Charm-quark Yukawa Coupling in $h \to c\bar{c}\gamma$ at LHC

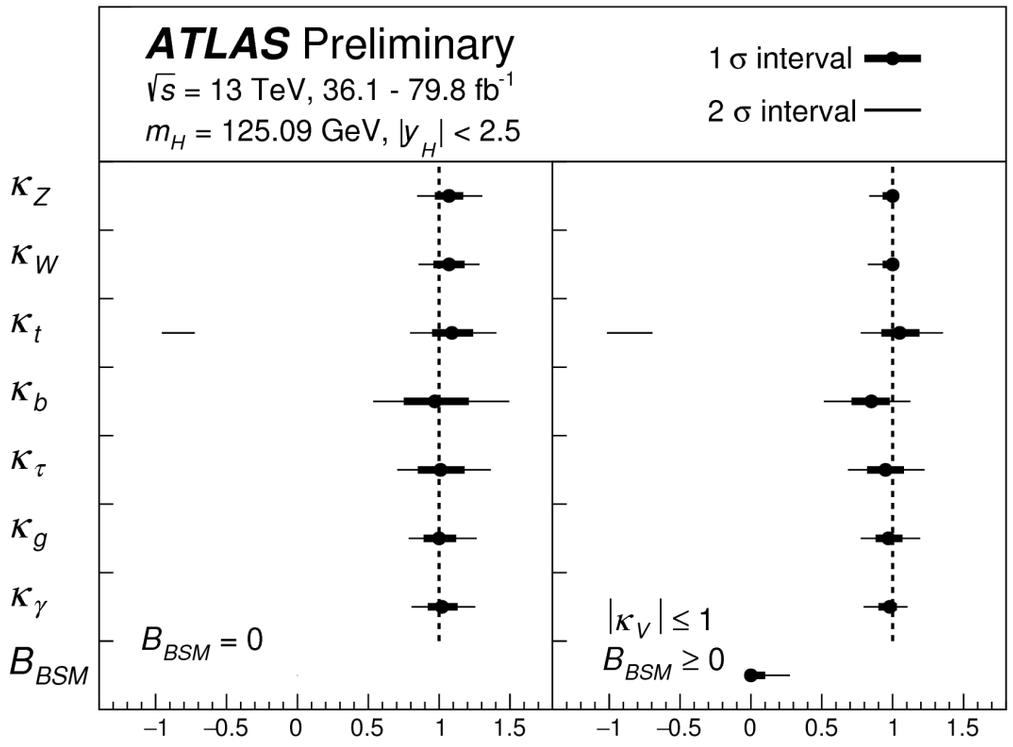
Xing Wang
University of Pittsburgh

QCD@LHC 2019, Buffalo, NY
July 16, 2019

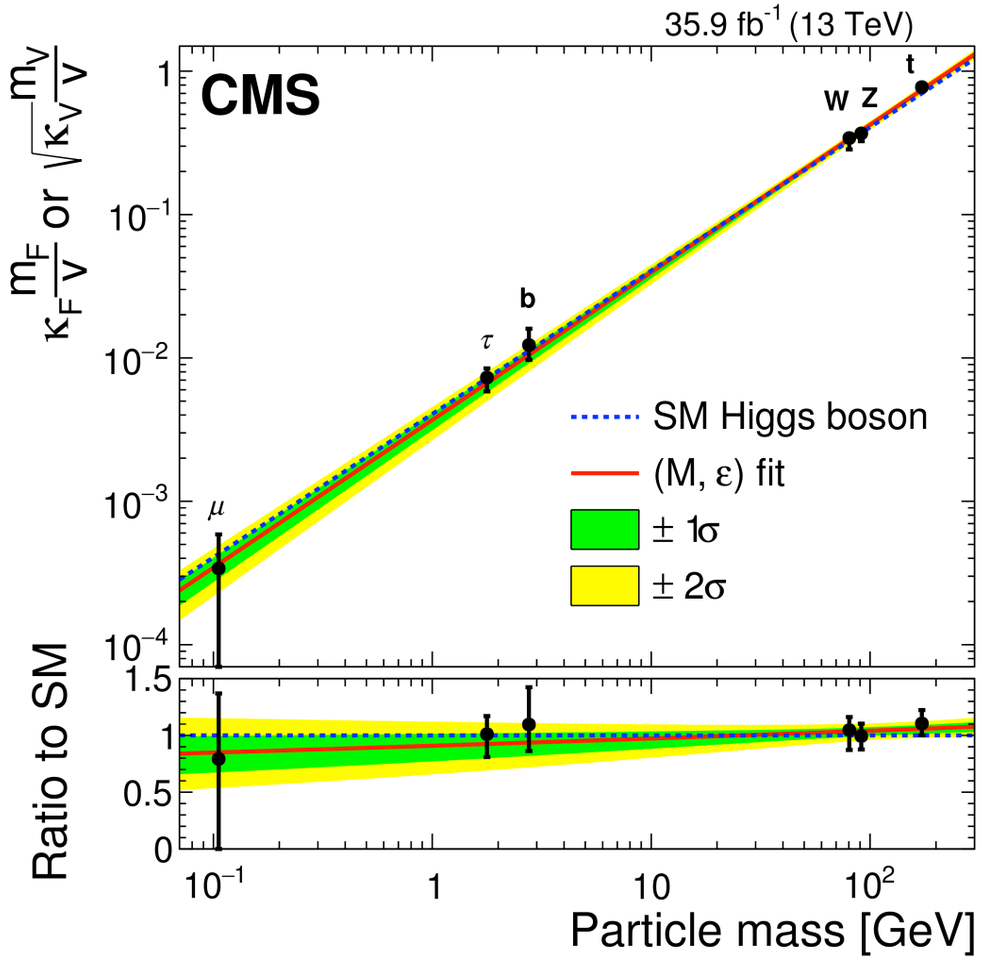
Tao Han, XW, JHEP 1710 (2017) 036, [arXiv:1704.00790]
Tao Han, Benjamin Nachman, XW, PLB 793 (2019) 90-96, [arXiv:1812.06992]

