Higgs boson couplings to b and c quarks

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on behalf of the CMS and ATLAS Collaborations
Higgs boson discovery opens up a new chapter for exploration

- detailed measurement of Higgs properties: couplings to 2nd and 3rd generation fermions and decay of Higgs to heavy-flavour quarks (b, c)
  - $H \rightarrow bb$ and $H \rightarrow cc$ couplings investigated in several Higgs production modes

- this talk will cover ATLAS and CMS results on Higgs couplings to heavy-flavours (b, c) using full Run 2 LHC dataset

Several new results since Higgs 2021 on ATLAS/CMS Hbb/Hcc!

Dedicated talk later in the session by J. Katzy on Higgs production in association with the top quark
### ATLAS/CMS $H \rightarrow bb / H \rightarrow cc$ with full Run 2 data

**New since Higgs 2021**

<table>
<thead>
<tr>
<th>$H \rightarrow bb$</th>
<th>ATLAS/CMS Experiment</th>
<th>CMS-PAS-HIG-20-001</th>
</tr>
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<tbody>
<tr>
<td>$VH(\rightarrow bb)$ inclusive &amp; STXS</td>
<td>ATLAS-CONF-2021-051</td>
<td>CMS-PAS-HIG-20-001</td>
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<td>$VH(\rightarrow cc)$</td>
<td>EPJC 82 (2022) 717</td>
<td>arXiv:2205.0550 (accepted PRL)</td>
</tr>
<tr>
<td>Boosted $H \rightarrow cc$</td>
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<td>CMS-PAS-HIG-21-012</td>
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</tbody>
</table>
Higgs couplings to bottom quarks

Largest branching ratio (~60%) - overwhelming jet production at LHC

Several analysis challenges

- flavour-tagging, modelling of copious QCD backgrounds, large uncertainties on V+jets

Analysis features and measurement strategies

- making use of several production modes, VH (golden channel), VBF, gluon fusion (dominant)
- refined strategies and innovations on b-tagging (e.g. tackling boosted Hbb)
- transitioning from inclusive μ to Simplified Template /Fiducial Cross-section
- efforts to constraint on effective interactions using EFT-sensitive observables/measurements
VH(-→bb) - analysis strategy

- Most sensitive production channel for Hbb couplings and large suppression of multi jet background
  - 3 channels depending on the decay of the vector boson (0-lep: Z→νν, 1lep: W→lν, 2lep: Z→ll)
  - FSR recovery, 2-lep kinematic fit and application of b-jet energy regression to improve m(bb) invariant mass

- Main backgrounds (V+ HF/LF jets and Top) constrained in 3 dedicated background-enriched CRs
  - DNN multi-classifier in 0-lep and 1-lep channel to optimally constrain background processes
  - DNN and BDT's in resolved and boosted signal regions for signal extraction

Several novelties for full Run 2 measurement:
- boosted analysis;
- STXS characterisation;
- updated V+jets modelling
Mass-based and VZ → bb cross-check analysis: VZ, Z → bb: μ = 1.16 ± 0.13

CMS Run 2 μ = 0.58 ± 0.18^{+0.19}_{-0.18} - observed (expected) significance: 3.3σ (5.2σ)

Stage 1.2 VH STXS approach - inclusion of dedicated high momentum phase-space

More details in N. Haubrich’s and A. Nigamova’s parallel session talks!
Interpretation of STXS $VH(bb)$ results to achieve constraints on effective interactions

- $VH(bb)$ analysis has sensitivity to Wilson coefficients impacting production vertices
- Both linear and quadratic terms included - impact of leading eigenvectors on STXS cross-section

$ATLAS$ Preliminary

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$VH, H \rightarrow b\bar{b}, \Lambda = 1$ TeV

Linear parameterisation

- Best-fit, observed
- Resolved (EPJC 81 178)
- Boosted (PLB 816 136204)
- Combination

Lin. + quad. parameterisation

- $c_{Hq}^{(3)} \times 10.0$
- $c_{Hu} \times 5.0$
- $c_{HW} \times 2.0$

Parameter value
Fiducial cross-section in VH(bb) 0lep channel in bins of MET (150-250 GeV, >250 GeV)

