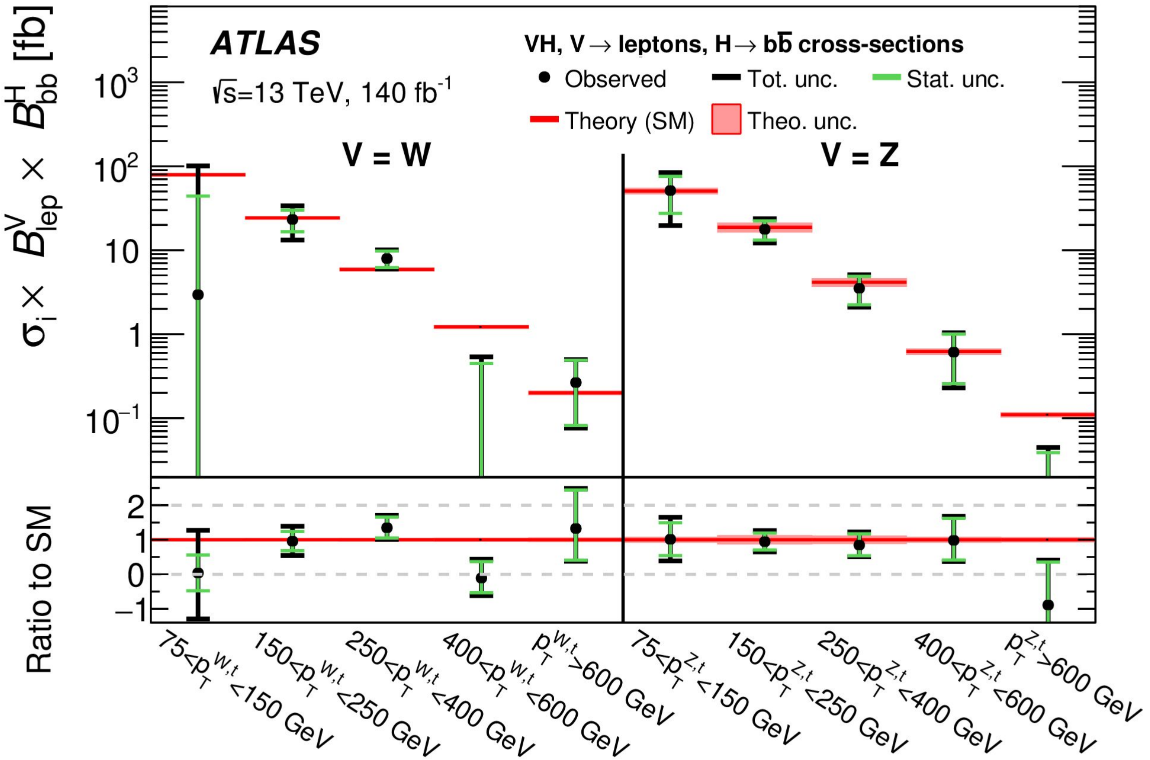
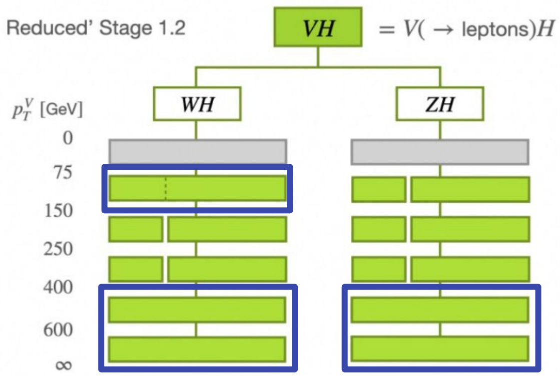
STXS VH(bb) measurements





New bins

Differential VH(bb) cross section measurement in p_T^V bins (STXS Reduced stage 1.2)

- *New bin at low p_T^V* (75-150 GeV) for WH(bb)
- *New splitting for boosted regime*
  - >400 → 400-600, > 600

Overall compatibility with SM: 90%

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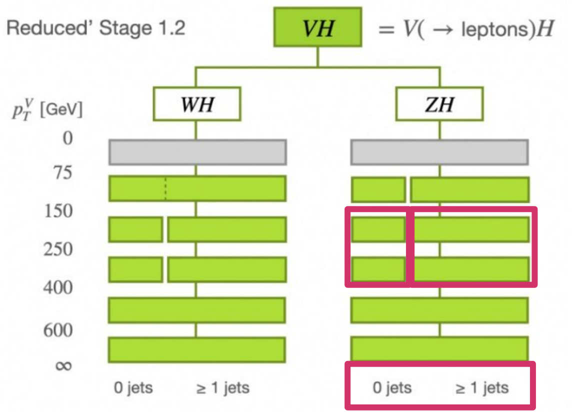
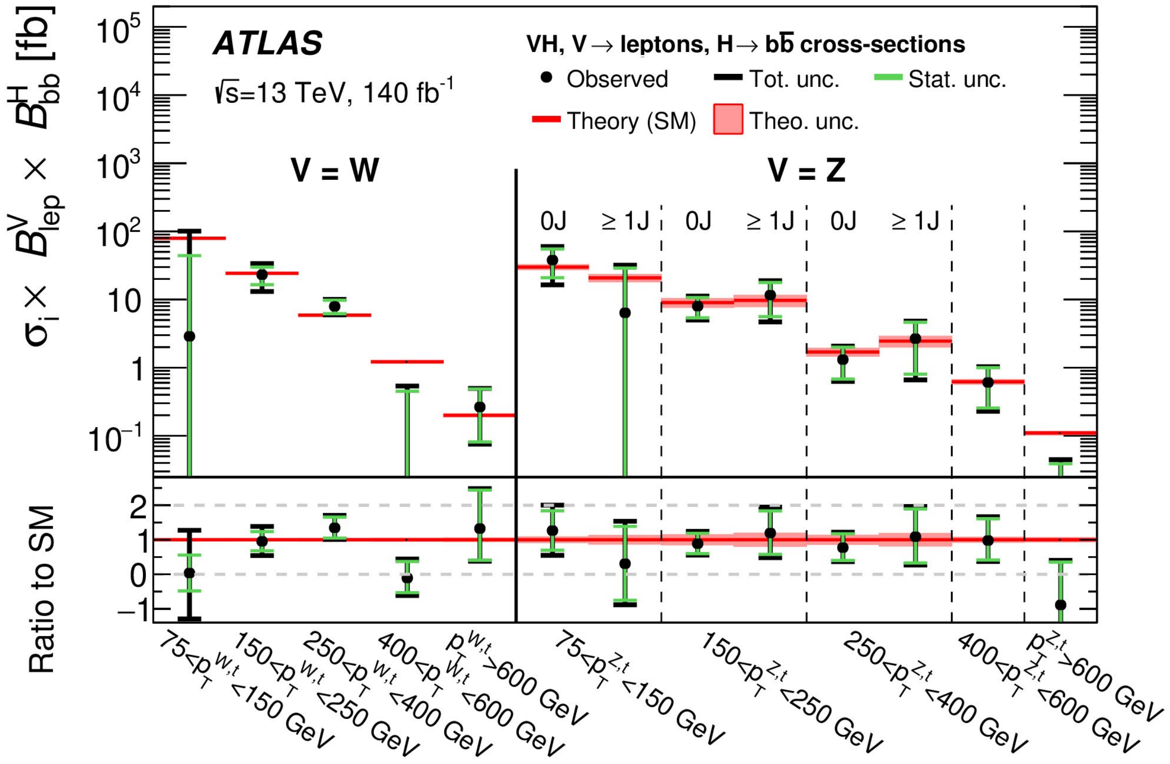
STXS VH(bb) measurements





Differential VH(bb) cross section measurement in p_T^V bins and $N_{add-jets}$ (STXS Reduced stage 1.2)

- New bin at low p_T^V (75-150 GeV) for WH(bb)
- New splitting for boosted regime
  - >400 → 400-600, > 600
- *Splitting in $N_{add-jets}$ for resolved ZH(bb) regime*

Overall compatibility with SM: 90%

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κ-framework interpretation

$\kappa_i^2 \equiv \Gamma^i / \Gamma^i_{SM}$

Fit results reinterpreted in the scope of the κ-modifiers framework. Only κ_b and κ_c parameterization.