Higgs Couplings

ATLAS-CONF-2018-031



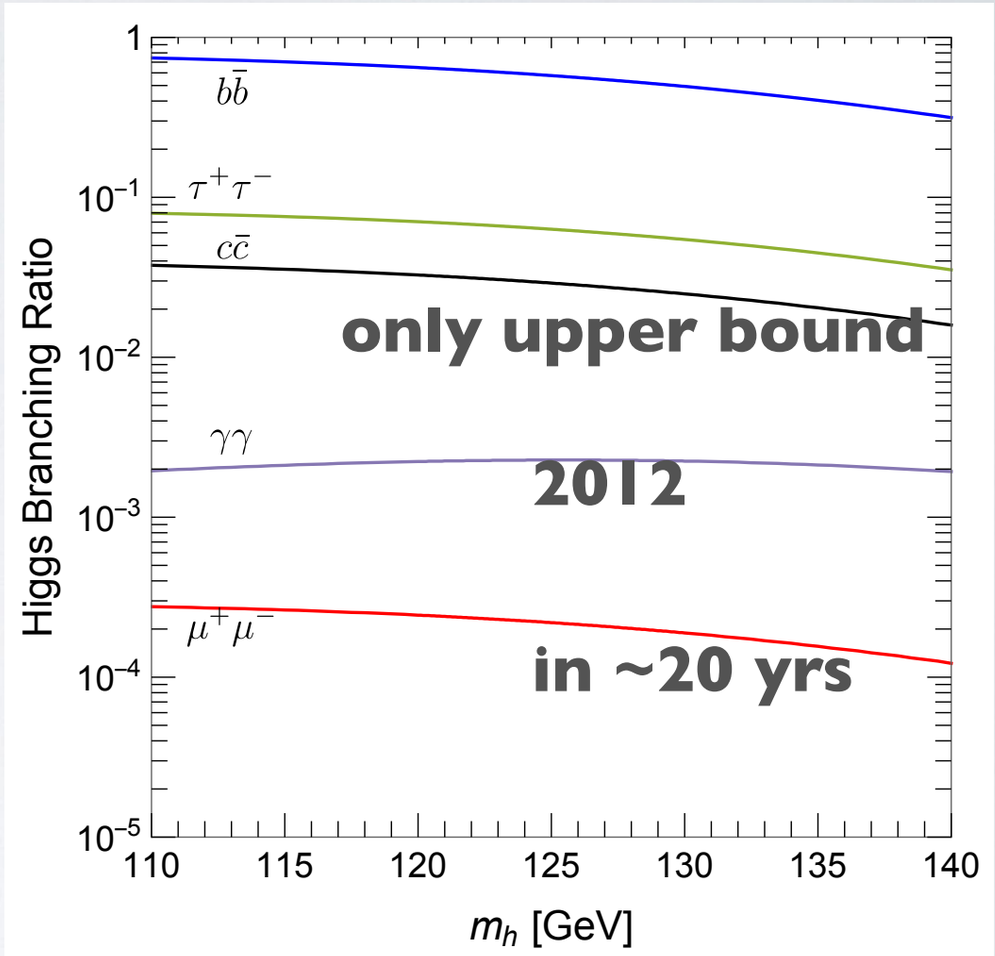
CMS-HIG-17-031



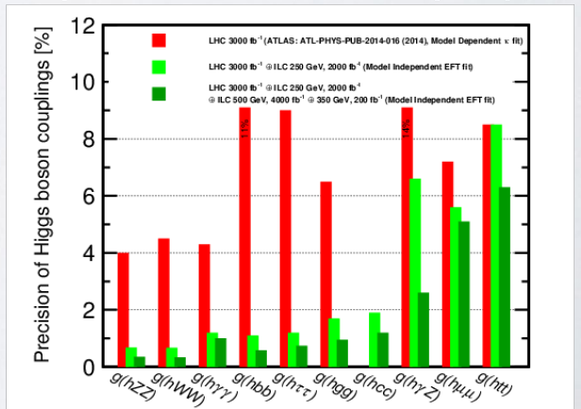
- All 3rd-gen Yukawa couplings observed with 5σ.
- Consistency check of the SM.

