Higgs boson decay to J/ψ via c-quark fragmentation

Xiaoze Tan

PITT PACC, University of Pittsburgh
Physics School, Harbin Institute of Technology

Higgs Potential 2022
July 25, 2022

arXiv: 2202.08273, in collaboration with
Tao Han, Adam K. Leibovich, Yang Ma (PITT)

Why Charm-Higgs coupling?

Higgs is special

- Higgs provides masses to all other elementary particles.
- Higgs is the only know elementary particle with spin 0.
- A portal to new physics beyond the Standard Model.

Determine the Higgs fermion couplings

Directly test whether the SM Higgs mechanism generates the masses.

- **Results so far:** y_t, y_b, and y_τ are measured to 5σ and **agree with SM**
- Questions: We actually do not know whether the SM mass-generation mechanism applies just to the heavy particles, or also to the 1st/2nd generations.
- **The next target is charm quark.**
  $\Rightarrow$ What if the Charm-Higgs coupling is not related to m_c ?

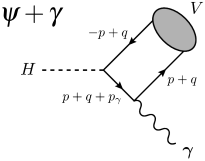
Current status of charm Yukawa coupling testing

Measuring $Hc\bar{c}$ coupling is not easy

- Branching fraction ($H \to c\bar{c}$): 2.9%
- Large QCD background at hadron colliders
- c-tagging is challenging

Current experimental searching

- κ framework: For $y_c^{\mathrm{SM}} = \sqrt{2}m_c/v$, set $y_c = \kappa_c y_c^{\mathrm{SM}}$
- $pp \to VH(c\bar{c})$
    - Need c-tagging.
    - LHC Run 2: ATLAS $\kappa_c \leq 8.5$ [ATLAS-CONF-2021-021, 2201.11428], CMS $1.1 < |\kappa_c| < 5.5$ [CMS-PAS-HIG-21-008, 2205.05550]
    - Future HL-LHC: $\kappa_c \leq 3$. [2201.11428, ATL-PHYS-PUB-2021-039]
- Production of $c\bar{c}$ bound states via Higgs decay: $H \to J/\psi + \gamma$
    - Clean final states $J/\psi \to \mu^+\mu^-$, avoid c-tagging
    - The rate is too low: $BR \sim 10^{-6}$. [1306.5770, 1407.6695]
    - Result is less sensitive: $\kappa_c \leq 100$. [1807.00802, 1810.10056]

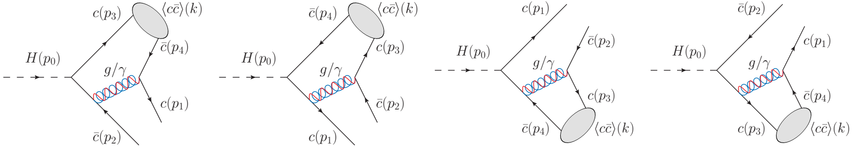


Higgs decay to charmonium in NRQCD

Our idea

$$H \to c + \bar{c} + J/\psi \text{ (or } \eta_c)$$

Color-singlet: Charm quark fragmentation to ${}^3S_1^{[1]}(J/\psi)$ and ${}^1S_0^{[1]}(\eta_c)$



Nonrelativistic QCD framework

$$\Gamma = \sum_{\mathbb{N}} \hat{\Gamma}_{\mathbb{N}}(H \to (Q\bar{Q})[\mathbb{N}] + X) \times \langle \mathscr{O}^h[\mathbb{N}] \rangle, \quad \mathrm{d}\hat{\Gamma}_{\mathbb{N}} = \frac{1}{2m_H} \frac{|\mathscr{M}|^2}{\langle \mathscr{O}^{Q\bar{Q}} \rangle} \mathrm{d}\Phi_3$$

Long distance matrix element (LDME)