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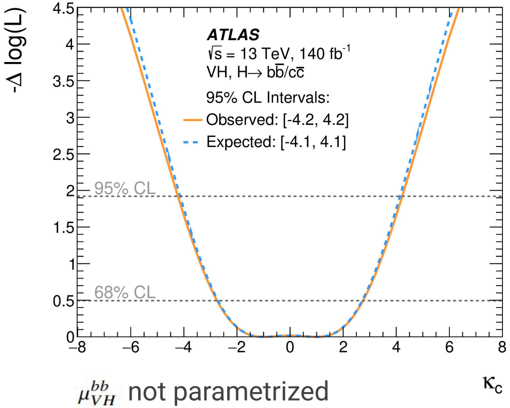
$\kappa_i^2 \equiv \Gamma^i / \Gamma^i_{SM}$

Fit results reinterpreted in the scope of the κ-modifiers framework. Only κ_b and κ_c parameterization.
1D scans (for $|\kappa_b|$ and $|\kappa_c|$ limits)

$\kappa_b = 1$, κ_c floating



μ_{VH}^{bb} not parametrized

$$\mu_{VH}^{cc} = \frac{\kappa_c^2}{1 + B_{Hcc}^{SM}(\kappa_c^2 - 1)}$$

$|\kappa_c| < 4.2\ (4.1)$ @ 95% CL
$0.65\ (0.72) < |\kappa_b| < 1.37\ (1.62)$ @ 95% CL

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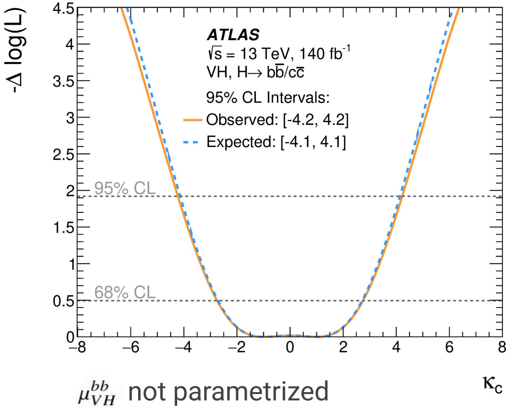
κ-framework interpretation

$\kappa_i^2 \equiv \Gamma^i / \Gamma^i_{SM}$

Fit results reinterpreted in the scope of the κ-modifiers framework. Only κ_b and κ_c parameterization.
1D scans (for $|\kappa_b|$ and $|\kappa_c|$ limits), 2D scan

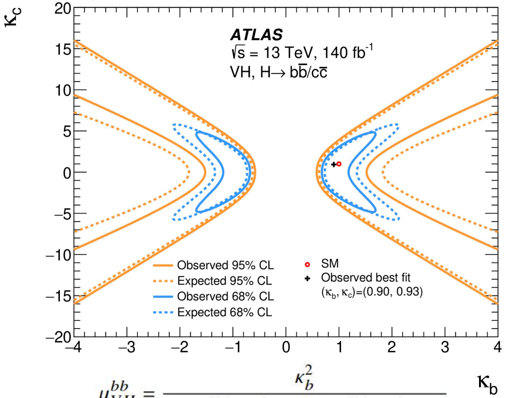
$\kappa_b = 1$, κ_c floating



μ^{bb}_{VH} not parametrized

$$\mu^{cc}_{VH} = \frac{\kappa_c^2}{1 + B^{SM}_{Hcc}(\kappa_c^2 - 1)}$$

κ_b, κ_c floating



$$\mu^{bb}_{VH} = \frac{\kappa_b^2}{1 + B^{SM}_{Hbb}(\kappa_b^2 - 1) + B^{SM}_{Hcc}(\kappa_c^2 - 1)}$$

$$\mu^{cc}_{VH} = \frac{\kappa_c^2}{1 + B^{SM}_{Hbb}(\kappa_b^2 - 1) + B^{SM}_{Hcc}(\kappa_c^2 - 1)}$$

$|\kappa_c| < 4.2$ (4.1) @ 95% CL
0.65 (0.72) $< |\kappa_b| < 1.37$ (1.62) @ 95% CL

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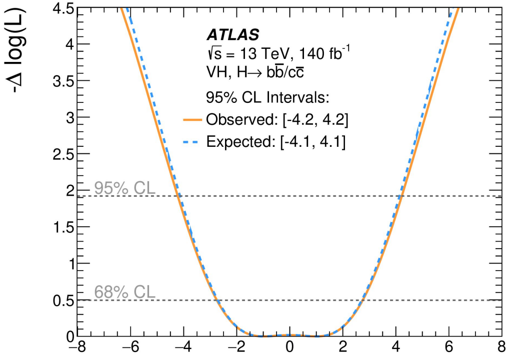
κ-framework interpretation

$$\kappa_i^2 \equiv \Gamma^i / \Gamma^i_{SM}$$

Fit results reinterpreted in the scope of the κ-modifiers framework. Only κ_b and κ_c parameterization.
1D scans (for $|\kappa_b|$ and $|\kappa_c|$ limits), 2D scan, $|\kappa_c/\kappa_b|$ limit extraction (no dependence on Γ_H assumptions)

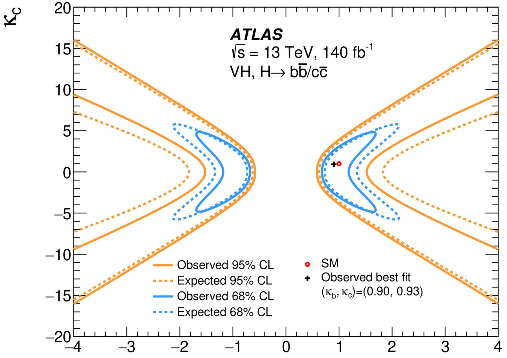
κ_b = 1, κ_c floating



μ_{VH}^{bb} not parametrized

$$\mu_{VH}^{cc} = \frac{\kappa_c^2}{1 + B_{Hcc}^{SM}(\kappa_c^2 - 1)}$$

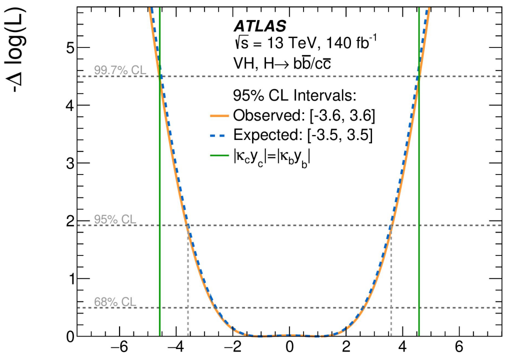
κ_b, κ_c floating



$$\mu_{VH}^{bb} = \frac{\kappa_b^2}{1 + B_{Hbb}^{SM}(\kappa_b^2 - 1) + B_{Hcc}^{SM}(\kappa_c^2 - 1)}$$

$$\mu_{VH}^{cc} = \frac{\kappa_c^2}{1 + B_{Hbb}^{SM}(\kappa_b^2 - 1) + B_{Hcc}^{SM}(\kappa_c^2 - 1)}$$

$|\kappa_c/\kappa_b|$ alternative param.