2nd-Gen Yukawa

- Confirm the Higgs mechanism.
- $h \to \mu^+\mu^-$ at 9σ at HL-LHC.
- $h \to c\bar{c}$ has large BR but difficult at hadron colliders.

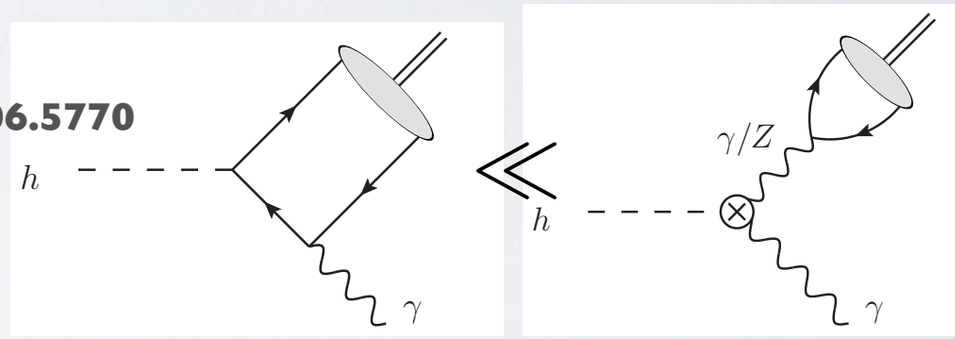


- Lepton colliders like ILC/CEPC are the best place. ~O(%)



Charm Yukawa at LHC

- $pp \to Zh \to (\ell\ell)\,(c\bar{c})$
  - c-tagging required.
  - Best chance so far, ~3 times of the SM Yukawa. **ATL-PHYS-PUB-2018-016**
  - Degenerate with $h \to b\bar{b}$
- $h \to J/\psi\,\gamma \to \ell\ell\gamma$ **Bodwin et al. arXiv:1306.5770**
  - Clean final state
  - Tiny BR~10^{-7}.
  - Less sensitive due to vector meson dominance, ~ 50 times. **ATL-PHYS-PUB-2015-043**

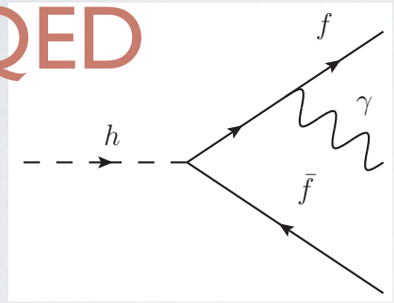


- $h \to c\bar{c}\gamma$ (this talk) **Han, XW, arXiv:1704.00790**
  Han, Nachman, XW, arXiv:1812.06992
- .....

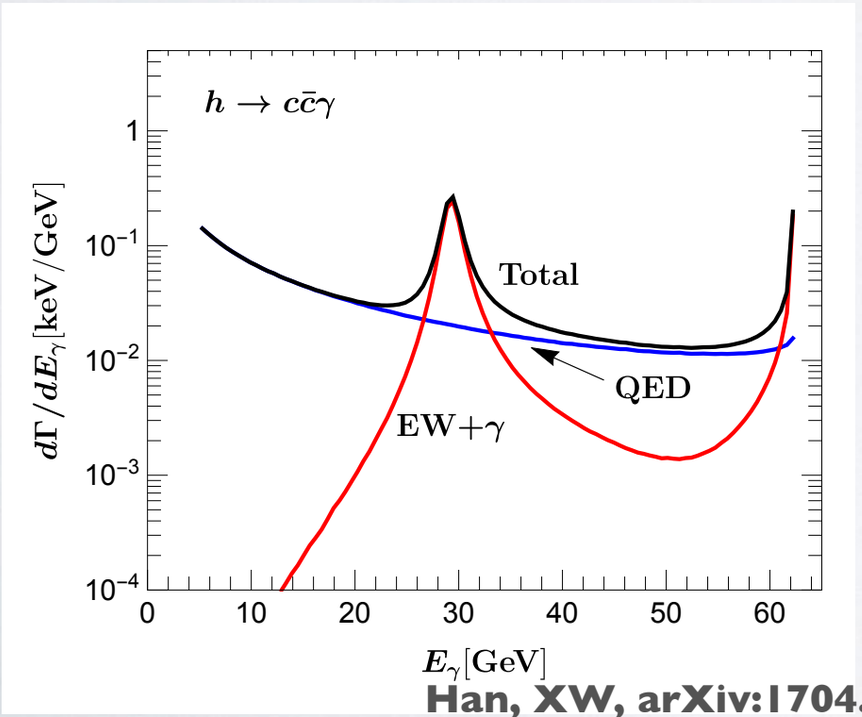
arXiv: 1503.00290, 1507.02916, 1606.09621, 1606.09253, 1609.06592, 1611.05463, 1705.09295

