Higgs Boson to Charm Quarks in Vector Boson Fusion plus a Photon

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Ben Carlson, Tao Han, SCL, arXiv: 2105.08738

Since the discovery of Higgs Boson…

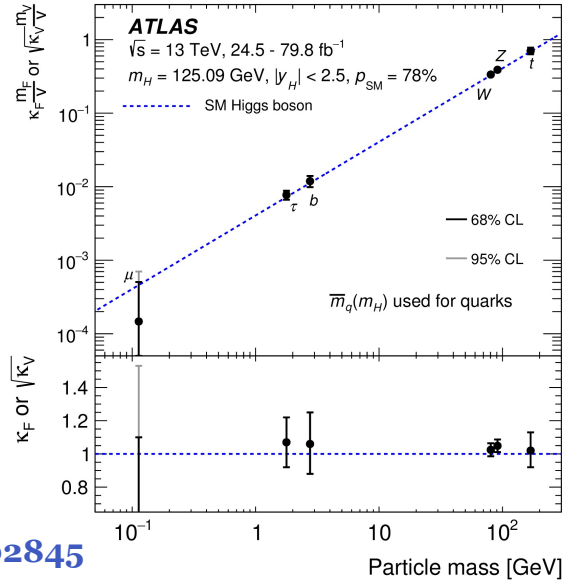
- (Precise) measurements of Higgs couplings are in high priority
- Higgs couplings to
  - Weak bosons: by spontaneous symmetry breaking, well measured

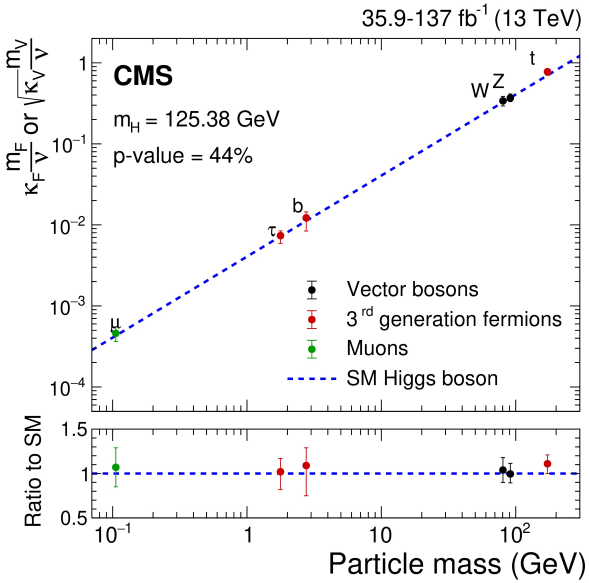
  - Fermions: by Yukawa interactions, not fully measured

$$y_f = \frac{\sqrt{2}m_f}{v}$$

Current Status of Yukawa Couplings

- 3rd generation Yukawa couplings observed at 5σ
- Consistent with SM
- Higgs couplings to 2nd generation are important
  - Confirm the Higgs mechanism and pattern of non-universal Yukawa couplings
  - Search for deviations from SM





arXiv:1909.02845

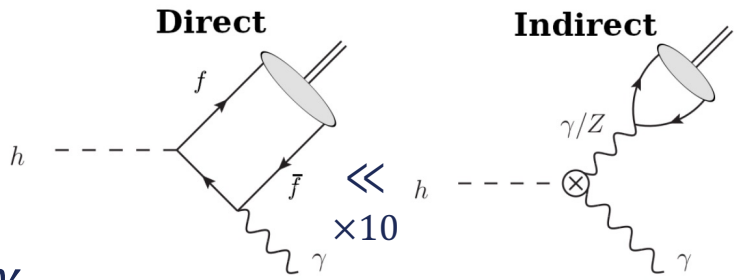
arXiv:2009.04363

Searches for Charm-Yukawa Coupling

- Branching ratio: 2.9%
- Large QCD background
- c-tagging is challenging

- Existing experimental searches:
  - $pp \to VH(c\bar{c})$
    - c-tagging required
    - best chance: $y_c \lesssim 3y_c^{SM}$ ATL-PHYS-PUB-2018-016 LHCb: arXiv:1808.08865 CMS: arXiv:1912.01662
  - $H \to J/\psi + \gamma$
    - tiny Br ~ 10^{-6} but clean final states
    - less sensitive: $y_c \lesssim 50y_c^{SM}$ ATL-PHYS-PUB-2015-043