μ_{VH}^{bb} free parameter

$$\mu_{VH}^{cc} = \left(\frac{\kappa_c}{\kappa_b}\right)^2 \mu_{VH}^{bb}$$

$|\kappa_c|$ < 4.2 (4.1) @ 95% CL
0.65 (0.72) < $|\kappa_b|$ < 1.37 (1.62) @ 95% CL

$|\kappa_c/\kappa_b|$ < 3.6 (3.5) @ 95% CL
- < m_b/m_c @ μ_R=125 GeV:

Higgs flavour universality excluded at 3σ level

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Conclusions

Overview of the ATLAS VH(bb/cc) analysis

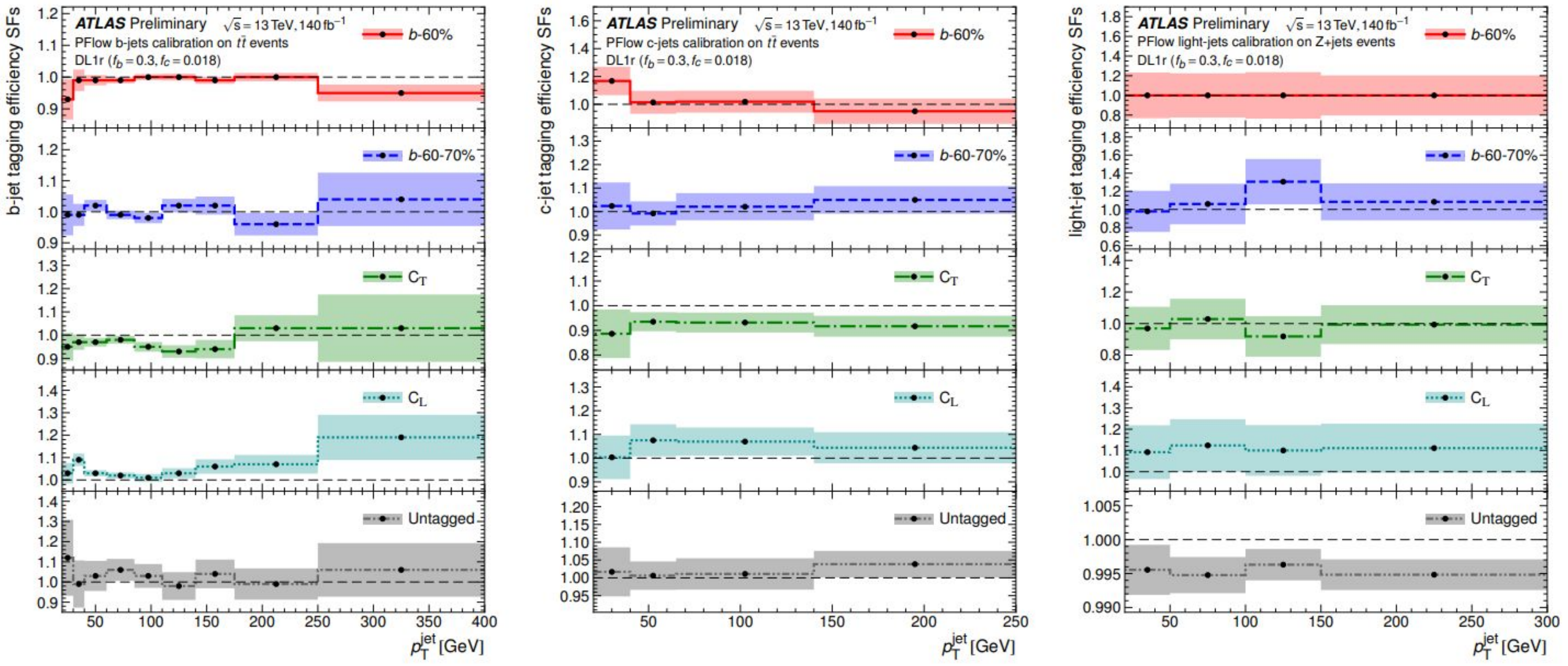
- combination of VH(bb) resolved, VH(cc), and VH(bb) boosted measurements
  - *ad hoc* 2D PCFT approach
  - MVA approach extended to VH(cc) and boosted VH(bb)
  - coherent modelling of main backgrounds in dedicated CRs

- significant achievements:
  - first observation of WZ(bb), VZ(cc) and WH(bb)
  - >100% improvement in VH(cc) limit, best observed constrain up to date
  - more granular STXS VH(bb) measurements
  - Higgs flavour universality excluded at 3σ level

Break

Backup

PCFT scale factors



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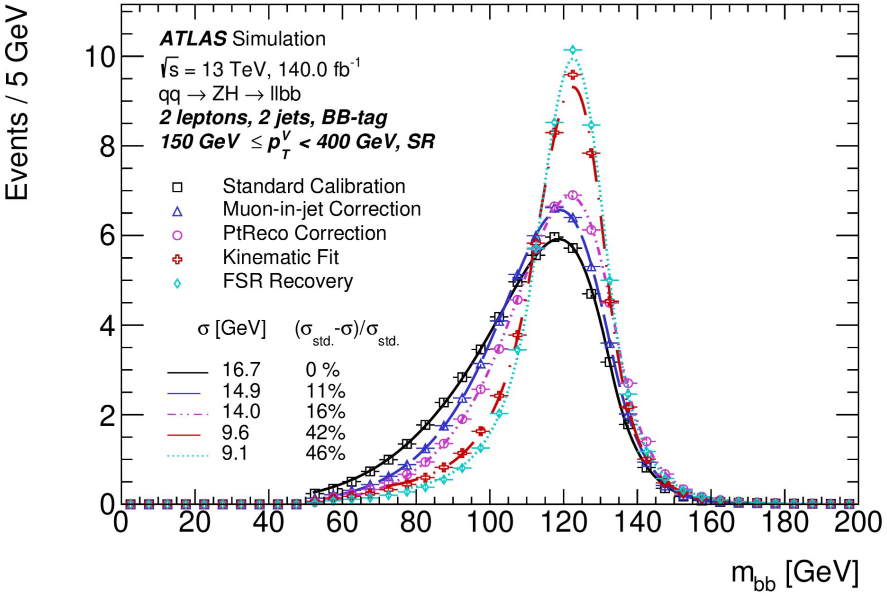
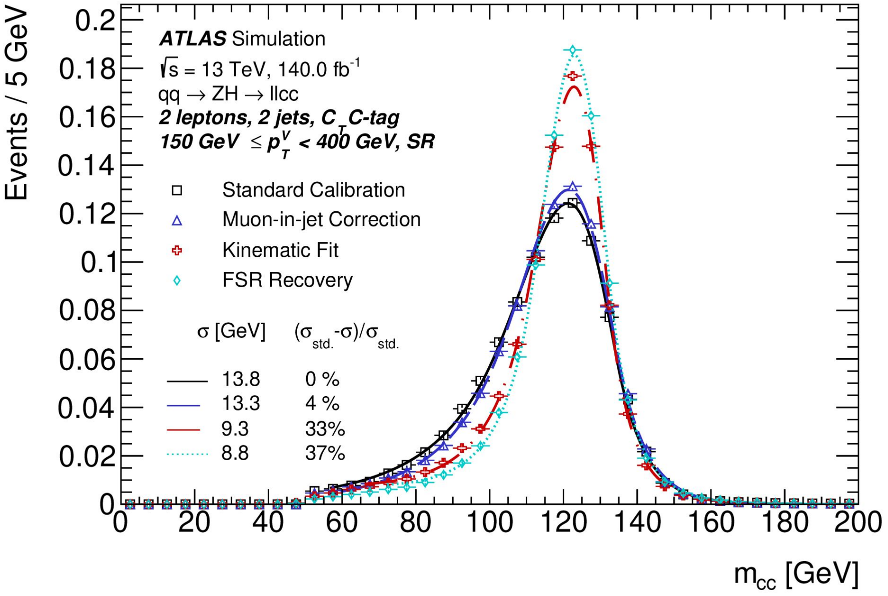
Dijet mass corrections





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Monte Carlo samples

Process	ME generator	ME PDF	PS and Hadronisation	UE tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to VH$	POWHEG BOX v2 + GOSAM + MINLO	PDF4LHC15NLO	PYTHIA 8.245	AZNLO	NNLO(QCD)$^{(\dagger)}$ + NLO(EW)
$gg \to ZH$	POWHEG BOX v2	PDF4LHC15NLO	PYTHIA 8.245	AZNLO	NLO+ NLL
Top quark, mass set to 172.5 GeV					
$t\bar{t}$	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	NNLO+NNLL
s-chan. single top	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO
t-chan. single top	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	NNLO
Wt	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	Approx. NNLO+NNLL
Vector boson + jets					
V+ jets	SHERPA 2.2.11	NNPDF3.0NNLO	SHERPA 2.2.11	Default	NNLO
Diboson					
$qq \to VV$	SHERPA 2.2.11	NNPDF3.0NNLO	SHERPA 2.2.11	Default	NLO$^{(\ddagger)}$
$gg \to VV$	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	Default	NLO$^{(\ddagger)}$