$h \to c\bar{c}\gamma$

- QED radiation at $\mathcal{O}(y_f^2\alpha)$

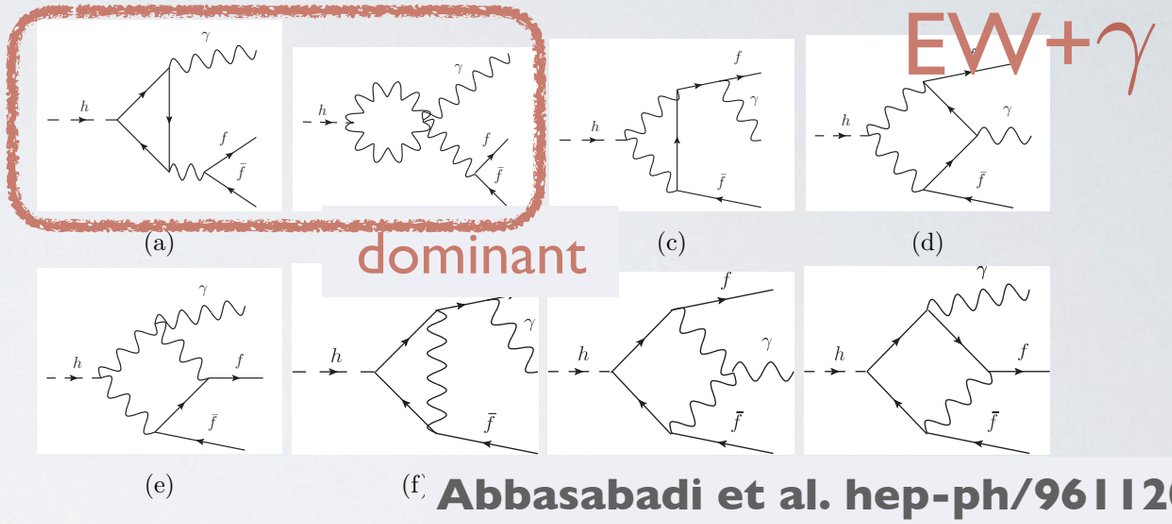


- Yukawa coupling
- Chirality flipping.



Han, XW, arXiv:1704.00790

- EW-loop-induced diagrams at $\mathcal{O}(y_t^2\alpha^3, \alpha^4)$



Abbasabadi et al. hep-ph/9611209

- No Yukawa couplings.
- Chirality-conserving.

- Photon helpful for trigger --- ggF.
- Down-type quark suppressed by Q_f^2.

Is $h \to c\bar{c}\gamma$ Doable at LHC?

- Decay products are soft $p_T \sim \mathcal{O}(10\ \mathrm{GeV})$
- Overwhelming QCD background from $pp \to jj\gamma, jjj$
- Not all data recorded at LHC.

$$\mathrm{pp\ collision\ @40\ MHz} \Rightarrow \mathrm{L1\ trigger\ @100\ kHz} \Rightarrow \mathrm{HLT\ @1\ kHz}$$

- Poor resolution & no flavor-tagging at L1 trigger.

Is $h \to c\bar{c}\gamma$ Doable at LHC?

- Decay products are soft $p_T \sim \mathcal{O}(10\ \mathrm{GeV})$
- Overwhelming QCD background from $pp \to jj\gamma, jjj$
- Not all data recorded at LHC.

$$\text{pp collision @40 MHz} \Rightarrow \text{L1 trigger @100 kHz} \Rightarrow \text{HLT @1 kHz}$$

- Poor resolution & no flavor-tagging at L1 trigger.

No existing trigger!

Trigger Consideration

- Require new trigger for $h \to c\bar{c}\gamma$

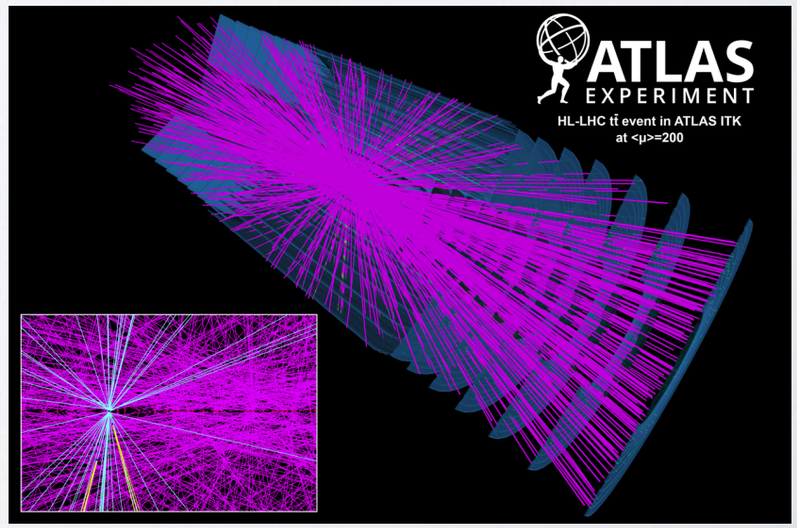
$$(\text{HL-LHC projection}) \Rightarrow \text{L1 trigger @ 1 MHz} \Rightarrow \text{HLT @ 10 kHz}$$

