SEARCH FOR THE HIGGS BOSON DECAYING TO CHARM QUARKS USING LARGE-RADIUS JETS WITH THE CMS EXPERIMENT

Huilin Qu
on behalf of the CMS collaboration

Higgs Couplings 2019, Oxford
October 1, 2019
**INTRODUCTION**

- Search for $H\rightarrow cc$:
  - directly probes the Yukawa coupling to 2nd-generation quarks
  - next milestone in Higgs coupling measurements
- $H\rightarrow cc$: very challenging to hunt at a hadron collider
  - small branching ratio in SM: $\sim 2.9\%$
    - $H\rightarrow bb$ (BR=58%): a background in this search
  - very large (hadronic) backgrounds
  - charm quark identification is the key
- Direct searches for $H\rightarrow cc$
  - ATLAS: $Z(\rightarrow ll)H$, 36.1 fb$^{-1}$ data
    - upper limits on $\mu := (\sigma \times \text{BR}) / (\sigma_{SM} \times \text{BR}_{SM})$
    - $\mu < 110$ (150) obs. (exp.) [PRL 120 (2018) 211802]
  - CMS: VH, 35.9 fb$^{-1}$ data [CMS-PAS-HIG-18-031]
    - new results!
    - see Luca's talk for an overview
**First Direct H→cc Search in CMS**

- **Exploits the VH production**
  - leptonic V decay: Z→νν, W→lν, Z→ll
    - 3 mutually exclusive channels: 0L, 1L, and 2L (L = e, μ)
  - provides handles for event triggering and QCD background suppression
  - main backgrounds
    - W/Z + jets, ttbar, diboson
- **Two complimentary approaches to fully explore the H→cc decay topology**
  - resolved-jet topology: reconstruct H→cc decay with two resolved jets (R=0.4)
  - merged-jet topology: reconstruct H→cc decay with one large-R jets (R=1.5)
  - advanced charm-tagging techniques exploited
The cornerstone of the merged-jet analysis is the reconstruction of the $H\rightarrow cc$ decay with a single large-$R$ jet

- focus on the boosted regime
  - better signal purity: the $p_T$ spectrum in VH signals is harder than that in V+jets backgrounds
  - but lower signal acceptance: falling $p_T$ spectrum in both signal and backgrounds

- choosing a suitable jet size
  - angular separation of the decay products $\Delta R \sim 2m_H / p_T$
  - $R = 1.5$ jets:
    - good efficiency to capture both quarks from Higgs with $p_T > \sim 150$ GeV
    - balance between signal purity and acceptance
  - capturing the showers of the two charm quarks in one jet can potentially lead to a better exploitation of the correlation between the two quarks from the Higgs decay

Reconstruction efficiency:
- Merged ($R=0.8 / R=1.5$): both quarks contained in an AK8 / AK15 jet (with $\Delta R(jet, c$-quark) $< 0.8 / 1.5$)
- Resolved: each quark is reconstructed as a resolved $R=0.4$ jet with $p_T > 25$ GeV and $|\eta| < 2.4$
H→cc IDENTIFICATION

- Advanced machine learning-based algorithm to identify the H→cc decay: “DeepAK8”
  - multi-class classifier for top quark and W, Z, Higgs boson tagging
    - sub-classes based on decay modes (e.g., Z→bb, Z→cc, Z→qq)
    - output scores can be aggregated/transformed for different tasks -> highly versatile tagger
  - uses deep neural networks to directly process jet constituents (PF candidates / secondary vertices)
    - architecture: ResNet inspired 1D convolutional neural networks
    - significant performance improvement

**Inputs**

- **Particles**
  - Up to 100 PF candidates(*)
  - Sorted in descending p_T order
  - Uses basic kinematic variables, Puppi weights, and track properties (quality, covariance, displacement, etc.)

- **Secondary vertices**
  - Up to 7 SVs(*) (inside jet cone)
  - Sorted in descending S_P2D order
  - Uses SV kinematics and properties (quality, displacement, etc.)