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Event selection

Analysis regime	resolved $VH(\rightarrow b\bar{b})$	$VH(\rightarrow c\bar{c})$
	Common Selections	
Jets	≥ 2 signal jets	
Candidate jets tagging	2 B-tags	≥ 1 T-tag [a]
Leading Higgs candidate jet p_T	> 45 GeV	
Sub-leading Higgs candidate jet p_T	> 20 GeV	
m_{bb} or m_{cc}	> 50 GeV (before correction)	
ΔR(jet1, jet2)	Upper cut $\Delta R < \pi$	
	0 Lepton	
Trigger	E_T^{miss} triggers	
Jets	≤ 4 jets	≤ 3 jets
Additional jets tagging	no T-tag	no B-tag[b]
Leptons	0 VH-loose lepton	
E_T^{miss}	> 150 GeV	
S_T	> 120 (2 jets), >150 GeV (3p jets)	
m_T^W	> 10 GeV (for events with at least one hadronic τ)	
$\|\min\Delta\phi(E_T^{\text{miss}}, \text{jet})\|$	$> 20°$ (2 jets), $> 30°$ (3 jets)	
$\|\Delta\phi(E_T^{\text{miss}}, H)\|$	$> 120°$	
$\|\Delta\phi(\text{jet1}, \text{jet2})\|$	$< 140°$	
	1 Lepton	
Trigger	e channel: single electron trigger μ channel: single muon trigger ($p_T^V < 150$ GeV) and E_T^{miss} triggers (above)	
Jets	≤ 3 jets	
Additional jets tagging	no T-tag	no B-tag[b]
Leptons	1 WH-signal lepton > 1 VH-loose lepton veto	
E_T^{miss}	> 30 GeV (e channel)	
S_T	> 120 (2 jets), >150 GeV (3 jets) (μ channel with E_T^{miss} trigger)	
m_T^W	> 20 GeV ($75 < p_T^V < 150$ GeV only)	
	2 Lepton	
Trigger	e channel: single electron trigger μ channel: single muon trigger ($p_T^V < 250$ GeV) and E_T^{miss} triggers (above)	
Additional jets tagging	-	no B-tag
Leptons	2 VH-loose leptons (≥ 1 ZH-signal lepton) Same flavour[c], opposite-charge for $\mu\mu$	
m_{ll}	$81 < m_{ll} < 101$ GeV	

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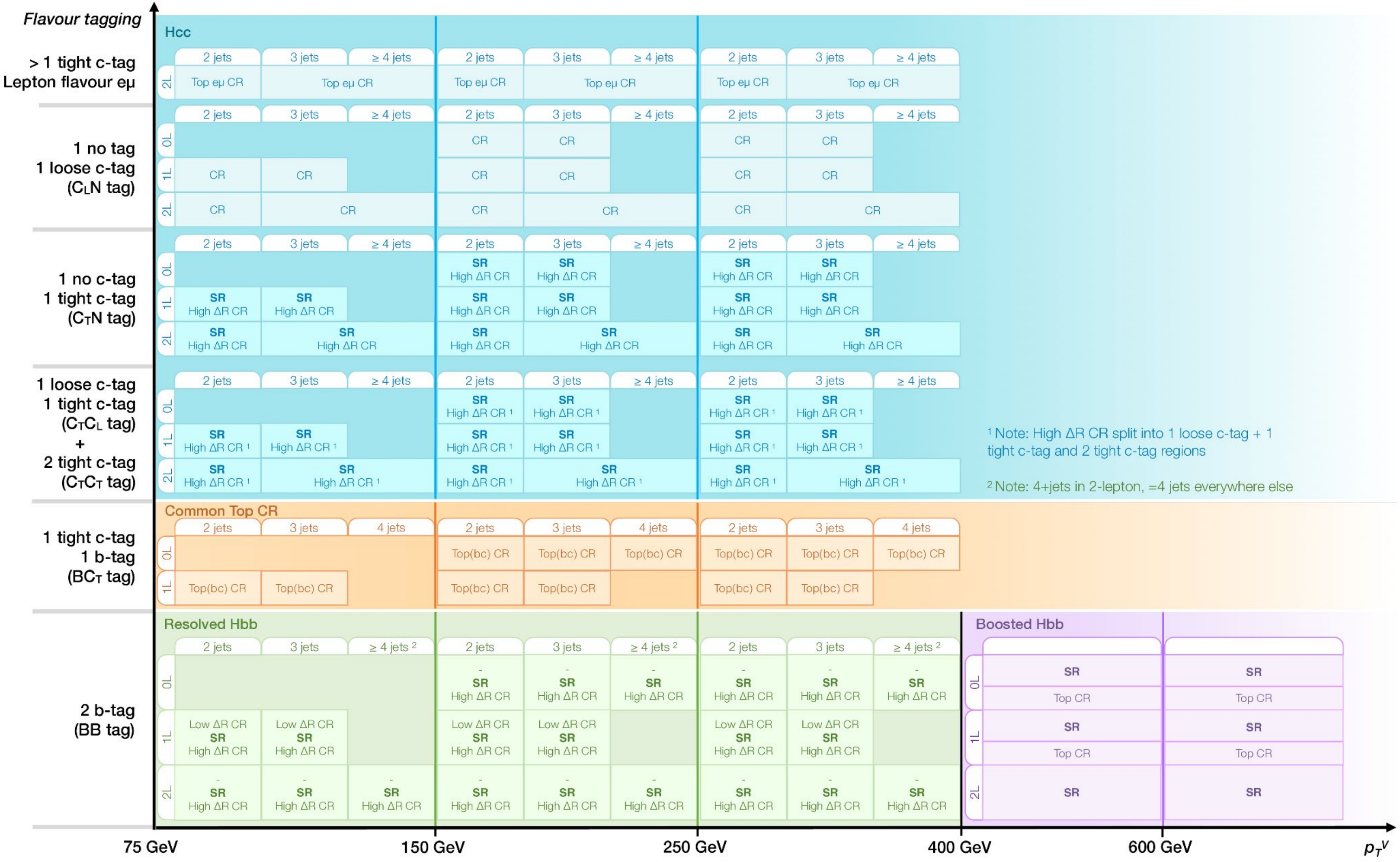
Event categorization



MVA input features

	Resolved $VH,\ H \to b\bar{b}, c\bar{c}$			Boosted $VH,\ H \to b\bar{b}$		
Variable	0-lepton	1-lepton	2-lepton	0-lepton	1-lepton	2-lepton
m_H	✓	✓	✓	✓	✓	✓
$m_{j_1 j_2 j_3}$	✓	✓	✓			
$p_T^{j_1}$	✓	✓	✓	✓	✓	✓
$p_T^{j_2}$	✓	✓	✓	✓	✓	✓
$p_T^{j_3}$				✓	✓	✓
$\sum p_T^{j_i},\ i > 2$	✓	✓	✓			
$\mathrm{bin}_{D_{\mathrm{DL1r}}}(j_1)$	✓	✓	✓	✓	✓	✓
$\mathrm{bin}_{D_{\mathrm{DL1r}}}(j_2)$	✓	✓	✓	✓	✓	✓
p_T^V	$\equiv E_T^{\mathrm{miss}}$	✓	✓	$\equiv E_T^{\mathrm{miss}}$	✓	✓
E_T^{miss}	✓	✓		✓	✓	
$E_T^{\mathrm{miss}}/\sqrt{S_T}$			✓			
$\lvert\Delta\phi(\boldsymbol{V}, \boldsymbol{H})\rvert$	✓	✓	✓	✓	✓	✓
$\lvert\Delta y(\boldsymbol{V}, \boldsymbol{H})\rvert$		✓	✓		✓	✓
$\Delta R(\boldsymbol{j_1}, \boldsymbol{j_2})$	✓	✓	✓	✓	✓	✓
$\min[\Delta R(\boldsymbol{j_i}, \boldsymbol{j_1} \text{ or } \boldsymbol{j_2})],\ i > 2$	✓	✓				
N(track-jets in J)				✓	✓	✓
N(add. small-R jets)				✓	✓	✓
colour ring				✓	✓	✓
$\lvert\Delta\eta(\boldsymbol{j_1}, \boldsymbol{j_2})\rvert$	✓					
$H_T + E_T^{\mathrm{miss}}$	✓					
m_T^W		✓				
m_{top}		✓				
$\min[\Delta\phi(\boldsymbol{\ell}, \boldsymbol{j_1} \text{ or } \boldsymbol{j_2})]$		✓				
p_T^{ℓ}					✓	
$(p_T^{\ell} - E_T^{\mathrm{miss}})/p_T^V$					✓	
$m_{\ell\ell}$			✓			
$\cos\theta^*(\boldsymbol{\ell^-}, \boldsymbol{V})$			✓			✓