- Current and future upgrades of the ATLAS and CMS trigger systems will allow for multi-object requirements.

$$90\ \text{GeV} < M_{jj\gamma} < 160\ \text{GeV}.$$

- Both ATLAS and CMS will implement some form of tracking for the HL-LHC.
  - Reject pile-ups.

$$r_c = \frac{\sum p_T^{\text{track}}}{p_T^{\text{jet}}} > 0.2$$



Trigger Consideration

- Require new trigger for $h \to c\bar{c}\gamma$

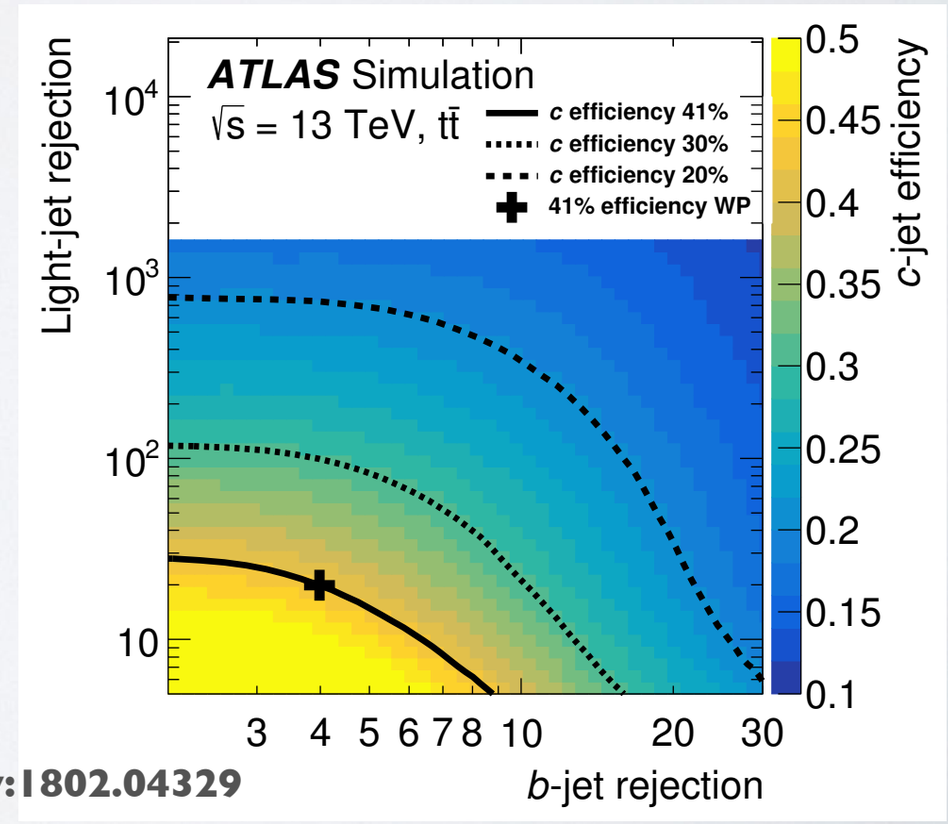
$$p_{Tj} > 27 \text{ GeV}, \quad p_{T\gamma} > 20 \text{ GeV},$$
$$|\eta| < 2.5, \quad \text{and} \quad \Delta R > 0.4$$
$$90 \text{ GeV} < M_{jj\gamma} < 160 \text{ GeV}.$$

$$r_c = \frac{\sum p_T^{\text{track}}}{p_T^{\text{jet}}} > 0.2$$

Simulation

- Madgraph - Pythia - Delphes pipeline, with PU $\mu = 200$
- 13 GeV smearing on top of Delphes to model jets resolution at L1.
- Fake photon rate $\epsilon_{j\to\gamma} = 2.5\ (0.7) \times 10^{-4}$, with isolation $E_T^{R<R_c} < 6$ GeV
- c-tag benchmarks.

