ATLAS results on Higgs decays to $b\bar{b}$ and $\mu\mu$

Aspen 2018
The Particle Frontier
30 March 2018

Aidan Robson
on behalf of the ATLAS Collaboration
ATLAS results on Higgs decays to $b\bar{b}$ and $\mu\mu$

- Motivation
- VH, $H\rightarrow bb$
- ttH, $H\rightarrow bb$
- $H\rightarrow \mu\mu$
- Prospects

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Motivations

- Higgs discovery: bosonic decay modes
- Direct measurement of couplings to $3^{\text{rd}}$-generation fermions more difficult
  - H$\rightarrow$bb: an important missing piece
    - largest branching fraction (~58%)
    - direct probe of coupling to quarks
    - drives the uncertainty on the total decay width (and therefore the measurement of absolute couplings)
  - Run 1 combined ATLAS+CMS:
    H$\rightarrow$bb expected $3.7\sigma$, measured $2.6\sigma$

- ttH: indirect measurement via gluon–gluon fusion production
- H$\rightarrow$ττ: not discussed here;
  4.5σ evidence by ATLAS JHEP 04 (2015) 117

- Couplings to $2^{\text{nd}}$-generation fermions much weaker -> test of Yukawa mechanism
  - H$\rightarrow$μμ: very low branching fraction (~0.02%); could be enhanced by BSM
VH, H-$\rightarrow$bb signatures and selection

Capture events through 0-, 1-, and 2-charged lepton channels (e/\(\mu\))

<table>
<thead>
<tr>
<th>0-lepton</th>
<th>1-lepton</th>
<th>2-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>MET &gt; 150 GeV (+ multijet suppression)</td>
<td>(p_T(V) &gt; 150) GeV isolated lepton</td>
<td>75(&lt;p_T(V)&lt;150) GeV or (p_T(V)&gt;150) GeV</td>
</tr>
<tr>
<td>(81&lt;m(\ell\ell)&lt;101) GeV (ele channel)</td>
<td>MET &gt; 30 GeV (ele channel)</td>
<td>2 or (\geq 3) jets</td>
</tr>
<tr>
<td>2 b-tagged jets with (p_T&gt;20) GeV, lead jet &gt; 45 GeV</td>
<td>Exactly 2 or 3 jets</td>
<td></td>
</tr>
<tr>
<td>Trigger based on single lepton and MET signatures</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tag b-jets for H reconstruction

Fit data to determine signal
Improvements

- **b-tagging:**
  - new innermost pixel layer (IBL) for Run 2
  - + updated MVA algorithm
  - → significantly improves efficiency and c-jet rejection

- **$m_{bb}$ corrections:**
  - $\mu$-in-jet, b-jet energy response correction, kinematic likelihood fit (2-lep)
  - → $m_{bb}$ resolution improved by 18–40%


- Event-level variables including $m_{bb}$ used in TMVA to train BDT for each signal channel and analysis region

- Likelihood fit applied across channels/regions to extract signal strength $\mu$ and normalisations of main backgrounds

- Shapes and relative normalisations across regions parametrised by nuisance parameters, constrained within allowed systematic uncertainties

<table>
<thead>
<tr>
<th>Variable</th>
<th>0-lepton</th>
<th>1-lepton</th>
<th>2-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(V)$</td>
<td>×</td>
<td></td>
<td>×</td>
</tr>
<tr>
<td>$E_{miss}^T$</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>$p_T^{b_1}$</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>$p_T^{b_2}$</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>$m_{bb}$</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>$\Delta R(b_1, b_2)$</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta(b_1, b_2)</td>
<td>$</td>
<td>×</td>
</tr>
<tr>
<td>$\Delta \phi(V, \bar{b}b)$</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta(V, \bar{b}b)</td>
<td>$</td>
<td>×</td>
</tr>
<tr>
<td>$m_{eff}$</td>
<td>×</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\min[\Delta \phi(\ell, \bar{b})]$</td>
<td>×</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_W$</td>
<td>×</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td></td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>$m_{top}$</td>
<td></td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta Y(V, \bar{b}b)</td>
<td>$</td>
<td></td>
</tr>
<tr>
<td>$p_T^{jet_3}$</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>$m_{bbj}$</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

Only in 3-jet events

JHEP 12(2017)024
Non-resonant backgrounds from W+jets, Z+jets, ttbar, and single top

W+jets / Z+jets mainly suppressed by b-jet requirement (except W/Z+bb)

ttbar mainly suppressed by $N_{\text{jet}}$ requirement

Resonant VZ, Z->bb backgrounds used to validate analysis procedure
VH, H->bb background strategy