(*) Number chosen to include all candidates for ≥ 90% of the events

**Architecture**

- **Particles**
  - 1D CNN (10 layers)
  - Features: particles, ordered by p_T

- **Secondary Vertices**
  - 1D CNN (10 layers)
  - Features: SVs, ordered by S_P2D

**Output**

- Fully connected
- Output

**Category** | **Label**
--- | ---
Higgs | H (bb)
H (cc)
H (WV→qqqq)
top (bcq)
top (bqq)
top (bc)
top (bq)
W (c-q)
Z (bb)
Z (cc)
Z (qq)
QCD (bb)
QCD (cc)
QCD (bc)
QCD (c)
QCD (others)

**Particles**

- **Particles**
- **Secondary Vertices**
- **Output**

** CMS Simulation Preliminary **

Higgs boson vs QCD multijet
1000 < p_T^{H} < 1500 GeV, |\eta| < 2.4
90 < m_{AK8} < 140 GeV

- Significantly better performance

(CMS-PAS-JME-18-002)
**H → cc IDENTIFICATION (II)**

- Mass-decorrelated tagger: “DeepAK8-MD”
  - the nominal version of DeepAK8 shows significantly improved performance, but also features strong “mass sculpting”
  - i.e., modification of the jet mass shape in background samples after tagging requirements
  - dedicated version designed to minimize mass sculpting
  - using “adversarial training” technique
  - significantly reduced mass sculpting yet still strong performance
  - allows us to fit the mass distribution for signal extraction

---

**Jet mass in di-jet sample**

- CMS Simulation Preliminary
- Higgs boson vs QCD multijet
- | < 2.4
- | < 150 GeV, | < 140 GeV
- best

---

**Adversarial training**

- Feature extractor
- Classifier
- Mass predictor
- Joint loss: \( L = L_C - \lambda L_{MP} \)
- CMS-PAS-JME-18-002
The DeepAK8-MD algorithm has been adapted to R=1.5 jets for the H→cc analysis with a dedicated training.

- **cc-tagging discriminant** defined as:
  \[
  \text{score}(Z \rightarrow c\bar{c}) + \text{score}(H \rightarrow c\bar{c})
  \]
  \[
  \text{score}(Z \rightarrow c\bar{c}) + \text{score}(H \rightarrow c\bar{c}) + \text{score}(\text{QCD})
  \]

- Right: performance in MC

- Three working points defined:
  
<table>
<thead>
<tr>
<th>Loose</th>
<th>Medium</th>
<th>Tight</th>
</tr>
</thead>
<tbody>
<tr>
<td>cc-discriminant</td>
<td>&gt;0.72</td>
<td>&gt;0.83</td>
</tr>
<tr>
<td>ε(V+jets)</td>
<td>5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>ε(H→cc)</td>
<td>46%</td>
<td>35%</td>
</tr>
<tr>
<td>ε(H→bb)</td>
<td>27%</td>
<td>17%</td>
</tr>
</tbody>
</table>

- Events are categorized into three mutually exclusive categories, based on the 3 WPs, to improve sensitivity.
  - High/medium/low purity (HP/MP/LP) categories

- cc-tagging discriminant calibrated in data
  - Using "proxy" jets from g(gluon)→cc
    - Similar characteristics as signal jets
  - Scale factors applied to H→cc / Z→cc jets
Baseline Event Selection