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Variables used in the CRs

<table>
<tr><th>Channel</th><th>Region</th><th>BB</th><th>C_TN</th><th>C_TC_L</th><th>C_TC_T</th><th>BC_T</th><th>C_LN</th></tr>
<tr><td rowspan="3">0-lepton</td><td>High-ΔR CR</td><td colspan="4">Norm. Only</td><td colspan="2">—</td></tr>
<tr><td>BC_T Top CR</td><td colspan="4">—</td><td>$m_{j_1 j_2}$</td><td>—</td></tr>
<tr><td>$V+lf$ CR</td><td colspan="5">—</td><td>Norm. Only</td></tr>
<tr><td rowspan="4">1-lepton</td><td>Low-ΔR CR</td><td>$\mathrm{BDT}_{\text{Low-}\Delta R\text{ CR}}$</td><td colspan="5">—</td></tr>
<tr><td>High-ΔR CR</td><td colspan="2">p_T^V</td><td colspan="2">$m_{j_1 j_2}$</td><td colspan="2">—</td></tr>
<tr><td>BC_T Top CR</td><td colspan="4">—</td><td>$m_{j_1 j_2}$</td><td>—</td></tr>
<tr><td>$V+lf$ CR</td><td colspan="5">—</td><td>p_T^V</td></tr>
<tr><td rowspan="3">2-lepton</td><td>High-ΔR CR</td><td colspan="2">p_T^V</td><td colspan="2">$m_{j_1 j_2}$</td><td colspan="2">—</td></tr>
<tr><td>Top $e\mu$ CR</td><td>—</td><td colspan="3">Norm. Only</td><td>–</td><td>—</td></tr>
<tr><td>$V+lf$ CR</td><td colspan="5">—</td><td>p_T^V</td></tr>
</table>

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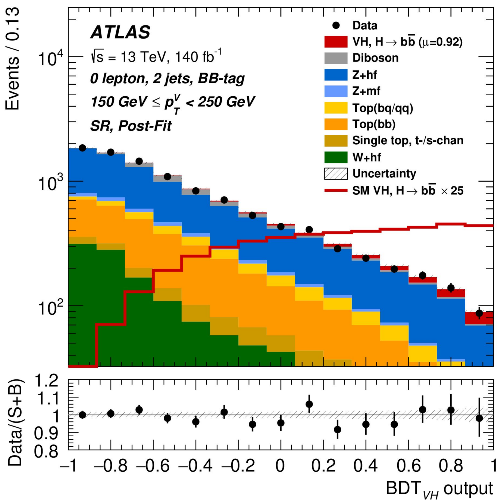
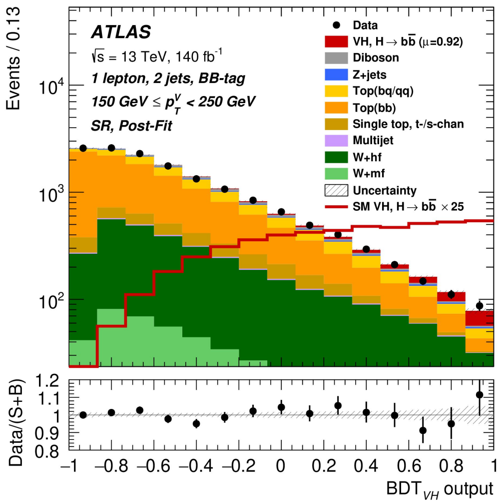
Some post-fit distributions

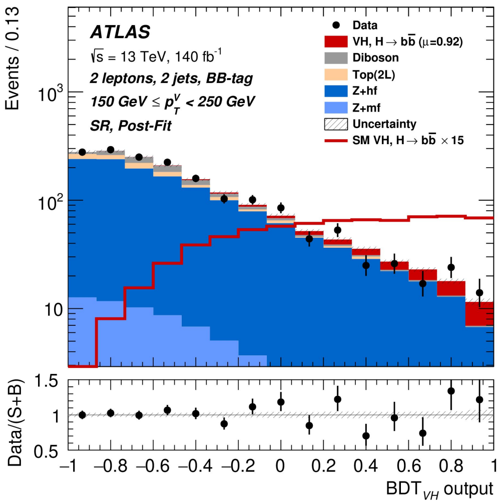
2jets, BB-tag, 150 < p_T^V < 250 GeV



0-lepton



1-lepton



2-lepton

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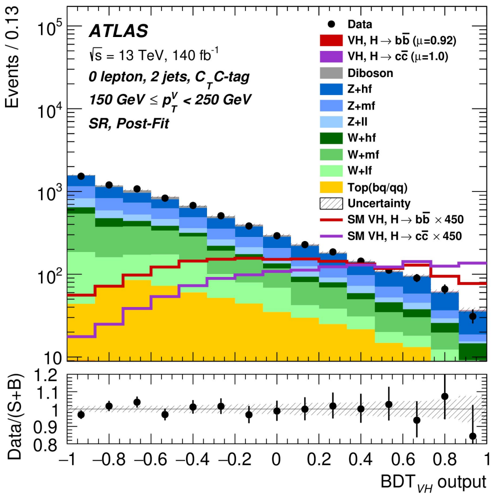
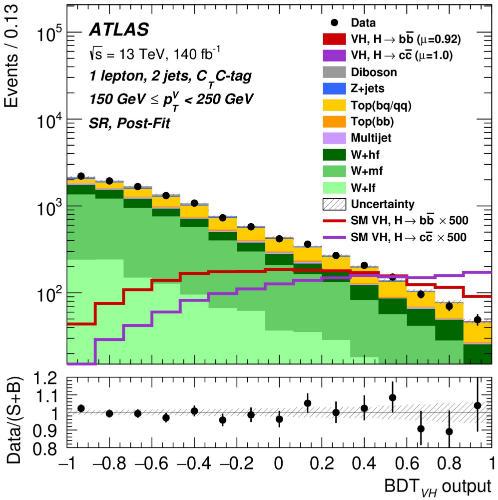
Some post-fit distributions

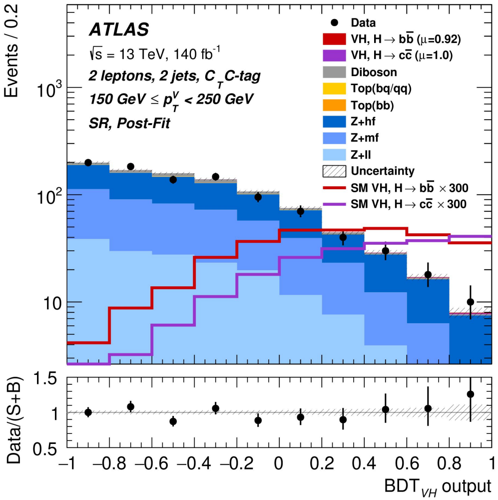
2jets, C_TC-tag, 150 < p_T^V< 250 GeV



0-lepton



1-lepton



2-lepton

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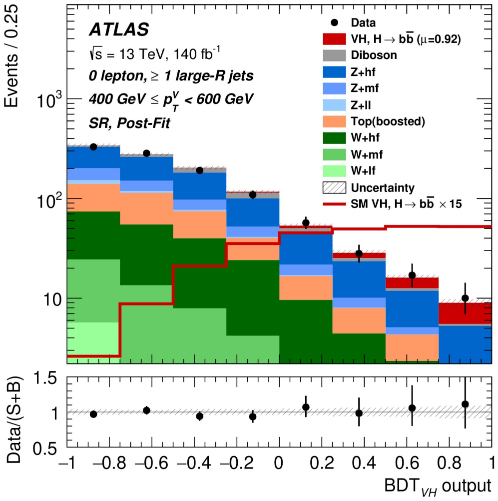
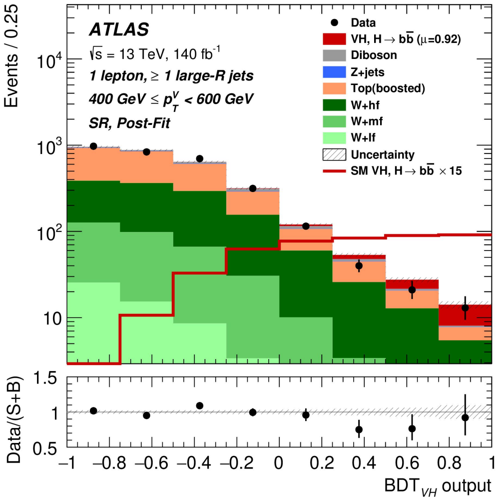
Some post-fit distributions