**Z+jets:** constrained in 2-lep extrapolated to 0-lep

**W+jets:** constrained in 1-lep with dedicated control region, extrapolated to 0-lep

**ttbar:**
- in 0-lep and 1-lep: constrained together by 3-jet region
- in 2-lep: constrained in a dedicated control region

<table>
<thead>
<tr>
<th>Process</th>
<th>Normalisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt 0 &amp; 1-lep</td>
<td>0.90±0.08</td>
</tr>
<tr>
<td>tt 2-lep 2-jet</td>
<td>0.97±0.09</td>
</tr>
<tr>
<td>tt 2-lep 3-jet</td>
<td>1.04±0.06</td>
</tr>
<tr>
<td>W+HF 2-jet</td>
<td>1.22±0.14</td>
</tr>
<tr>
<td>W+HF 3-jet</td>
<td>1.27±0.14</td>
</tr>
<tr>
<td>Z+HF 2-jet</td>
<td>1.30±0.10</td>
</tr>
<tr>
<td>Z+HF 3-jet</td>
<td>1.22±0.09</td>
</tr>
</tbody>
</table>

1-lep W+jets control region:
- $m_{bb} < 75$GeV and $m_{top} > 225$ GeV
- $\rightarrow \sim 75$-80% purity

2-lep ttbar control region:
- require $e\mu$
- $\rightarrow > 99\%$ purity
VZ, Z->bb validation

- Use same variables to train BDT$_{VZ}$ with VZ, Z->bb as signal
  → adapted for different mass, softer $p_T$ spectrum

$$\mu = \frac{\sigma x Br}{(\sigma x Br)_{SM}}$$

- observe VZ, Z->bb with 5.8$\sigma$ significance
  (5.3$\sigma$ expected)
- validates BDT analysis

JHEP 12(2017)024
Observe VH,H->bb excess with 3.5σ significance (3.0σ expected)

Evidence of VH(bb)!

Consistent in WH and ZH; measure:

\[ \sigma(\text{WH}) \times \text{Br}(H\rightarrow bb) = 1.08^{+0.54}_{-0.47} \text{ pb} \]

\[ \sigma(\text{ZH}) \times \text{Br}(H\rightarrow bb) = 0.57^{+0.26}_{-0.23} \text{ pb} \]

JHEP 12(2017)024
Alternative approach as validation of BDT analysis: fit to $m_{bb}$
+ additional category $p_T(V) > 200$ GeV
+ additional cut on $\Delta R(b_1, b_2)$

Higgs signal strength $\mu = 1.30^{+0.28}_{-0.27}$ (stat.)$^{+0.37}_{-0.29}$ (sys)
3.5$\sigma$ observed significance (2.8$\sigma$ expected)
consistent with BDT analysis
VH, H->bb dominant uncertainties

Systematic uncertainties are dominant:

- **Background modelling** – improved modelling needed, especially for extrapolation from control regions

- **B-tagging calibration uncertainty** – MC-to-data correction factors parametrised in $p_T$ and $\eta$

- **Signal modelling** – variations in $p_T(V)$, $m_{bb}$ from changing QCD scale and PS tunes

- **Monte Carlo statistics** – few events with high $p_T$, 2 b-tags, and high BDT values (despite generator slicing / filtering)

$\rightarrow$ prospects for improvement!

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\sigma_\mu$</th>
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</thead>
<tbody>
<tr>
<td>Total</td>
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<tr>
<td>Statistical</td>
<td>0.24</td>
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<tr>
<td>Systematic</td>
<td>0.31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experimental uncertainties</th>
<th>$\sigma_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets</td>
<td>0.03</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>0.03</td>
</tr>
<tr>
<td>Leptons</td>
<td>0.01</td>
</tr>
<tr>
<td>$b$-jets</td>
<td>0.09</td>
</tr>
<tr>
<td>$c$-jets</td>
<td>0.04</td>
</tr>
<tr>
<td>light jets</td>
<td>0.04</td>
</tr>
<tr>
<td>extrapolation</td>
<td>0.01</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.01</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Theoretical and modelling uncertainties</th>
<th>$\sigma_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>0.17</td>
</tr>
<tr>
<td>Floating normalisations</td>
<td>0.07</td>
</tr>
<tr>
<td>$Z +$ jets</td>
<td>0.07</td>
</tr>
<tr>
<td>$W +$ jets</td>
<td>0.07</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.07</td>
</tr>
<tr>
<td>Single top quark</td>
<td>0.08</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.02</td>
</tr>
<tr>
<td>Multijet</td>
<td>0.02</td>
</tr>
</tbody>
</table>