- VH events have a clear signature
  - vector boson recoiling against the Higgs boson
  - little additional activity in the event
- Vector boson reconstructed with lepton and/or missing transverse momentum (MET)
  - 2L: \( V := \) opposite-sign same-flavor lepton pair; 
    \( 75 < m(\text{LL}) < 105 \text{ GeV} \) [compatible w/ Z mass]
  - 1L: \( V := \) lepton + MET; \( \Delta \phi(\text{lep}, \text{MET})<2.0 \) [compatible w/ W decay]
  - 0L: \( V := \) MET; MET>170 GeV [due to trigger requirement], 
    \( \Delta \phi(\text{MET, j})>0.5, \Delta \phi(\text{pfMET, tkMET})<0.5 \) [suppress QCD]
- Baseline selection
  - high \( p_T > 200 \text{ GeV} \) vector boson and \( H_{\text{cand}}, \) back-to-back \( (\Delta \phi(V, H_{\text{cand}})>2.5) \)
  - the large-R jet leading in \( p_T \) selected as the Higgs candidate \( (H_{\text{cand}}) \)
    - requires \( p_T > 200 \text{ GeV}, \) soft-drop (SD) groomed jet mass \( m_{SD}(H_{\text{cand}}) \in [50, 200] \text{ GeV} \)
  - veto events with additional R=0.4 jets \( (\Delta R(j, H_{\text{cand}})>1.5) \) to suppress \( tt\bar{t} \) contribution
**Analysis Strategy**

- Analysis strategy overview
  - event-level kinematic BDT developed in each channel to better suppress the dominant backgrounds (V+jets, ttbar)
    - using only event kinematics, NOT the intrinsic properties (e.g., flavor/mass) of $H_{\text{cand}}$
  - cc-tagging discriminant used to select cc-flavor jets and reject light/bb-flavor jets
  - distinct $m(H_{\text{cand}})$ shapes between signal and V+jets/ttbar background: fit the $m(H_{\text{cand}})$ shape to extract the $H \rightarrow cc$ signal

- Kinematic BDT, cc-tagging discriminant and $m(H_{\text{cand}})$ largely independent of each other
  - allowing for a simple and robust strategy for background estimation and signal extraction
**Signal Extraction**

- The VH(cc) signal is extracted via a binned fit to the mass of the Higgs candidate \([m(H_{cand})]\)
  - \([m(H_{cand})]\) shapes taken directly from MC
    - validated in control regions: very good data/MC agreement
- Dedicated control regions (CRs) are set up to constrain the normalizations of major backgrounds
  - V+jets: use low BDT region (i.e., BDT<0.5)
  - ttbar: invert the cut on N(additional R=0.4 jets) (i.e, \(N_{aj}\)\(\geq\)2)
    - only for 0L and 1L; ttbar contribution is negligible for 2L
  - CRs designed to have similar flavour composition as SRs
    - by applying the same cc-tagging requirement as the corresponding SR
- Normalization of the major backgrounds (V+jets and ttbar) are obtained via a simultaneous fit of SR and the CRs
  - effects of the mistag SFs of the cc-tagging discriminant will be taken into account
    - because the same cc-tagging requirement is applied in CRs and the SR
    - therefore, cc-tagging SFs only needed for VH(cc)/VZ(cc) (not needed for BKGs)

Full analysis validated in two data samples:
- low \(p_T(V)\)
- low values of the cc-discriminant

---

Search for H-cc using large-radius jets - October 1, 2019 - Huilin Qu (UCSB)
# Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>0-lepton</th>
<th>1-lepton</th>
<th>2-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of simulated samples</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MET unclustered energy</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>c tagging efficiency</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Lepton efficiency</td>
<td>shape (rate)</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Pileup reweighting</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>top $p_T$ reweighting</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T(\nu)$ reweighting</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>PDF</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Renormalization and factorization scales</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VH: $p_T(\nu)$ NLO EWK correction</td>
<td>shape</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Luminosity</td>
<td>rate</td>
<td>2.5%</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>MET trigger efficiency</td>
<td>rate</td>
<td>2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single top cross section</td>
<td>rate</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td>Diboson cross section</td>
<td>rate</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>VH: cross section (PDF)</td>
<td>rate</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VH: cross section (scale)</td>
<td>rate</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- **Dominant sources:**
  - size of the MC simulation / data control samples, cc-tagging, simulation modeling
Results: Post-fit Distributions

- Good agreement between the predicted background and the observed data
**VZ\text{(cc)} Validation**