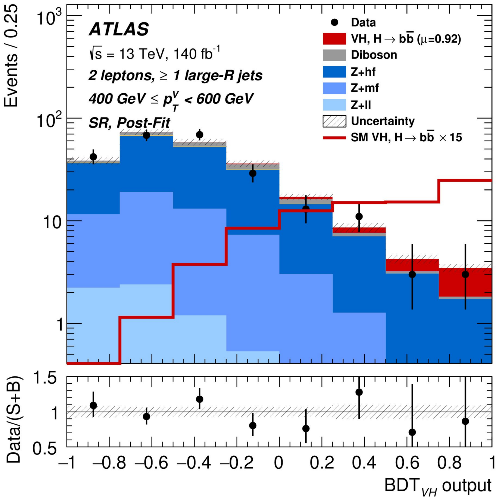
2jets, C_TC-tag, 150 < p_T^V< 250 GeV



0-lepton



1-lepton



2-lepton

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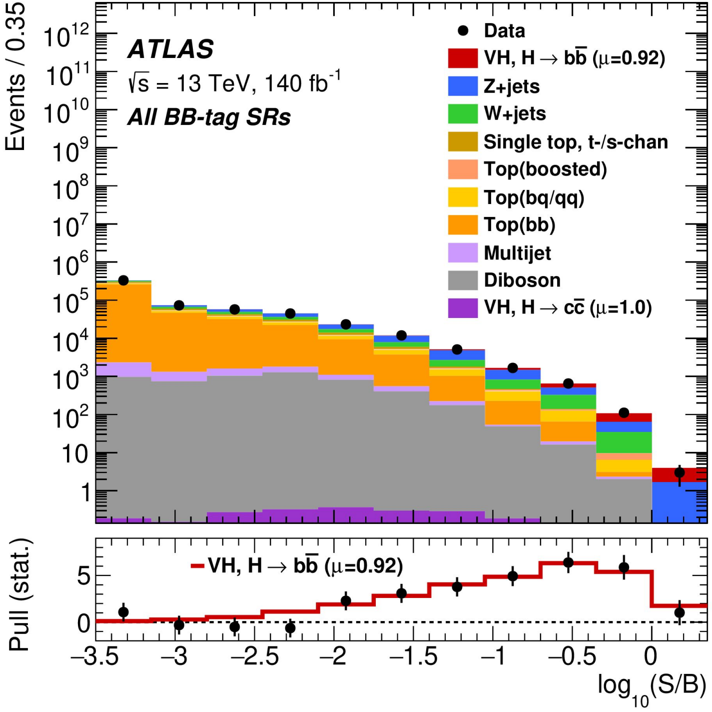
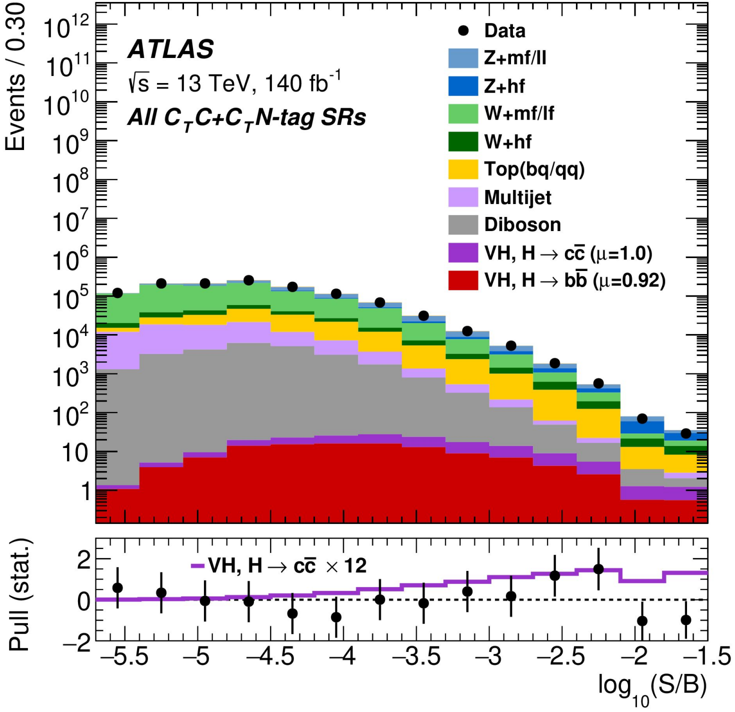
$\log_{10}(S/B)$


ATLAS
√s = 13 TeV, 140 fb-1
All BB-tag SRs
Data
VH, H → bb̄ (μ=0.92)
Z+jets
W+jets
Single top, t-/s-chan
Top(boosted)
Top(bq/qq)
Top(bb)
Multijet
Diboson
VH, H → cc̄ (μ=1.0)
Events / 0.35
Pull (stat.)
log10(S/B)


ATLAS
√s = 13 TeV, 140 fb-1
All CTC+CTN-tag SRs
Data
Z+mf/ll
Z+hf
W+mf/lf
W+hf
Top(bq/qq)
Multijet
Diboson
VH, H → cc̄ (μ=1.0)
VH, H → bb̄ (μ=0.92)
VH, H → cc̄ × 12
Events / 0.30
Pull (stat.)
log10(S/B)

Post-fit normalizing factors

p_T^V interval	Number of jets	$W+hf$	$W+mf$	$W+lf$
75–150 GeV	2	1.09 ± 0.06	1.20 ± 0.03	1.03 ± 0.04
	≥3	1.30 ± 0.07	1.16 ± 0.04	1.07 ± 0.05
150–250 GeV	2	1.00 ± 0.05	1.31 ± 0.03	1.08 ± 0.03
	≥3	1.28 ± 0.07	1.31 ± 0.04	1.07 ± 0.04
250–400 GeV	2	0.97 ± 0.08	1.35 ± 0.07	1.05 ± 0.03
	≥3	1.46 ± 0.12	1.32 ± 0.07	1.10 ± 0.04
400–600 GeV	-	1.49 ± 0.25		–
> 600 GeV	-	2.03 ± 0.25		–

p_T^V interval	Number of jets	$Z+hf$	$Z+mf$	$Z+lf$
75–150 GeV	2	1.20 ± 0.04	1.04 ± 0.04	1.12 ± 0.03
	≥3	1.49 ± 0.06	1.11 ± 0.05	1.12 ± 0.05
	3/≥3	0.77 ± 0.03	–	–
150–250 GeV	2	1.30 ± 0.04	1.08 ± 0.04	1.17 ± 0.02
	≥3	1.59 ± 0.07	1.14± 0.05	1.17 ± 0.04
	3/≥3	0.80 ± 0.04	–	–
250–400 GeV	2	1.40 ± 0.07	1.31 ± 0.08	1.16 ± 0.03
	≥3	1.78 ± 0.09	1.32 ± 0.07	1.20 ± 0.04
	3/≥3	0.74 ± 0.04	–	–
>400 GeV	-	1.63 ± 0.13		–

p_T^V interval	Number of jets	Top(bb)	Top(bq,qq)	Top 2L
75–150 GeV	2	1.02 ± 0.04	0.98 ± 0.05	1.05 ± 0.05
	3	0.97 ± 0.03	0.98 ± 0.03	0.98 ± 0.05
150–250 GeV	2	0.89 ± 0.05	0.83 ± 0.04	1.07 ± 0.16
	3	0.91 ± 0.03	0.86 ± 0.03	0.95 ± 0.14
	4	0.97 ± 0.02	0.95 ± 0.03	
250–400 GeV	2	0.78 ± 0.08	0.82 ± 0.05	1.10 ± 0.50
	3	0.83 ± 0.04	0.80 ± 0.03	
	4	0.93 ± 0.05	0.86 ± 0.04	
400–600 GeV	-	0.83 ± 0.05		–
>600 GeV	-	0.69 ± 0.07		–