Related to the wave function at origin

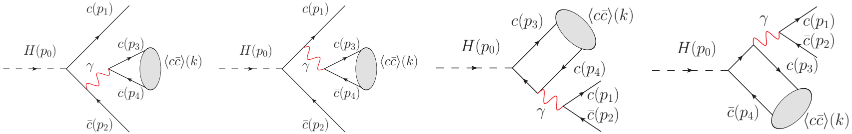
$$\langle \mathscr{O}^{J/\psi}[{}^3S_1^{[1]}] \rangle = \frac{3N_c}{2\pi}|R(0)|^2, \quad \langle \mathscr{O}^{\eta_c}[{}^1S_0^{[1]}] \rangle = \frac{N_c}{2\pi}|R(0)|^2$$

$$\langle \mathscr{O}^{Q\bar{Q}} \rangle = 6N_c, \text{ for } {}^3S_1^{[1]}, \quad \langle \mathscr{O}^{Q\bar{Q}} \rangle = 2N_c, \text{ for } {}^1S_0^{[1]}$$

More corrections from QED and EW sector

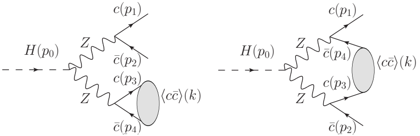
Pure QED diagrams: sizable correction to ${}^3S_1^{[1]}(J/\psi)$ production

Single photon fragmentation (SPF) ⇒ **logarithmic enhancement**



Electroweak correction from the HZZ diagrams

One of the Z can be on shell ⇒ **resonance enhancement**



Charmonium productiuon via color octet states

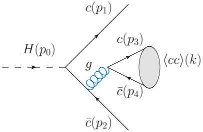
A key property of NRQCD

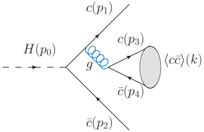
- A quarkonium can also be produced through color-octet $Q\bar{Q}$ Fork states
- New states involved: ${}^3S_1^{[8]}$, ${}^1S_0^{[8]}$, ${}^3P_J^{[8]}$, and ${}^1P_1^{[8]}$
- The LDMEs $\langle \mathscr{O}^h[{}^{2S+1}L_J^{[\text{color}]}]\rangle$ need to be fitted from experimental data

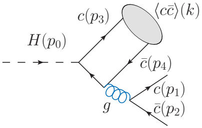
Reference	$\langle \mathscr{O}^{J/\psi}[{}^1S_0^{[8]}]\rangle$	$\langle \mathscr{O}^{J/\psi}[{}^3S_1^{[8]}]\rangle$	$\langle \mathscr{O}^{J/\psi}[{}^3P_0^{[8]}]\rangle/m_c^2$
G. Bodwin,	$(9.9\pm2.2)\times10^{-2}$	$(1.1\pm1.0)\times10^{-2}$	$(4.89\pm4.44)\times10^{-3}$
K.T. Chao,	$(8.9\pm0.98)\times10^{-2}$	$(3.0\pm1.2)\times10^{-3}$	$(5.6\pm2.1)\times10^{-3}$
Y. Feng,	$(5.66\pm4.7)\times10^{-2}$	$(1.77\pm0.58)\times10^{-3}$	$(3.42\pm1.02)\times10^{-3}$

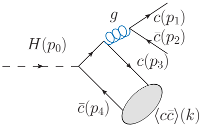
New diagrams for ${}^3S_1^{[8]}$

Single gluon fragmentation (SGF) ⇒ **logarithmic enhancement**









Standard Model results (I)

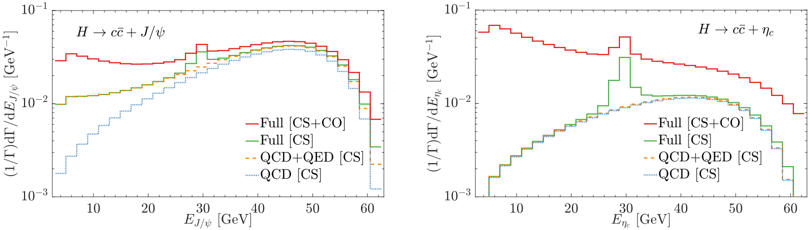
Numerical parameters

$$\alpha = 1/132.5, \quad \alpha_s(2m_c) = 0.235, \quad m_c^{\rm pole} = 1.5~\text{GeV}, \quad m_c(m_H) = 0.694~\text{GeV},$$
$$m_H = 125~\text{GeV}, \quad m_W = 80.419~\text{GeV}, \quad m_Z = 91.188~\text{GeV}, \quad v = 246.22~\text{GeV}.$$
$$y_c^{\rm SM} = \frac{\sqrt{2}m_c(m_H)}{v} \approx 3.986 \times 10^{-3},$$