$\text{MC statistical}$: 0.13

JHEP 12(2017)024
Combination with 7 & 8 TeV results from LHC Run 1 – combined observed significance 3.6\sigma (4.0\sigma expected)

consistent with Standard Model

JHEP 12(2017)024
ttH, H->bb categorization

- ttH measurements target top-Yukawa coupling
- exploit large Br(H->bb) => ttH(bb) gives important contribution ttH measurement

- Categorized into sub-channels to increase sensitivity
  - number of leptons, number of jets, and b-tags corresponding to different working points:

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>none</th>
<th>loose</th>
<th>medium</th>
<th>tight</th>
<th>very-tight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discriminant value</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

2-lepton
- Exactly two opposite-sign leptons, veto Z-candidates, no hadronic τ
- Require ≥3 jets and ≥2 medium b-tagged jets

1-lepton
- Exactly one lepton
- Resolved category:
  ≥5 jets & ≥2 very-tight or ≥3 medium b-tagged jets
- Boosted category:
  reconstruct Higgs and top decay products in two large R=1.0 jets, p_T(H)>200GeV, p_T(t)>250GeV
Regions constructed for 3 and ≥4 jets (2-lepton) and for 5 and ≥6 jets (1-lepton) (boosted channel is not categorized further)

- Control regions for tt+b, tt+c and tt+light to constrain background systematics
- Highest signal purity is in 4 very-tight b-tag bins
ttH, H->bb multivariate analysis

- In signal regions, MVA techniques used to separate signal and background
- Reconstruction BDT (all resolved SRs)
  identify best assignment of jets to partons from ttH(bb)

- Likelihood discriminator (1-lep resolved SRs only)
  probability of signal/background based on PDFs for each

- Matrix Element (SR≥6 only)
  likelihood estimation from ME method

- Discriminating variables e.g. $m_{bb}$, $\Delta \eta_{bb}$
  -> all inputs to classification BDT for sig/bck separation
Simultaneous fit to all SRs & CRs

Fit (1-lepton)

$\tt \pm 1\text{b/c}$ normalisation freely floating in the fit

$\tt H$, $H \rightarrow bb$ fit
**ttH, H->bb results**

- **ttH(bb)** at 1.4σ observed (1.6σ expected)
- combine with ttH multilepton and subcategories of H->γγ and H->ZZ → evidence for ttH production observed at 4.2σ

### Uncertainty source

<table>
<thead>
<tr>
<th>Source</th>
<th>Δμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt + ≥1b modeling</td>
<td>+0.46</td>
</tr>
<tr>
<td>Background-model stat. unc.</td>
<td>+0.29</td>
</tr>
<tr>
<td>b-tagging efficiency and mis-tag rates</td>
<td>+0.16</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>+0.14</td>
</tr>
<tr>
<td>ttH modeling</td>
<td>+0.22</td>
</tr>
<tr>
<td>Total statistical uncertainty</td>
<td>+0.29</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>+0.64</td>
</tr>
</tbody>
</table>

modelling of tt+hf background is limiting factor

### Observation

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed</th>
<th>Expected</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multilepton</td>
<td>1.6 ±0.5</td>
<td>1.0 ±0.4</td>
<td>4.1σ 2.8σ</td>
</tr>
<tr>
<td>H → bb</td>
<td>0.8 ±0.6</td>
<td>1.0 ±0.6</td>
<td>1.4σ 1.6σ</td>
</tr>
<tr>
<td>H → γγ</td>
<td>0.6 ±0.7</td>
<td>1.0 ±0.8</td>
<td>0.9σ 1.7σ</td>
</tr>
<tr>
<td>H → 4ℓ</td>
<td>&lt; 1.9</td>
<td>1.0 ±3.2</td>
<td>— 0.6σ</td>
</tr>
<tr>
<td>Combined</td>
<td>1.2 ±0.3</td>
<td>1.0 ±0.3</td>
<td>4.2σ 3.8σ</td>
</tr>
</tbody>
</table>

arXiv:1712.08895 submitted to PRD

arXiv:1712.08891 submitted to PRD
\( H \rightarrow \mu\mu \)

- Clean experimental signature
- Excellent mass resolution
- but small \( Br \approx 2.18 \times 10^{-4} \)
  \( \rightarrow \) tiny signature buried under Drell-Yan