- The full procedure of this analysis is validated by measuring the VZ(cc) process
  - following exactly the same procedure, but extract the VZ(cc) signal strength instead of VH(cc)
  - VH(cc) fixed to the SM expectation

**Results:**
- best-fit signal strength: \( \mu_{VZ\text{(cc)}} = 0.69^{+0.89}_{-0.75} \)
  - consistent with SM expectation (\( \mu_{VZ\text{(cc)}}=1 \)) within uncertainty
- observed (expected) significance: 0.9 (1.3) \( \sigma \)
**VH(cc) RESULTS**

- **Upper limits on the signal strength $\mu_{VH(cc)}$ at 95% confidence level**
  - $\mu_{VH(cc)} < 71$ obs. (49 $^{+24}_{-15}$ exp.)

<table>
<thead>
<tr>
<th></th>
<th>Merged-jet (inclusive)</th>
<th></th>
<th></th>
<th>All channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0L</td>
<td>1L</td>
<td>2L</td>
<td></td>
</tr>
<tr>
<td>Expected UL</td>
<td>$81^{+39}_{-24}$</td>
<td>$88^{+43}_{-27}$</td>
<td>$90^{+48}_{-29}$</td>
<td>$49^{+24}_{-15}$</td>
</tr>
<tr>
<td>Observed UL</td>
<td>74</td>
<td>120</td>
<td>76</td>
<td>71</td>
</tr>
</tbody>
</table>

- **Best-fit signal strength:** $\mu_{VH(cc)} = 21^{+26}_{-24}$

- **Results are combined with resolved-jet analysis**
  - to remove overlap, requires:
    - $p_T(V) < 300$ GeV for the resolved-jet topology
    - $p_T(V) \geq 300$ GeV for the merged-jet topology
  - “inclusive” merged-jet analysis requires $p_T(V) > 200$ GeV

**Upper limits at 95% confidence level**

<table>
<thead>
<tr>
<th></th>
<th>resolved-jet ($p_T(V) &lt; 300$ GeV)</th>
<th>merged-jet ($p_T(V) \geq 300$ GeV)</th>
<th>combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected</td>
<td>$45^{+18}_{-13}$</td>
<td>$73^{+34}_{-22}$</td>
<td>$37^{+16}_{-11}$</td>
</tr>
<tr>
<td>observed</td>
<td>86</td>
<td>75</td>
<td>70</td>
</tr>
</tbody>
</table>
A search for the Higgs boson decaying to charm quarks using large-radius jets with the CMS experiment is presented

- a novel approach
  - reconstructs both quarks from the Higgs decay with a single large-R jet
  - utilizes an advanced ML-based algorithm to identify $H \rightarrow cc$ decays

- very competitive results
  - an observed (expected) upper limit on the VH production cross section times the $H \rightarrow cc$ branching ratio of 71 (49) times the SM expectation

Still, a long way ahead

- so far we have explored only ~25% of the collected Run 2 data, and less than ~1% of the full expected dataset of the (HL-)LHC
- needs breakthroughs in many areas:
  - better charm quark (pair) identification algorithm
  - more advanced signal extraction / background estimation methods
  - reduced systematics with improved event generators / simulation tools
  - upgrades of the detector (tracking / timing / etc.)

The charming journey has just started!
BACKUPS
**Kinematic BDT**

- Kinematic BDT developed to separate VH signals from major backgrounds (V+jets, ttbar)
  - using only event kinematics, NOT the intrinsic properties (e.g., flavor/mass) of H_{cand}
  - the resulting BDT is largely uncorrelated with mass and the cc-tagging discriminant of H_{cand}
- Two regions are defined based on the BDT
  - search region (SR): high BDT (≥0.5)
  - control region (CR): low BDT (<0.5)