- **Fiducial phase-space**: particle-level selection close to detector-level: minimal model-dependency and mitigation of extrapolation uncertainties

- **Cross-section using profile-likelihood unfolding**

  - **Particle-level categories**: reconstructed events passing particle-level selection and have particle-level MET in 150-250 or 250+ bins (T)

  - **Off-fiducial categories (O)**: reco events in particle-level ET miss bin failing other particle level selection criteria

- **Extract signal in detector level categories using $m(bb)$ separately for fiducial and out-of-fiducial volumes**
VBF - second most dominant Higgs production at the LHC - VBF jets with large $\eta$ gap and little activity in the central region

CMS analysis strategy: MVA used to slice SR and $m(bb)$ employed as observable for signal extraction

- analysis categories: VBF, GGF and Z+jets production
- gluon-fusion treated as part of the signal
- two freely-floating parameters for signal and normalisation of Z+jets background
- uncertainty dominated by VBF PS+hadronisation model achieved as 2-point systematics

Exclusive VBF production (gluon-fusion to SM predictions): $\mu=0.97\pm0.48$, significance: 2.4$\sigma$ (observed), 2.7$\sigma$ (expected)

Inclusive measurement of Higgs production in association with two jets (gluon-fusion included): $\mu=0.92\pm0.44$, significance: 2.5$\sigma$ (observed), 2.9$\sigma$ (expected)

More details in S. Mukherjee’s parallel session talk!
Highly-boosted Higgs (ptH>450 GeV) recoiling against a jet in overwhelming QCD background

- selection based on large-R jets containing b-tagged track-jets
- SR (double b-tagged jets) for signal extraction; validation and control regions to model backgrounds (V+jets, QCD and Top)

\[ Z(\rightarrow bb) + \text{jets used to validate analysis (} \mu = 1.29 \pm 0.22) \]

Several measurements of ATLAS H→bb boosted results

- inclusive signal strength - \( \mu = 0.8 \pm 3.2 \) (still stat. limited)
- gluon-fusion STXS-like bins, fiducial/differential cross-section using pt(H)
Higgs couplings to charm quarks

Higgs couplings to 2nd generation quarks ($H \rightarrow cc$) at the LHC extremely challenging

- $H \rightarrow cc$ branching ratio significantly smaller than $H \rightarrow bb$
- c-tagging is more difficult than b-tagging
  - dedicated ML-based taggers and precise methods to calibrate charm tagging in data
  - charm-jet energy regression to improve $m(cc)$ resolution using ML techniques (CMS)

Novel analysis/flavour tagging techniques have paid off - reaching sensitivity expected with larger dataset!
**VH (→cc) analysis strategy & results**

- Most stringent constraints on Higgs-charm Yukawa coupling at the LHC
- Charm-jet identification algorithm (ParticleNet) largely enhances signal efficiency
- Resolved (AK4) and merged jet (AK15) topologies
- CRs used to constrain main processes (V+c, V+b, TT)
- Cross-check VZ, Z→cc analysis: \( \mu = 1.01 \pm 0.22 \) → first observation of VZ, Z→cc at hadron collider
- Kinematic BDT (resolved-jet topology) or mass of H candidate (merged-jet topology) as discriminants → observed limit: 14 X SM (7.6 X SM expected)
- Analysis is statistically-dominated
  - dominant systematics uncertainties: finite simulation statistics and c-jet identification/calibrations

More details in M. Stamenkovic parallel session talk
Flavour tagging - identification of c-jets and orthogonality with VH(bb)

- c-tagging + b-veto w/ efficiency WP's (MV2c10/DL1)

Dedicated studies on V+jets uncertainty modelling

Simultaneous fit of SRs+CRs using m(cc) for signal extraction + diboson analysis as cross-check → observed limit: 26 X SM (31 X SM expected)

Uncertainty dominated by 2-point systematics on V+jets modelling and data statistics

Interpretation of ATLAS/CMS Hcc results → direct constraints on charm-coupling modifiers - ATLAS VHbb+VHcc combination probes b/c coupling universality
**VH (→cc) - constraints on H→cc couplings**

- **Direct coupling modifiers:** observed $|k(c)|<8.5 \times \text{SM} @ 95\% \text{ CL}$ (expected 12.4) assuming all other coupling are SM-like.