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Uncertainties breakdown

Source of uncertainty	σ_μ			
	$VH, H \to b\bar{b}$	$WH, H \to b\bar{b}$	$ZH, H \to b\bar{b}$	$VH, H \to c\bar{c}$
Total	0.153	0.204	0.216	5.31
Statistical	0.097	0.139	0.153	3.94
Systematic	0.118	0.149	0.153	3.57
Statistical uncertainties				
Data statistical	0.090	0.129	0.139	3.67
$t\bar{t}$ $e\mu$ control region	0.009	0.014	0.027	0.08
Background floating normalisations	0.034	0.049	0.042	1.24
Other VH floating normalisation	0.007	0.018	0.014	0.33
Simulation samples size	0.023	0.033	0.030	1.62
Experimental uncertainties				
Jets	0.027	0.035	0.030	1.02
E_T^{miss}	0.010	0.005	0.021	0.23
Leptons	0.003	0.002	0.010	0.25
b-tagging: b-jets	0.020	0.018	0.026	0.29
b-tagging: c-jets	0.013	0.017	0.012	0.73
b-tagging: light-flavour jets	0.005	0.008	0.008	0.66
Pile-up	0.008	0.017	0.002	0.23
Luminosity	0.006	0.007	0.006	0.08
Theoretical and modelling uncertainties				
Signal	0.076	0.074	0.101	0.72
Z + jets	0.042	0.018	0.081	1.77
W + jets	0.054	0.087	0.026	1.42
$t\bar{t}$ and Wt	0.018	0.033	0.018	1.02
Single top-quark (s-, t-ch.)	0.010	0.018	0.002	0.16
Diboson	0.033	0.039	0.049	0.52
Multijet	0.005	0.010	0.005	0.55

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STXS measurements

Process	$p_T^{V,t}$ interval	N_{jet}^t	SM prediction [fb]	Measurement [fb]	Stat. unc. [fb]	Syst. unc. [fb] Th. sig.	Th. bkg.	Exp.
$W(\ell\nu)H$	75–150 GeV	≥0	79 .2 ± 2.8	3 ± 102	41	13	89	36
	150–250 GeV	≥0	24.3 ± 1.0	23 ± 10	7	2	7	3
	250–400 GeV	≥0	5.90 ± 0.25	7.9 ± 2.1	1.8	0.5	0.8	0.3
	400–600 GeV	≥0	1.03 ± 0.05	-0.11 ± 0.54	0.46	0.05	0.25	0.09
	> 600 GeV	≥0	0.20 ± 0.01	0.26 ± 0.21	0.20	0.02	0.04	0.03
$Z(\ell\ell/\nu\nu)H$	75–150 GeV	≥0	50.7 ± 3.9	51 ± 32	24	5	18	11
		=0	29.9 ± 2.5	38 ± 22	17	3	12	6
		≥1	20.7 ± 2.6	6 ± 25	22	4	9	8
	150–250 GeV	≥0	18.7 ± 3.5	17.7 ± 5.8	4.6	1.7	3.0	1.0
		=0	9.0. ± 1.3	8.0 ± 3.1	2.7	0.6	1.4	0.5
		≥1	9.7 ± 1.9	11.6 ± 7.1	6.1	1.0	3.2	1.4
	250–400 GeV	≥0	4.15 ± 0.45	3.5 ± 1.5	1.3	0.4	0.5	0.2
		=0	1.70 ± 0.22	1.31 ± 0.72	0.66	0.14	0.25	0.10
		≥1	2.45 ± 0.45	2.7 ± 2.1	1.9	0.3	0.7	0.3
	400–600 GeV	≥0	0.62 ± 0.05	0.61 ± 0.40	0.37	0.05	0.12	0.08
	> 600 GeV	≥0	0.11 ± 0.01	-0.10 ± 0.12	0.12	0.01	0.03	0.01

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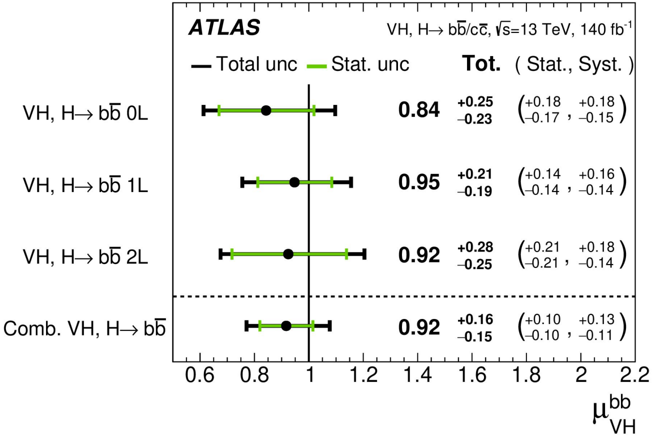
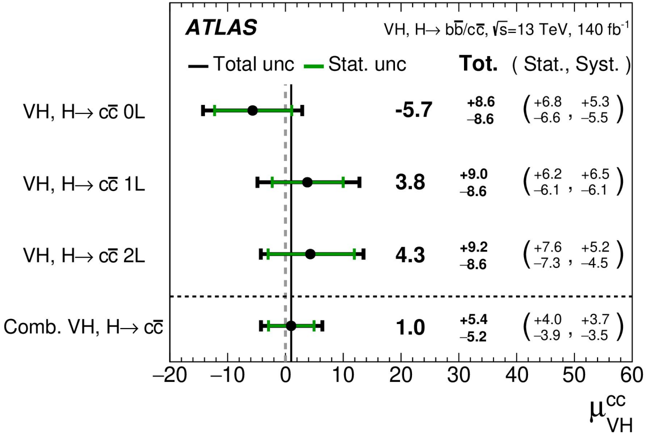
Lepton channel decorrelation



VH(bb)



VH(cc)

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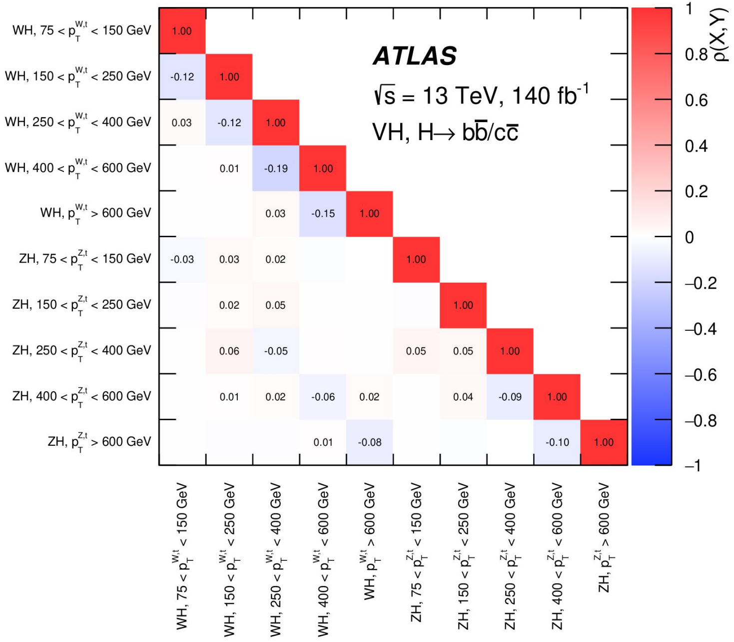
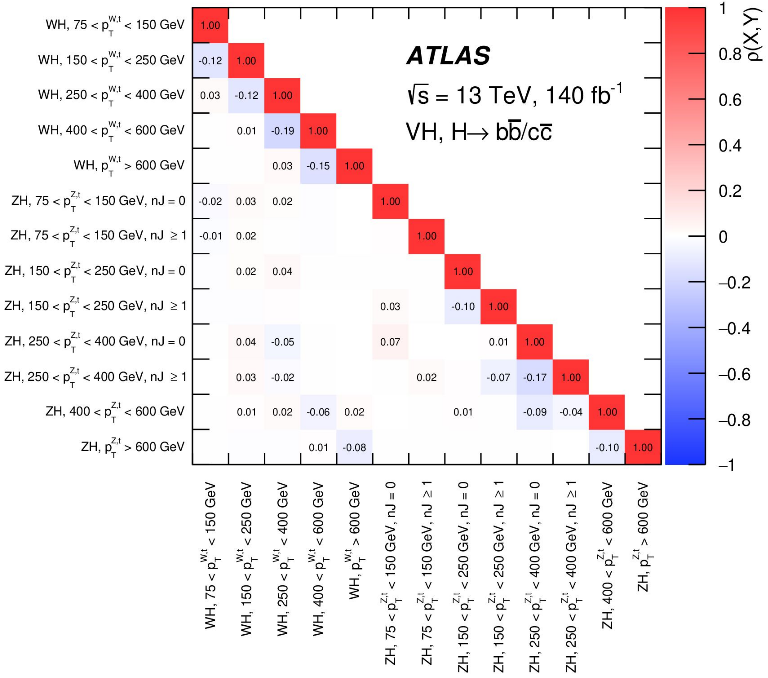
STXS correlations





