Constraints on the Higgs-charm coupling by CMS

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Introduction and outlook

➢ On the way to fully characterize the Higgs boson: coupling to charm
➢ Few ways to constrain Higgs charm coupling at CMS:
  ✷ Direct search for $H \rightarrow c\bar{c}$ decay: in ggH and VH channels
  ✷ Indirect constraints from Higgs kinematics
  ✷ Rare $H \rightarrow J/\psi + \gamma$ decay
➢ What is the projection for HL-LHC?

Nature 607 (2022) 60-68
$ggH(\bar{c}c)$

Search in ggH channel

- Higgs candidate is a anti-kt jet with R=0.8 (AK8), $p_T > 450$ GeV
  - not a pure ggH signal:
    - 50% ggF (ggH+jet)
    - 30% VBF
- Double-charm tagging with NN:
  - CNN/RNN with low level inputs
  - Mass independent using dedicated simulation samples

Recent! CMS-PAS-HIG-21-012
ggH(cc) results

- Limit at 45 (38) x SM @95% CL
- Validation of techniques with $Z \rightarrow c\bar{c}$ candle
  - Observation with $>>$ 5 sigma
- See poster by Andrzej Novak for more details
$V + H(c\bar{c})$
VH(cc) search at a glance

**VH channel categories**

- **(Z → l^+l^-) + H**
  - 2L channel
  - Cleanest

- **(Z → νν) + H**
  - 0L channel
  - Large $E_T^{miss}$

- **(W → lν) + H**
  - 1L channel
  - Larger production than ZH; larger BR of the W decay, compared to Z→ l^+l^-.

**H → cc**

- 2 small-cone (AK4) charm-tagged jets ("2 jets topology")
- 1 large cone (AK15) cc-tagged jet ("boosted topology")

Backgrounds: Z+jets, W+jets, tt (1L), VZ, QCD (0L)
ParticleNet: charm tagger for AK15 jets

- **ParticleNet**: a multi-class jet classifier for t/H/W/Z tagging of fat jets
  - permutation-invariant GNN with EdgeConv
  - jet = unordered set of particles
- Use low-level jet features as inputs (PF candidates, SVs)
- Scores for: $X \rightarrow b\overline{b}$, $X \rightarrow c\overline{c}$, $X \rightarrow 4q$, QCD ($b\overline{b}$, $c\overline{c}$, $b$, $c$, others)

cc-tagging discriminant defined as

\[
P(X \rightarrow cc) / [P(X \rightarrow cc) + P(QCD)]
\]

Great tagging performance for large-R jets:

*Phys. Rev. D 101, 056019*
Analysis sketch: boosted topology

- Train **BDT:** signal vs \((V+\text{jets} \text{ and } t\bar{t})\)
- Use cc-tagger score to define 3 regions (for high BDT score)
- Fit the jet mass (also using dedicated mass regression)
- Normalization of \(V+\text{jets}\) and \(t\bar{t}\) bkg from CRs (low BDT, \(N_{aj}>2\))
DeepJet: charm tagger for AK4 jets

- Charm jet properties are in-between udsg and b-jets
- DNN multiclassifier is used to tag the AK4 jets: DeepJet
- Efficiencies of the Working Point (for jet with highest charm-tag score):
  - 42% c-jet eff
  - 15% b-jet mistag rate
  - 4% light jet mistag rate
Analysis sketch: 2 jets topology

- Train BDT (signal vs all backgrounds), including the mass of the H candidate as input
  - Fit the BDT distributions to set the limit
- Constrain background normalization from CRs (V+LFj, V+HFj, V+CC, tt)
Expected limits and Z(\text{cc}) validation

- Final result combines merged and resolved analyses (separation on AK15 jet $p_T=300$)
- Observed (expected) UL on VH(\text{cc}) signal strength at 95% CL: $\mu_{\text{VH}(\text{cc})} < 14 \ (7.6)$
  - Strongest limit on VH(\text{cc}) process to date
  - Analysis validated with $Z \rightarrow c\overline{c}$ candle:
    - $\mu_{\text{VZ}(\text{cc})} = 1.01 +/- 0.21$
Constraint on $k_c$

- Constraint on $k_c$ can be placed under assumption that all other H couplings fixed to SM values

\[ \mu_{VH}(H \rightarrow cc) = \frac{\kappa_c^2}{1 + B_{SM}(H \rightarrow cc) \times (\kappa_c^2 - 1)} \]

- The 95% CL intervals obtained with likelihood scans
  - Observed: $1.1 < |k_c| < 5.5$
  - Expected: $|k_c| < 3.4$

- Strongest constraint on $|k_c|$ from CMS (and HEP)
Indirect constraints from Higgs boson kinematics
Indirect constraints from H kinematics

- Differential distributions ($p_T$, $|y|$, $N_{jets}$ of the H) are sensitive to H couplings

Phys. Rev. Lett. 118, 121801

$H \rightarrow J/\psi + \gamma$
Search for $H \to J/\psi + \gamma$ decays

$y_c$-dependent

$y_c$-independent (dominant contribution)


$\mathcal{B}(H \to J/\psi + \gamma) < 220 \times \text{SM (obs)}$

Phys. Rev. D 90, 113010
JHEP 08 (2015) 012
Phys. Rev. D 95, 054018
Phys. Rev. D 100, 054038
Projections to HL-LHC
Projection to HL-LHC

- From VH(cc) boosted analysis alone: simultaneous extraction of $H \rightarrow b\bar{b}$ and $H \rightarrow c\bar{c}$ signal strengths:

  $\mu_{\text{VH}(H \rightarrow bb)} = 1.00 \pm 0.03 \text{ (stat.)} \pm 0.04 \text{ (syst.)} = 1.00 \pm 0.05 \text{ (total)}$

  $\mu_{\text{VH}(H \rightarrow cc)} = 1.0 \pm 0.6 \text{ (stat.)} \pm 0.5 \text{ (syst.)} = 1.0 \pm 0.8 \text{ (total)}$

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- global (95% CL)
- direct search (95% CL)
- kinematic (95% CL)
- width (off-shell, 68% CL)
- width (int., 95% CL)
- exclusive (95% CL)

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arXiv:1902.00134

CMS-HIG-21-008
Summary

➢ CMS has released two $H \rightarrow c\bar{c}$ analysis with full Run-2 dataset
  • $ggH(c\bar{c})$:
    • Exploring $H$+jet topology with boosted large-cone jets
    • Limit set at $45xSM$
  • $VH(c\bar{c})$
    • Using two complementary approaches to fully explore the $VH(H \rightarrow c\bar{c})$ decay topology ($AK4/AK15$ jets).
    • Limit set at $14xSM$; $1.1<|k_c|<5.5$ (95%CL interval)
      - Most stringent limit to date
  • The analyses are validated by measuring $Z \rightarrow cc$ process rate

➢ Constraints on $|k_c|$ from kinematics in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$
  • $|k_c| < 35$ (partial dataset)

➢ Limit on $H \rightarrow J/\psi+\gamma$ process: $< 220xSM$
The End