Bodwin et al. arXiv:1306.5770

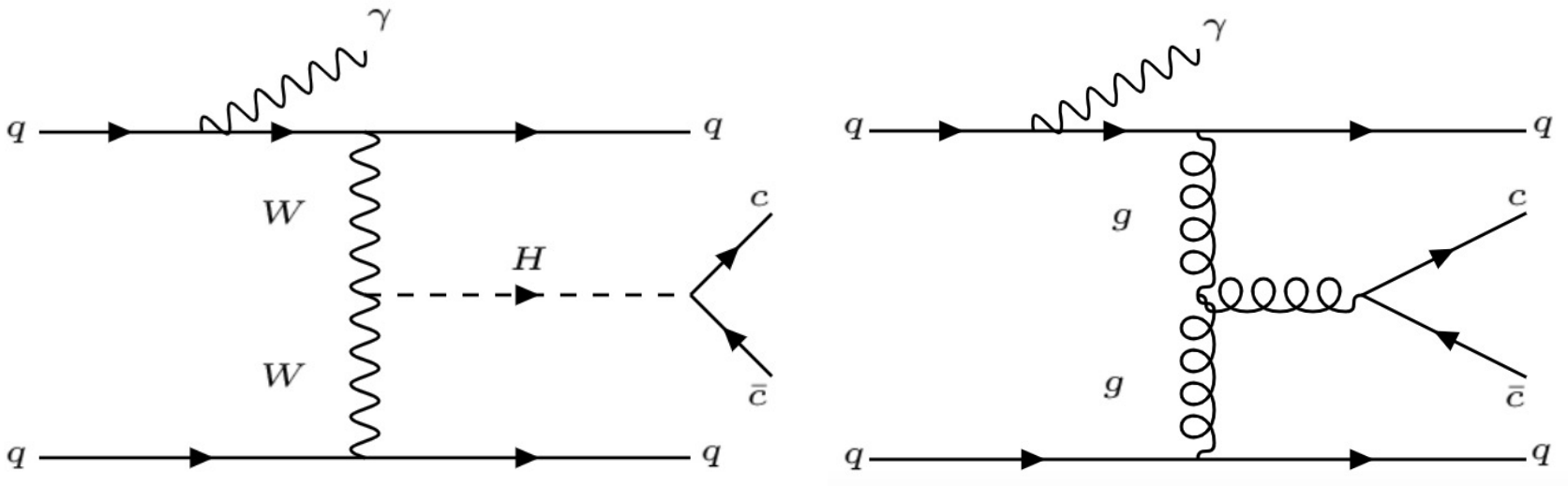


- Other proposals: $gc \to Hc$, global fit, $H \to c\bar{c}\gamma$ …

arXiv: 1503.00290, 1507.02916, 1606.09621, 1609.06592, 1611.05463, 1702.05753, 1705.09295, 1812.06992, 1905.03764, 1905.09360, 1909.05279, 2008.12538, 2101.04119

A New Approach: VBF + γ

- Striking signatures and sizable signal events
- Additional photon results in lower rate
- Compensated by
  - Extra handle to trigger on
  - Suppression of gluon-rich background



Trigger Strategy

- Not all data recorded at LHC
- pp collision @40 MHz => L1 trigger @100 kHz => HLT @1 kHz

ATLAS trigger for $VBF(H \to b\bar{b})$:

arXiv: 1807.08639, 2010.13651

- Photon $E_{\mathrm{T}}^{\gamma} > 30$ GeV;
- At least four jets with $p_{\mathrm{T}}^{j} > 40$ GeV;
- At least one pair of jets with $m_{jj} > 700$ GeV;
- At least one b-tagged jet with 77% efficiency.