- **Higgs-charm couplings** also extracted *indirectly* (e.g. differential $p_T^H$ measurements from other decay modes) or with *exclusive* decays ($H\to J/\Psi \gamma$) [more in G. Umoret’s talk later in this session!]

- **Probing b/c universality:** observed $|k(c)/k(b)|<4.5$ - experimentally show for the first time that the $H_{cc}$ is weaker than $H_{bb}$ coupling.

![Graphs showing constraints on $k_{c}$ and $k_{b}$](image_url)

Inclusive H→cc in boosted topology

- AK8 double b-tagging algorithm (DeepDoubleX) for selection and SR/CR definition
  - Soft-drop mass used as template fit
- QCD modeling using data-driven in CR and propagated to SR
- Cross check Z→cc to validate the method → first observation of Z→cc (boosted) at hadron collider
- Observed (expected) upper limit: 45(38)X SM (still stat. limited, large additional uncertainties on QCD modeling)
Impressive suite of results by ATLAS and CMS on characterisation of Higgs boson couplings to b/c quarks

Several production modes and decays explored by CMS and ATLAS to characterise Yukawa sector

- explored all production modes and H→bb decays using inclusive, STXS, fiducial, differential analyses - approaching precision measurement era

- exciting results on H→cc in ATLAS and CMS

Improvements on all fronts from the experimental community in the Higgs heavy-flavour sector

Additional outstanding Run 2 results still in the pipeline - Hbb/Hcc community also actively engaged to preparing results and further extend the Yukawa sector characterisation with Run 3 LHC data!
Backup slides
VH(\rightarrow bb) - inclusive results & cross-checks

- Inclusive Run 2 signal strength: $\mu = 0.58^{+0.18}_{-0.18}$ - observed
(expected) significance: $3.3\sigma$ ($5.2\sigma$)

- uncertainty dominated by $V+\text{jets}$ modelling and simulation
statistics; background scale-factors extracted in-situ

- Several cross-checks of DNN-based analysis results:
  - $VZ, Z\rightarrow bb$: $\mu = 1.16\pm0.13$
  - direct visualisation of VH/VZ signal peaks with dijet
invariant mass (mass-decorrelated DNN) - $\mu = 0.34\pm0.34$

Jackknife compatibility test on 2017 results against previously
published analysis: $2\sigma$
compatibility, $\sim50$
analysis correlation
per-channel p-value vs inclusive signal strength: 1.9σ; vs SM: 2.9σ (entirely dominated by 2lep)

ZH vs 0lep/2lep compatibility p-value: 20%
STXS POI correlations
ATLAS Preliminary VH, H → b̅b

\(|\hat{s}| = 13\text{ TeV}, 139\text{ fb}^{-1}\)


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<tbody>
<tr>
<td>WH, 150 &lt; (p_T^{W,t}) &lt; 250 GeV</td>
<td>0.70</td>
<td>+0.52 (-0.33, -0.39)</td>
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<td>WH, 250 &lt; (p_T^{W,t}) &lt; 400 GeV</td>
<td>1.10</td>
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<td>ZH, 150 &lt; (p_T^{Z,t}) &lt; 250 GeV</td>
<td>1.06</td>
<td>+0.35 (-0.27, -0.19)</td>
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<td>ZH, 250 &lt; (p_T^{Z,t}) &lt; 400 GeV</td>
<td>0.97</td>
<td>+0.40 (-0.36, -0.14)</td>
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<td>ZH, (p_T^{Z,t}) &gt; 400 GeV</td>
<td>0.29</td>
<td>+0.92 (-0.69, -0.50)</td>
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\(|\hat{s}| = 13\text{ TeV}, 139\text{ fb}^{-1}\)