Operating Point	ϵ_c	ϵ_b	ϵ_j
I	20%	33%	0.13%
II	30%	33%	1%
III	41%	50%	3.3%



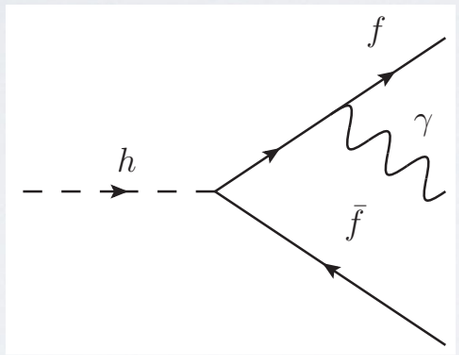
ATLAS, arXiv:1802.04329

Result

- Event selection

$$p_{Tj}^{\max} > 40 \text{ GeV}$$

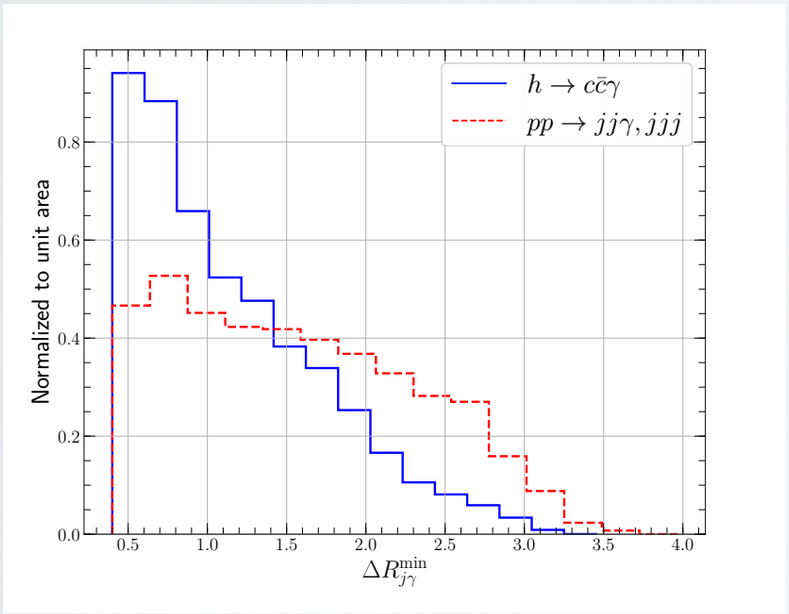
$$\Delta R_{j\gamma}^{\min} < 1.8$$



Expected # of events, in the range of

$$100 < M_{jj\gamma} < 140 \text{ GeV}$$

at HL-LHC $\mathcal{L} = 3 \text{ ab}^{-1}$



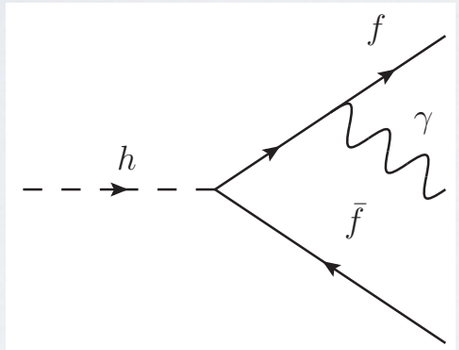
	Working Point	Signal (QED)	Background events	Background event rate [Hz]	$S/\sqrt{S+B}$ $[10^{-2}]$
Level-1 (L1)	No Tag	-	-	9.55×10^3	-
1 c-tag	I	269	3.37×10^8	5.62	1.47
	II	349	5.18×10^8	8.63	1.54
	III	401	8.83×10^8	14.7	1.35
2 c-tags	I	29	1.14×10^7	0.191	0.878
	II	66	2.23×10^7	0.371	1.42
	III	126	5.79×10^7	0.966	1.66