- for $H \to c\bar{c}$: require a charm tag or raise m_{jj} threshold

Analysis Set-up

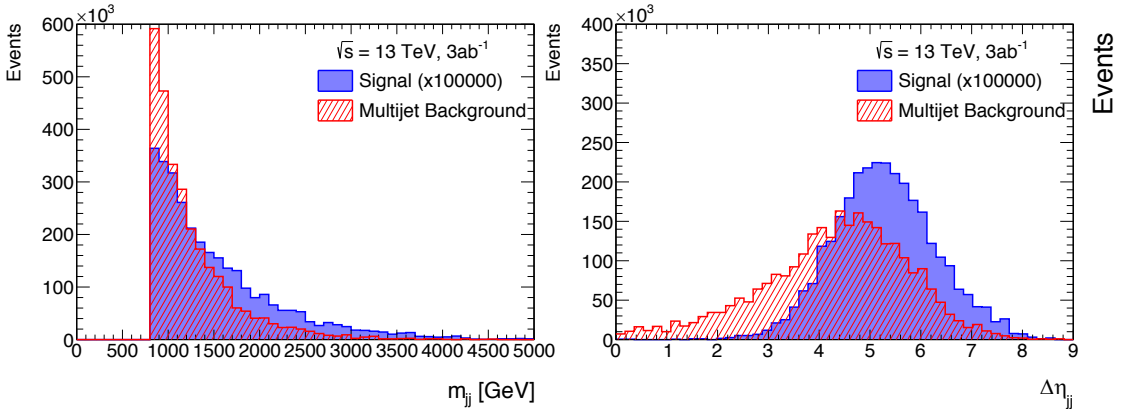
- MG5 + Pythia8 + Delphes3
- $\sqrt{s}$ = 13 TeV

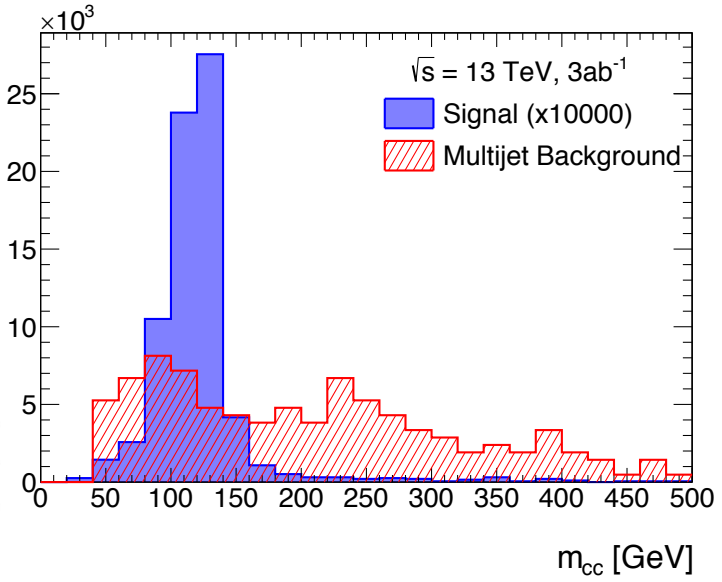
Pre-selections:

- $E_T^{\gamma} > 30$ GeV, $\eta^{\gamma} < 1.37$ or within $1.52 - 2.37$
- 4 jets with $p_T^j > 40$ GeV and $\eta^j < 4.4$
- VBF jets with $m_{jj} > 800$ GeV
- At least 2 c-tagged jet with 41% (25%, 5% mistag rate for b, light jets) efficiency with $\eta^c < 2.5$
- Signal c-jets with $p_T^{cc} > 80$ GeV

Cut-based Analysis

- m_{jj}, $m_{jj\gamma} > 1000$ GeV, $p_T^{jj} < 300$ GeV, $p_T^{balance} < 0.2$
- $\Delta\eta_{jj} > 4$, $\Delta R(c_{1,2}, \gamma) > 1.4$, $\Delta\phi(jj) < 2.1$, $\Delta\phi(cc, jj) > 2.3$
- centrality$(\gamma, jj) < 0.35$, $m_{cc\gamma} < 700$ GeV