\(V = W\) and \(V = Z\) lep. (resolved + boosted)
Prospects on VH ($\rightarrow bb$) ATLAS @ HL-LHC

Studies available on VHbb extrapolations @ HL-LHC

ATLAS-PHYS-PUB-2021-039

ATLAS Preliminary
Projection from Run 2 data
VH, $H \rightarrow b\bar{b}$ $\sqrt{s}=14$ TeV, 3000 fb$^{-1}$

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<td>0.8</td>
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<td>$0.07$</td>
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<td>$-0.10$</td>
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<td>1.6</td>
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$\sigma \times B$ normalised to SM
- VBF - second most dominant Higgs production at the LHC - distinctive features with VBF jets with large pseudorapidity gap and little activity in the central region

- Additional mode: associated production with a photon - ATLAS analysis targets both processes

- All-hadronic final state using ANN (adversarial neural network) to categorise events and fit $m(bb)$

- Hadronic + photon final state using BDT to categorise events and fit $m(bb)$ in each region

- Expected (observed) combination: $2.9\sigma$ ($2.9\sigma$), two-dimensional scan of gluon-fusion and vector-boson fusion signal strengths also provided
Expected (observed) combination: $2.9\sigma$ ($2.9\sigma$), dominated by all-hadronic channel

2-dimensional scan of gluon-fusion and vector-boson fusion also provided
Dominant unfolding uncertainties → presence of out-of-fiducial events and contamination of events from different particle-level categories in detector-level categories

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
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<tbody>
<tr>
<td>Total</td>
<td>0.71</td>
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<td>Statistical</td>
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<td>Systematic</td>
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<td><strong>Experimental</strong></td>
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<tr>
<td>Jets</td>
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<td>Missing transverse momentum</td>
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<td><strong>Flavour-tagging</strong></td>
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<td>$b$-jets</td>
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<td>$c$-jets</td>
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<td><strong>Light-flavour jets</strong></td>
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<td>Leptons</td>
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<td>Pile-up</td>
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<td>Luminosity</td>
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<td><strong>Background modelling</strong></td>
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<td>Dibosons</td>
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<td>$Z$ + jets</td>
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<tr>
<td>$W$ + jets</td>
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<tr>
<td>Single top quark</td>
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<tr>
<td><strong>Fiducial templates modelling</strong></td>
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<td>Unfolding uncertainty, $T_1$</td>
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<td>$&lt; 0.01$</td>
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<td>PS model acceptance</td>
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<td>Unfolding uncertainty, $T_2$</td>
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<td>$WH/ ZH$</td>
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<td>QCD scale acceptance, $ggZH$</td>
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<td>2/3 jets ratio</td>
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<td>PS model $m_{bb}$ shape</td>
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<tr>
<td>QCD scale acceptance</td>
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<td>PDF acceptance</td>
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<tr>
<td>Floating normalizations</td>
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</tbody>
</table>
VH(→bb) - STXS Stage 1.2

Stage 1.2

\[ VH \quad = \quad V(\rightarrow \text{leptons})H \]

- \( q\bar{q}' \rightarrow WH \)
- \( q\bar{q} \rightarrow ZH \)
- \( gg \rightarrow ZH \)

\( p_T^V \)

- 0
- 75
- 150
- 250
- 400
- \( \infty \)

- 0-jet
- 1-jet
- \( \geq 2\)-jet

Normalization fixed to SM expectation

Merge of Njets

\( qqZH \) and \( ggZH \) categories merged

Splitting of categories with

- \( 250 \text{ GeV} < Vp_T < 400 \text{ GeV} \) and \( Vp_T > 400 \text{ GeV} \)
VH(→bb) - CMS analysis strategy

CMS Simulation Preliminary

2017 (13 TeV)

Entries / 5 GeV

CMS Preliminary

138 fb⁻¹ (13 TeV)

ZH → l(νν) b̅b

WH → lν b̅b

σ × BR(V → lep.) × BR(H → b̅b) (fb)

Ratio to SM
Simultaneous extraction of Hbb and Hcc signal strengths

expected sensitivity is approaching the SM value for Hcc couplings