- Selection:
  - two isolated muons with \( p_T > 15 \text{GeV} \)
  - \( \text{MET} < 80 \text{ GeV} \)
  - b-jet veto
  - \( 110 < m_{\mu\mu} < 160 \text{ GeV} \)

- Six gluon-gluon fusion categories based on \( \eta_\mu \) and \( p_T^{\mu\mu} \)
- Two VBF categories with \( N_{\text{jets}} \geq 2 \), selected by a BDT
- \( S/\sqrt{B}=0.37 \) in VBF tight region!
H-$\mu\mu$ results

Fit di-muon mass spectra:
- bump-hunt with parametrised background function
  $(BW \times Gauss + \exp(A.m_{\mu\mu}) / m_{\mu\mu}^3)$ fit to data in sidebands
- simultaneous fit to observed $m_{\mu\mu}$ in all categories to extract signal strength

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Upper limit / SM (95%CL) observed (expected)</th>
<th>Signal strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 2 (13 TeV)</td>
<td>3.0 (3.1)</td>
<td>$-0.1 \pm 1.5$</td>
</tr>
<tr>
<td>Run 1 + Run 2 (7,8,13 TeV)</td>
<td>2.8 (2.9)</td>
<td>$-0.1 \pm 1.4$</td>
</tr>
</tbody>
</table>

- Statistics-limited

PRL 119 (2017) 051802
$H \rightarrow \mu\mu$ candidate

$m(\mu\mu) = 124$ GeV

$m(\text{jet, jet}) = 1237$ GeV
Prospects

- All results shown with 36.1 fb\(^{-1}\) data at \(\sqrt{s}=13\) TeV
- Run 2 total expected to be 120–150 fb\(^{-1}\)
- VH, Hbb: published result is systematics-dominated – now working on background modelling, b-tagging, and MC stats in order to reach 5\(\sigma\) observation in Run 2. Beyond with HL-LHC: can study differential distributions
- ttH: working on background modelling, especially ttbb, towards 5\(\sigma\) observation in Run 2
- H\(\mu\mu\): potential for combined ATLAS/CMS result to reach SM sensitivity with Run 2 data. HL-LHC: new ATLAS tracker layout \(\rightarrow 25\%\) improvement in H\(\mu\mu\) mass resolution; 8.6\(\sigma\) sensitivity estimated with 3000 fb\(^{-1}\) (assuming \(\langle p\rangle=200\))

ATLAS muon upgrade TDR, ATLAS-TDR-026 (2017)
Conclusions

- First LHC evidence for H->bb, in VH,H->bb at $3.6\sigma$ with 36.1 fb$^{-1}$ at $\sqrt{s}=13$ TeV
  - signal strength uncertainty ~25–30%; consistent with SM

- First evidence for ttH production at $4.2\sigma$ with 36.1 fb$^{-1}$ at $\sqrt{s}=13$ TeV;
  - ttH,H->bb contributes 1.4$\sigma$

- Search for H->$\mu\mu$ gives upper limit of 2.8 $\sigma_{SM} \times Br$
  - potential for SM sensitivity with complete Run 2 dataset and ATLAS/CMS combination