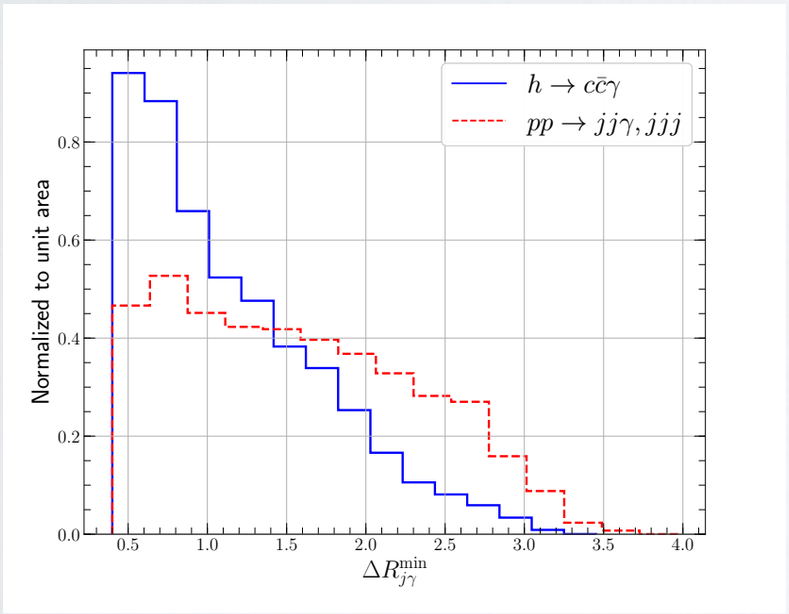
Result

- Event selection

$$p_{Tj}^{\max} > 40 \text{ GeV}$$

$$\Delta R_{j\gamma}^{\min} < 1.8$$





Expected # of events, in the range of

$$100 < M_{jj\gamma} < 140 \text{ GeV}$$

at HL-LHC $\mathcal{L} = 3 \text{ ab}^{-1}$

Less than 1% of the total bandwidth

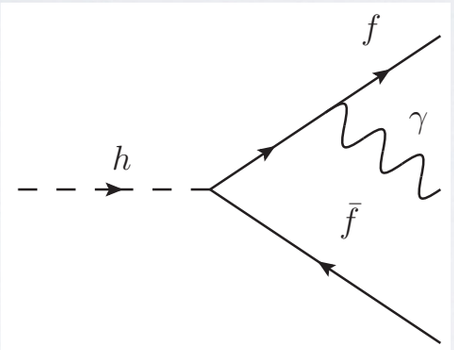
	Working Point	Signal (QED)	Background events	Background event rate [Hz]	$S/\sqrt{S+B}$ $[10^{-2}]$
Level-1 (L1)	No Tag	-	-	9.55×10^3	-
1 c-tag	I	269	3.37×10^8	5.62	1.47
	II	349	5.18×10^8	8.63	1.54
	III	401	8.83×10^8	14.7	1.35
2 c-tags	I	29	1.14×10^7	0.191	0.878
	II	66	2.23×10^7	0.371	1.42
	III	126	5.79×10^7	0.966	1.66

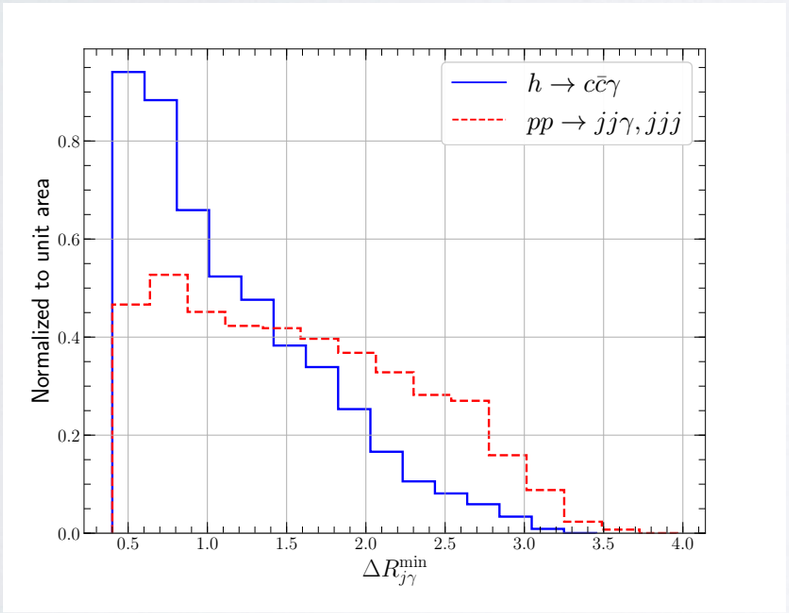
Result

- Event selection

$$p_{Tj}^{\max} > 40 \text{ GeV}$$

$$\Delta R_{j\gamma}^{\min} < 1.8$$





Expected # of events, in the range of

$$100 < M_{jj\gamma} < 140 \text{ GeV}$$

at HL-LHC $\mathcal{L} = 3 \text{ ab}^{-1}$

Less than 1% of the total bandwidth

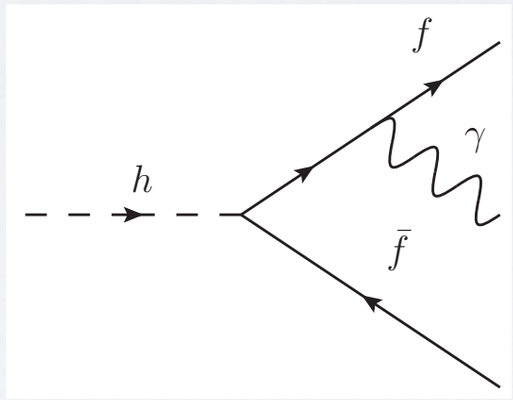
	Working Point	Signal (QED)	Background events	Background event rate [Hz]	$S/\sqrt{S+B}$ $[10^{-2}]$
Level-1 (L1)	No Tag	-	-	9.55×10^3	-
1 c-tag	I	269	3.37×10^8	5.62	1.47
	II	349	5.18×10^8	8.63	1.54
	III	401	8.83×10^8	14.7	1.35
2 c-tags	I	29	1.14×10^7	0.191	0.878
	II	66	2.23×10^7	0.371	1.42
	III	126	5.79×10^7	0.966	1.66