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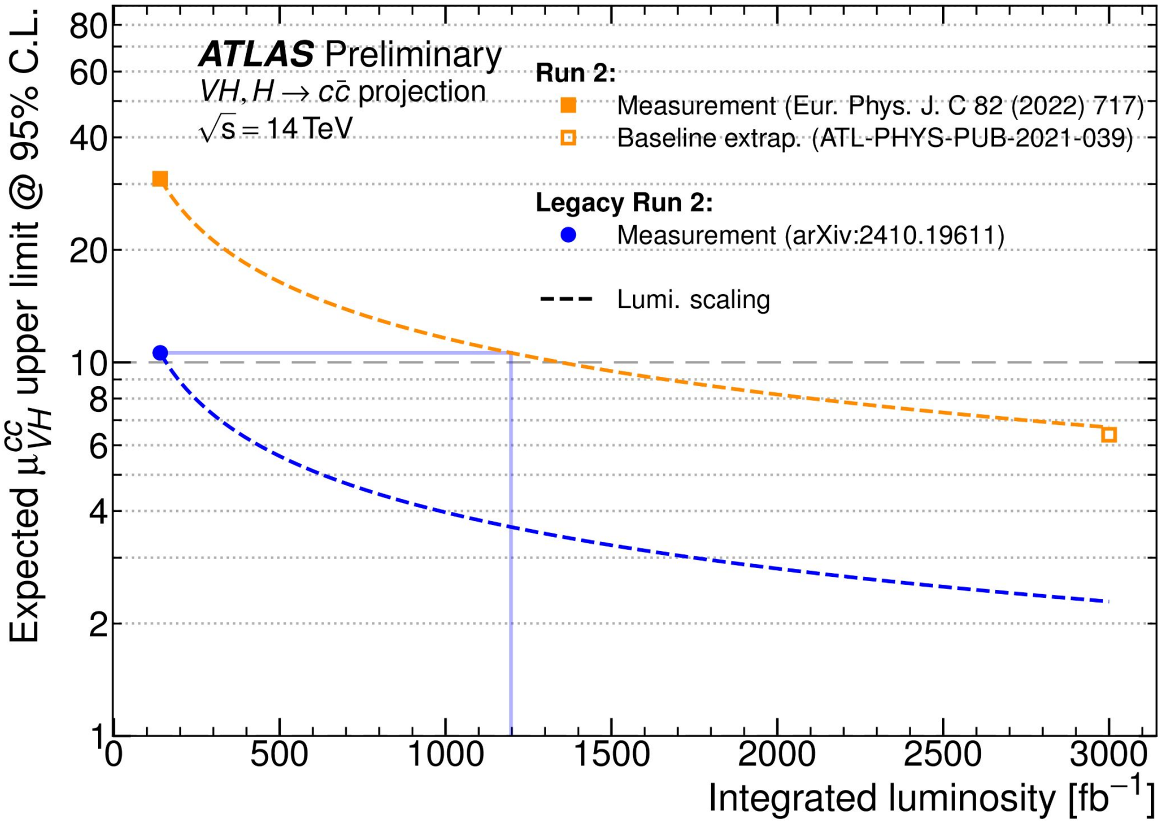
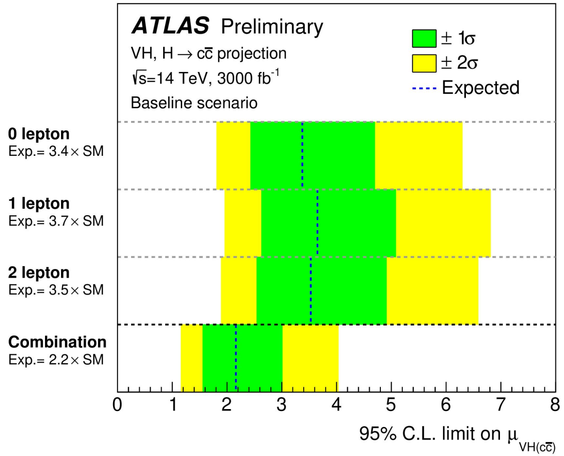
VH(cc) projections for HL-LHC





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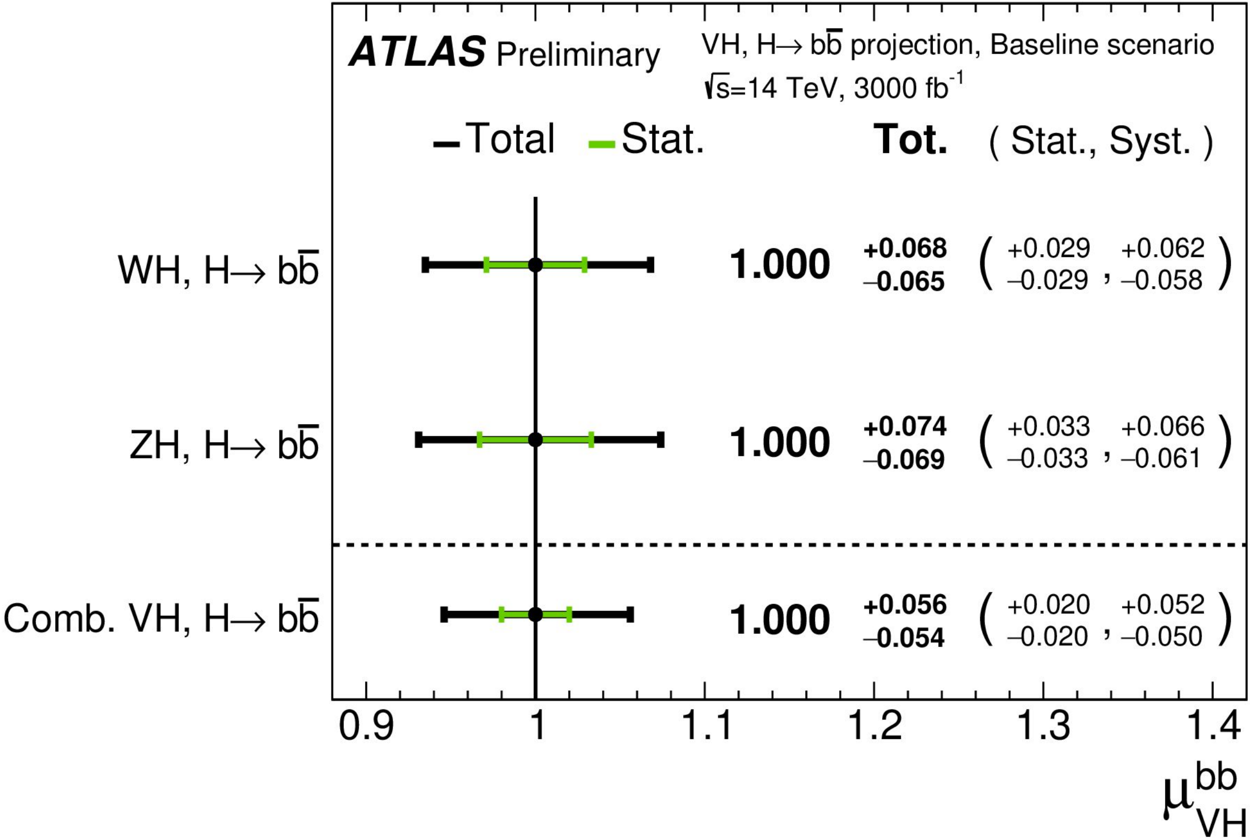
VH(bb) projections for HL LHC



ATL-PHYS-PUB-2025-012