→ Looking forward to 120–150 fb$^{-1}$!
Backups
# VH generators

<table>
<thead>
<tr>
<th>Process</th>
<th>ME generator</th>
<th>ME PDF</th>
<th>PS and Hadronisation</th>
<th>UE model tune</th>
<th>Cross-section order</th>
<th>ace2.5 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\rightarrow \ell\nu\ell\nu$</td>
<td>Powheg-Box v2</td>
<td>NNPDF3.0NLO(*)</td>
<td>Pythia8.212</td>
<td>AZNLO</td>
<td>NNLO(QCD)(1)+NLO(EW)</td>
</tr>
<tr>
<td></td>
<td>$qq \rightarrow ZH$</td>
<td>GoSam + MiNLO</td>
<td>NNPDF3.0NLO(*)</td>
<td>Pythia8.212</td>
<td>AZNLO</td>
<td>NLO+NNLL [32,33,34,35,36]</td>
</tr>
<tr>
<td></td>
<td>$\rightarrow \ell\nu\ell\nu/\ell\ell\ell\nu$</td>
<td>Powheg-Box v2</td>
<td>NNPDF3.0NLO(*)</td>
<td>Pythia8.212</td>
<td>AZNLO</td>
<td>NLO+NNLL [32,33,34,35,36]</td>
</tr>
<tr>
<td></td>
<td>$gg \rightarrow ZH$</td>
<td>Powheg-Box v2</td>
<td>NNPDF3.0NLO(*)</td>
<td>Pythia8.212</td>
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</tr>
<tr>
<td>Top quark</td>
<td>$tt$</td>
<td>Powheg-Box v2 [37]</td>
<td>NNPDF3.0NLO</td>
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<td>A14 [38]</td>
<td>NNLO+NNLL [39]</td>
</tr>
<tr>
<td></td>
<td>t-channel</td>
<td>Powheg-Box v1 [40]</td>
<td>CT10f1</td>
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<td>P2012</td>
<td>NLO [45]</td>
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<td>$Wt$</td>
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<td>CT10</td>
<td>Pythia6.428</td>
<td>P2012</td>
<td>NLO [47]</td>
</tr>
<tr>
<td>Vector boson + jets</td>
<td>$W \rightarrow \ell\nu$</td>
<td>Sherpa 2.2.1 [16,48,49]</td>
<td>NNPDF3.0NNLO</td>
<td>Sherpa 2.2.1 [50,51]</td>
<td>Default</td>
<td>NNLO [52]</td>
</tr>
<tr>
<td></td>
<td>$Z/\gamma^* \rightarrow \ell\ell$</td>
<td>Sherpa 2.2.1</td>
<td>NNPDF3.0NNLO</td>
<td>Sherpa 2.2.1</td>
<td>Default</td>
<td>NNLO</td>
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<tr>
<td></td>
<td>$Z \rightarrow \nu\nu$</td>
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<tr>
<td>Diboson</td>
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<tr>
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<td></td>
<td>$ZZ$</td>
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<td>NLO</td>
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VH background systematics

<table>
<thead>
<tr>
<th>Z + jets</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Z + ll normalisation</td>
<td>18%</td>
</tr>
<tr>
<td>Z + cl normalisation</td>
<td>23%</td>
</tr>
<tr>
<td>Z + bb normalisation</td>
<td>Floating (2-jet, 3-jet)</td>
</tr>
<tr>
<td>Z + bc-to-Z + bb ratio</td>
<td>30 – 40%</td>
</tr>
<tr>
<td>Z + cc-to-Z + bb ratio</td>
<td>13 – 15%</td>
</tr>
<tr>
<td>Z + bl-to-Z + bb ratio</td>
<td>20 – 25%</td>
</tr>
<tr>
<td>0-to-2 lepton ratio</td>
<td>7%</td>
</tr>
<tr>
<td>$m_{bb}$, $p_T^V$</td>
<td>S</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W + jets</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W + ll normalisation</td>
<td>32%</td>
</tr>
<tr>
<td>W + cl normalisation</td>
<td>37%</td>
</tr>
<tr>
<td>W + bb normalisation</td>
<td>Floating (2-jet, 3-jet)</td>
</tr>
<tr>
<td>W + bl-to-W + bb ratio</td>
<td>26% (0-lepton) and 23% (1-lepton)</td>
</tr>
<tr>
<td>W + bc-to-W + bb ratio</td>
<td>15% (0-lepton) and 30% (1-lepton)</td>
</tr>
<tr>
<td>W + cc-to-W + bb ratio</td>
<td>10% (0-lepton) and 30% (1-lepton)</td>
</tr>
<tr>
<td>0-to-1 lepton ratio</td>
<td>5%</td>
</tr>
<tr>
<td>W + HF CR to SR ratio</td>
<td>10% (1-lepton)</td>
</tr>
<tr>
<td>$m_{bb}$, $p_T^V$</td>
<td>S</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ttbar (all are uncorrelated between the 0+1 and 2-lepton channels)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ttbar normalisation</td>
<td>Floating (0+1 lepton, 2-lepton 2-jet, 2-lepton 3-jet)</td>
</tr>
<tr>
<td>0-to-1 lepton ratio</td>
<td>8%</td>
</tr>
<tr>
<td>2-to-3-jet ratio</td>
<td>9% (0+1 lepton only)</td>
</tr>
<tr>
<td>W + HF CR to SR ratio</td>
<td>25%</td>
</tr>
<tr>
<td>$m_{bb}$, $p_T^V$</td>
<td>S</td>
</tr>
</tbody>
</table>

Single top quark

| Cross-section                                              | 4.6% (s-channel), 4.4% (t-channel), 6.2% (Wt) |
| Acceptance 2-jet                                          | 17% (t-channel), 35% (Wt) |
| Acceptance 3-jet                                          | 20% (t-channel), 41% (Wt) |
| $m_{bb}$, $p_T^V$                                         | S (t-channel, Wt) |