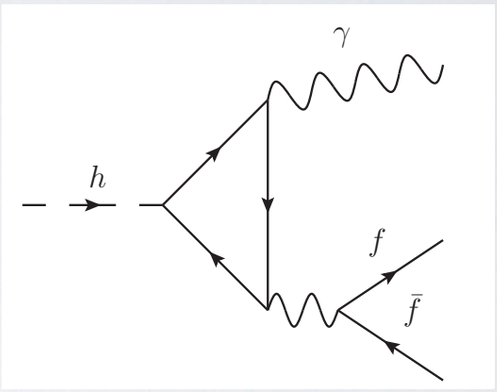
B/S ~ 10^5-10^6

Bound on Yukawa Coupling

- Parametrize the modification of charm Yukawa as

$$y_c^{\rm BSM} = \kappa_c\, y_c^{\rm SM} \implies N_{\rm sig} \simeq \kappa_c^2 N_{\rm sig,QED}^{\rm SM} + \cdots$$





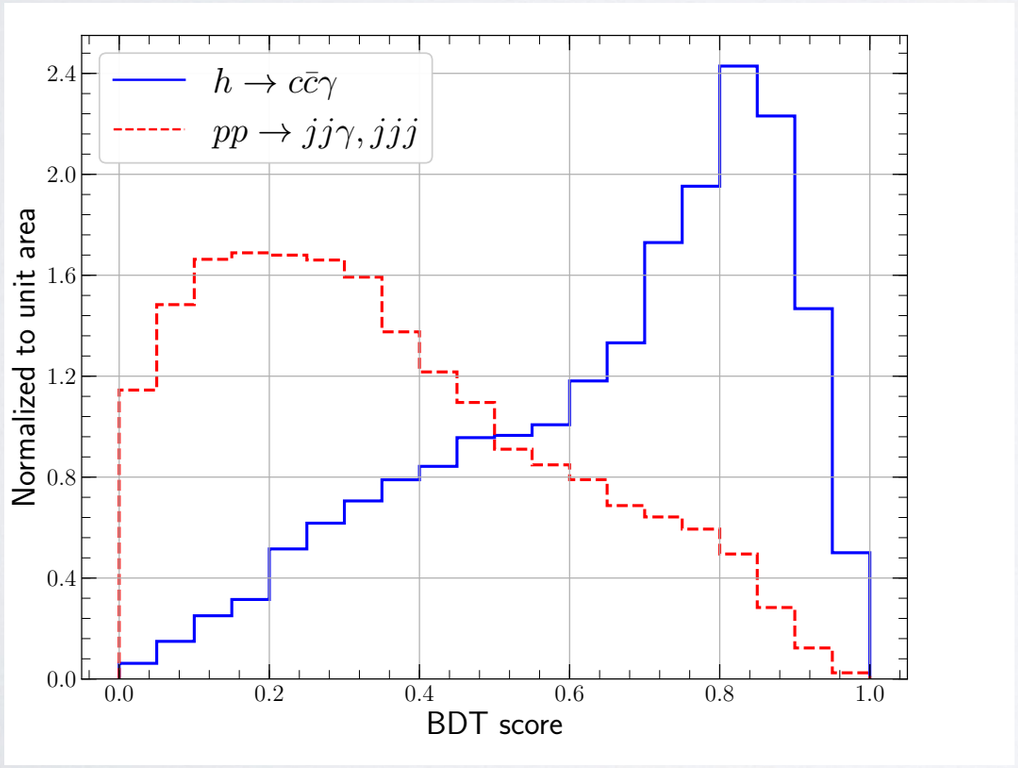
Bound on Yukawa Coupling

- Parametrize the modification of charm Yukawa as

$$y_c^{\rm BSM} = \kappa_c\, y_c^{\rm SM} \implies N_{\rm sig} \simeq \kappa_c^2 N_{\rm sig,QED}^{\rm SM}$$

- At 95% CL_S and in the absence of systematics

$$\kappa_c = \sqrt{\mu} < 10.4,\ \ 9.4,\ \ 9.3$$



- Optimized using Boosted Decision Tree (BDT)

$$\kappa_c < 9.6,\ \ 8.8,\ \ 8.6$$

$M_{j\gamma}^{\rm max},\ M_{j\gamma}^{\rm min},\ M_{jj},\ p_{T\gamma},\ p_{Tj}^{\rm max},\ p_{Tj}^{\rm min},\ \eta_\gamma,\ \eta_j^{\rm max},\ \eta_j^{\rm min},\ \Delta R_{j\gamma}^{\rm max},\ \Delta R_{j\gamma}^{\rm min},\ \Delta R_{jj},\ p_{Tjj\gamma}$

Summary

- Probing the charm-quark Yukawa coupling in $h \to c\bar{c}\gamma$
- Novel triggering strategy proposed.
- 8 times of the SM value at 2σ level at the HL-LHC .