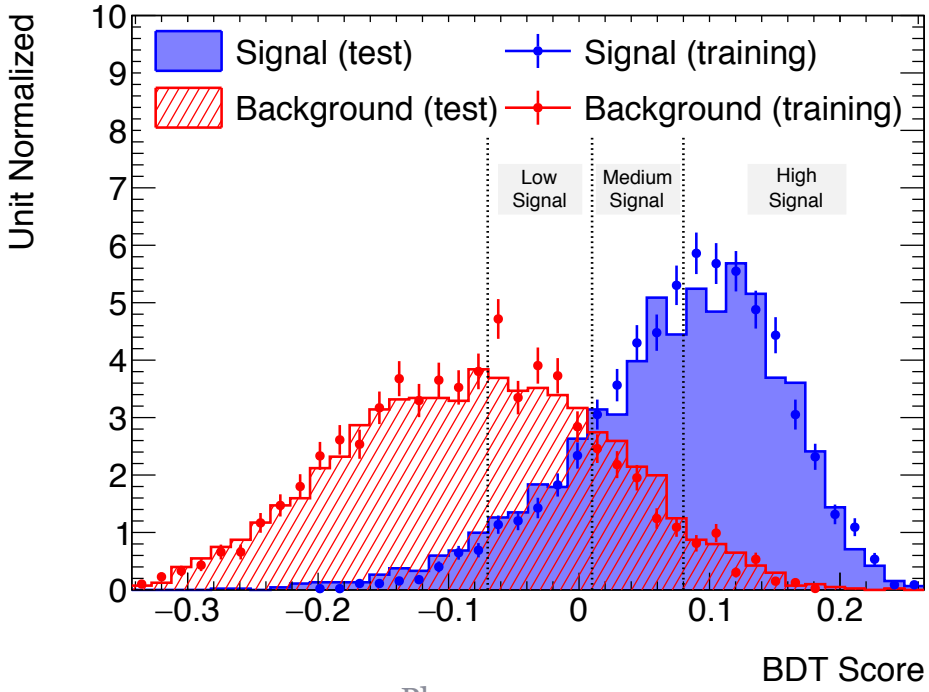


Cut-Based		
	S	B
Pre-selections	31	2.8×10^6 (cc: 38%, cb: 5.6%, cj: 28%, bb: 4.6%, bj: 5.7%, jj: 18%)
Optimized selections	7.4	8.8×10^4
mass cut Eq. (3.11)	5.1	1.2×10^4
$S/\sqrt{B}$		0.047