### BDT Inputs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>0L</th>
<th>1L</th>
<th>2L</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_{T}(V)</td>
<td>vector boson transverse momentum</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>p_{T}(H_{cand})</td>
<td>H_{cand} transverse momentum</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>absolute value of the H_{cand} pseudorapidity</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δφ(V, H_{cand})</td>
<td>azimuthal angle between vector boson and H_{cand}</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>p_{T}^{miss}</td>
<td>missing transverse momentum</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(H_{cand}, f)</td>
<td>difference in pseudorapidity between H_{cand} and the lepton</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(H_{cand}, V)</td>
<td>difference in pseudorapidity between H_{cand} and vector boson</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, f)</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(f, j)</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(f, j)</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(H_{cand}, j)</td>
<td>min. difference in pseudorapidity between H_{cand} and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, H_{cand})</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Δη(V, j)</td>
<td>min. difference in pseudorapidity between vector boson and small-R jets</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Calibration of CC-tagging Discriminant

- CC-tagging discriminant calibrated via proxy jets
  - Impossible to isolate a pure Z/H→cc sample...
  - Instead, uses proxy jets (gluon→cc) that share similar characteristics as signal jets
  - Corrections are then transferred to signal jets

- Proxy jets obtained from a di-jet sample
  - Requires the presence of at least one secondary vertex in each subjet
    - Similar CC-tagging discriminant shapes between proxy and signal jets after this selection
    - Further enhances g→bb/cc fraction

- Template fit method used to extract the data/MC scale factors (SFs)
  - Define 3 MC templates: bb(+b), cc(+c) and udsg
  - Fit variable: the CSVv2 b-tagging discriminant

- SFs typically between 0.9 to 1.4, with 10 - 30% uncertainty
  - Also validated in γ+jets sample: consistent results

- SFs applied only on VH(cc) signal and VZ(cc)
  - And bb-mistag SF applied on VH(bb) and VZ(bb)
  - Systematics uncertainties propagated
  - Not applied on BKG (estimation is data-driven)
**RESULTS (Resolved & Merged)**

- Resolved & Merged: Inclusive

<table>
<thead>
<tr>
<th></th>
<th>Resolved-jet (inclusive)</th>
<th>Merged-jet (inclusive)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0L 1L 2L All channels</td>
<td>0L 1L 2L All channels</td>
</tr>
<tr>
<td>expected UL</td>
<td>84 79 59 38</td>
<td>81 88 90 49</td>
</tr>
<tr>
<td>observed UL</td>
<td>66 120 116 75</td>
<td>74 120 76 71</td>
</tr>
</tbody>
</table>

- Resolved & Merged: Exclusive & Combination

<table>
<thead>
<tr>
<th></th>
<th>95% CL exclusion limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>resolved-jet (p_T(V) &lt; 300 GeV)</td>
</tr>
<tr>
<td></td>
<td>0L 1L 2L All channels</td>
</tr>
<tr>
<td>expected</td>
<td>45±18 73±34</td>
</tr>
<tr>
<td>observed</td>
<td>86 75</td>
</tr>
</tbody>
</table>

**CMS Preliminary**

- Observed
- Median expected
- 68% expected
- 95% expected

**Best fit µ:**

- ZH(H→cτ): µ = 36±24
- WH(H→cτ): µ = 57±36
- 0L µ = 20±36
- 1L µ = 30±28
- 2L µ = 46±29

**CMS Preliminary pp→ VH(H→cτ) µ=37±19(stat.+syst.)**

δσ = 35.9 ± 3.5 fb⁻¹ (13 TeV)
DeepAK8

**Top vs QCD**

**W vs QCD**
Ablation Study of DeepAK8

- DeepAK8 shows substantial gain compared to traditional approaches.

- To understand the main sources of the improvement, alternative versions of DeepAK8 were trained using a subset of the input features:
  - Particle (kinematics): only kinematic info of PF candidates
    - four momenta, distances to the jet and subjet axes, etc.
  - Particle (w/o Flavour): adding experimental info
    - charge, particle identification, track quality, etc.
  - Particle Full + SV (the full DeepAK8): adding features related to heavy-flavour tagging
    - track displacement, track-vertex association, SV features, etc.