Multi-jet (1-lepton)

| Normalisation                                            | 60 – 100% (2-jet), 100 – 400% (3-jet) |
| BDT template                                             | S |

V+jets normalisation / acceptance uncertainties from:
- renorm & fact scales x0.5 and x2
- CKKW merging scale 30->15GeV
- parton shower/resum scale x0.5 and x2
- difference with alternative ME (Madgraph5_aMC@NLO)

Shape distributions in $m_{bb}$ and $p_T^V$
dominated by Sherpa vs Madgraph

Shape distributions in $m_{bb}$ and $p_T^V$
dominated by Sherpa vs Madgraph
# VH background systematics

<table>
<thead>
<tr>
<th></th>
<th>$ZZ$</th>
<th>$WZ$</th>
<th>$WW$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalisation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-to-2 lepton ratio</td>
<td></td>
<td>26%</td>
<td></td>
</tr>
<tr>
<td>Acceptance from scale variations (var.)</td>
<td></td>
<td>13 – 21% (Stewart–Tackmann jet binning method)</td>
<td></td>
</tr>
<tr>
<td>Acceptance from PS/UE var. for 2 or more jets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceptance from PS/UE var. for 3 jets</td>
<td></td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>$m_{bb}, p_T^V$, from scale var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}, p_T^V$, from PS/UE var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$, from matrix-element var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$, from scale var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$, from PS/UE var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$, from matrix-element var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$, from scale var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$, from PS/UE var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$, from matrix-element var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$, from scale var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$, from PS/UE var.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$, from matrix-element var.</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
# VH signal systematics

<table>
<thead>
<tr>
<th>Signal</th>
<th>0.7% ((qq)), 27% ((gg))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-section (scale)</td>
<td>1.9% ((qq \rightarrow WH)), 1.6% ((qq \rightarrow ZH)), 5% ((gg))</td>
</tr>
<tr>
<td>Cross-section (PDF)</td>
<td>1.7%</td>
</tr>
<tr>
<td>Branching ratio</td>
<td>2.5 – 8.8% (Stewart–Tackmann jet binning method)</td>
</tr>
<tr>
<td>Acceptance from scale variations (var.)</td>
<td>10 – 14% (depending on lepton channel)</td>
</tr>
<tr>
<td>Acceptance from PS/UE var. for 2 or more jets</td>
<td>13%</td>
</tr>
<tr>
<td>Acceptance from PS/UE var. for 3 jets</td>
<td>0.5 – 1.3%</td>
</tr>
<tr>
<td>Acceptance from PDF+(\alpha_S) var.</td>
<td></td>
</tr>
<tr>
<td>(m_{bb}), (p_T^V), from scale var.</td>
<td>S</td>
</tr>
<tr>
<td>(m_{bb}), (p_T^V), from PS/UE var.</td>
<td>S</td>
</tr>
<tr>
<td>(m_{bb}), (p_T^V), from PDF+(\alpha_S) var.</td>
<td>S</td>
</tr>
<tr>
<td>(p_T^V) from NLO EW correction</td>
<td>S</td>
</tr>
</tbody>
</table>
## Regions used in likelihood fit

<table>
<thead>
<tr>
<th>Channel</th>
<th>SR/CR</th>
<th>Categories</th>
<th>$75 \text{ GeV} &lt; p_T^V &lt; 150 \text{ GeV}$</th>
<th>$p_T^V &gt; 150 \text{ GeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2 jets</td>
<td>3 jets</td>
<td>2 jets</td>
</tr>
<tr>
<td>0-lepton</td>
<td>SR</td>
<td>-</td>
<td>-</td>
<td>BDT</td>
</tr>
<tr>
<td>1-lepton</td>
<td>SR</td>
<td>-</td>
<td>-</td>
<td>BDT</td>
</tr>
<tr>
<td>2-lepton</td>
<td>SR</td>
<td>BDT</td>
<td>BDT</td>
<td>BDT</td>
</tr>
<tr>
<td>1-lepton</td>
<td>$W + \text{HF CR}$</td>
<td>-</td>
<td>-</td>
<td>Yield</td>
</tr>
<tr>
<td>2-lepton</td>
<td>$e\mu \text{ CR}$</td>
<td>$m_{bb}$</td>
<td>$m_{bb}$</td>
<td>Yield</td>
</tr>
</tbody>
</table>