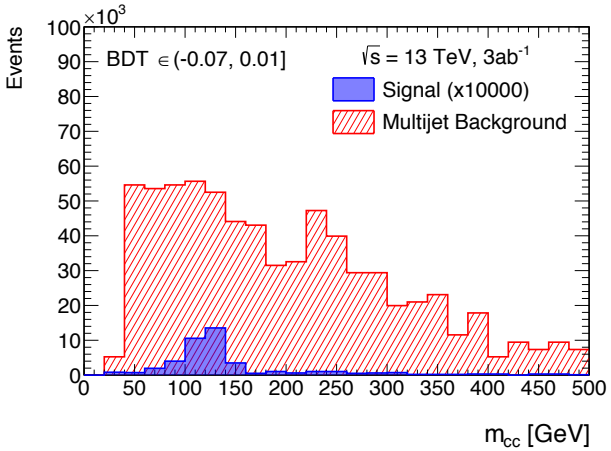
mass cut: 100 GeV < m_{cc} < 140 GeV

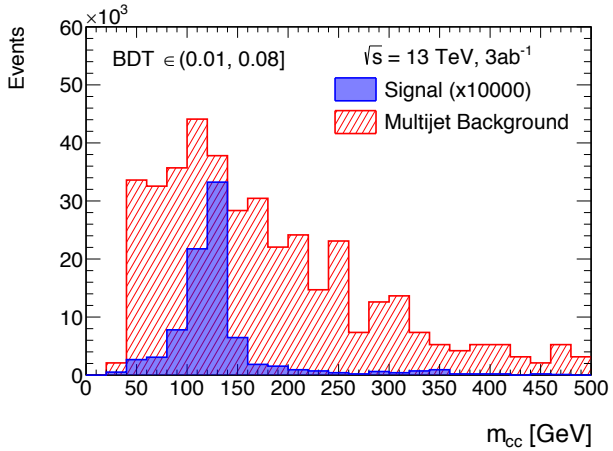
Multivariate Analysis: Boosted Decision Tree

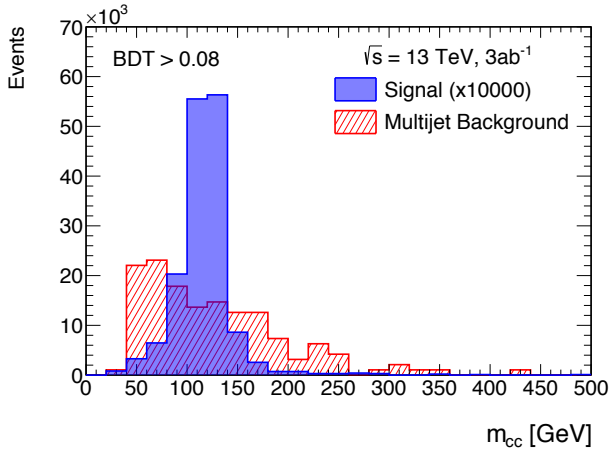
- TMVA package
- Trained with same set of observables used in cut-based analysis
- Low signal: -0.07 – 0.01, medium: 0.01 – 0.08, high: > 0.08



BDT Results







	Low signal		Medium signal		High signal	
	S	B	S	B	S	B
BDT cut	4.5	7.6×10^5	8.5	4.1×10^5	16	1.5×10^5
mass cut Eq. (3.11)	2.4	1.1×10^5	5.5	8.2×10^4	11	2.8×10^4
$S/\sqrt{B}$	0.0073		0.019		0.066	
$S/\sqrt{B}$ combined			0.070			

Constraint on y_c

- Parametrize the modification to charm-Yukawa coupling:

$$y_c = \kappa_c y_c^{SM} \Rightarrow N_{sig} \backsimeq \kappa_c^2 N_{sig}^{SM}$$

- Upper bound on κ_c at 95% C.L in absence of systematics:

	LHC	Cut-based	BDT	ZH [16, 17]	Fit [33]	Hc [31]	$H \to c\bar{c}\gamma$ [41]
κ_c	36.1 fb^{-1}	20	16	10	-	-	-
	3 ab^{-1}	6.5	5.4	2.5	1.2	2.6 - 3.9	8.6

- Constraint comparable to current projections
- Complementary to other channels
- Direct probe of y_c (vs. global fit)

High Energy Projection

- Same analysis with increase in cross-sections
- Basically scaling with $\sqrt{s}$

	13 TeV	14 TeV	30 TeV	100 TeV
$\sigma_{\mathrm{VBF}+\gamma}$ (pb)	0.024	0.027	0.099	0.43
$\sigma_{pp\to 4j+\gamma}$ (pb)	830	940	3700	21000

$\sqrt{s}$	13 TeV	30 TeV	100 TeV
$S/\sqrt{B}$ (3 ab^{-1})	0.07	0.14	0.25
κ_c reach	5.4	3.8	2.8

Summary

- Precise measurements of Higgs coupling to charm quarks is crucial to confirm Yukawa interactions in SM and search for deviations from SM
- A new channel **VBF + γ** is studied, giving a constraint of **5** times y_c^{SM} at HL-LHC at 95% C.L.
- Comparable to current projections, better constraint on y_c than some previous work
- Combination of all channels may get close to the SM value
- Projections at high energies are investigated