Decay width and branching fraction

	QCD [CS]	QCD+QED [CS]	Full [CS]	Full [CO]	Full [CS+CO]
$\Gamma(H \to c\bar{c} + J/\psi)$ (GeV)	4.8×10^{-8}	5.8×10^{-8}	6.1×10^{-8}	2.2×10^{-8}	8.3×10^{-8}
$\mathrm{BR}(H \to c\bar{c} + J/\psi)$	1.2×10^{-5}	1.4×10^{-5}	1.5×10^{-5}	5.3×10^{-6}	2.0×10^{-5}
$\Gamma(H \to c\bar{c} + \eta_c)$ (GeV)	4.9×10^{-8}	5.1×10^{-8}	6.3×10^{-8}	1.8×10^{-7}	2.4×10^{-7}
$\mathrm{BR}(H \to c\bar{c} + \eta_c)$	1.2×10^{-5}	1.2×10^{-5}	1.5×10^{-5}	4.5×10^{-5}	6.0×10^{-5}

Charmonium energy distributions



Standard Model results (II)

Color-octet contributions

	${}^3S_1^{[8]}$	${}^1S_0^{[8]}$	${}^1P_1^{[8]}$	${}^3P_J^{[8]}$	Total
$\Gamma(H \to c\bar{c} + J/\psi)$ (GeV)	2.0×10^{-8}	9.8×10^{-10}	-	2.2×10^{-10}	2.2×10^{-8}
$\mathrm{BR}(H \to c\bar{c} + J/\psi)$	5.0×10^{-6}	2.4×10^{-7}	-	5.3×10^{-8}	5.3×10^{-6}
$\Gamma(H \to c\bar{c} + \eta_c)$ (GeV)	1.8×10^{-7}	3.6×10^{-11}	1.0×10^{-10}	-	1.8×10^{-7}
$\mathrm{BR}(H \to c\bar{c} + \eta_c)$	4.5×10^{-5}	8.9×10^{-9}	2.5×10^{-8}	-	4.5×10^{-5}

Contributions with respect to QCD

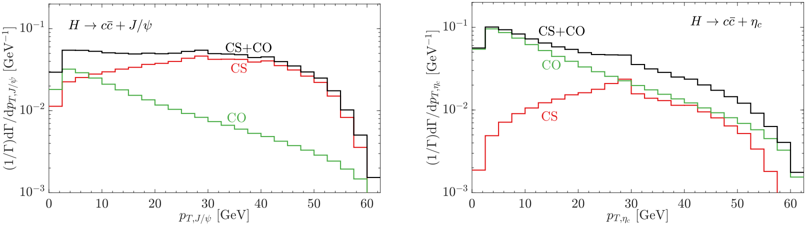
$\hat{\Gamma}_{\mathbb{N}}/\hat{\Gamma}_{\mathbb{N}}^{\mathrm{QCD}}$	${}^1S_0^{[1]}$	${}^3S_1^{[1]}$	${}^1S_0^{[8]}$	${}^3S_1^{[8]}$	${}^1P_1^{[8]}$	${}^3P_0^{[8]}$	${}^3P_1^{[8]}$	${}^3P_2^{[8]}$
QCD	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
QED	1.1×10^{-4}	0.077	0.0073	1.1×10^{-5}	0.0068	0.0073	0.0073	0.0073
QCD×QED	0.021	0.14	-0.17	0.0012	-0.15	-0.17	-0.17	-0.17
EW	0.24	0.051	0.28	2.6×10^{-4}	1.4	0.29	0.33	1.5

Some observations

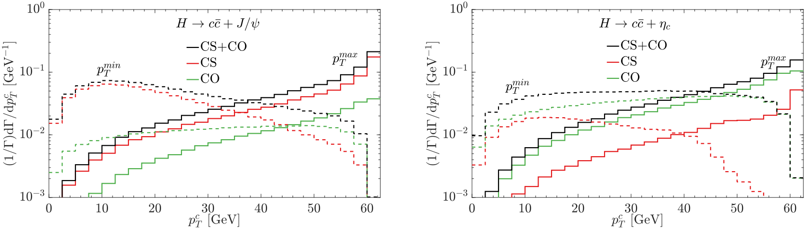
- QCD is dominant in most of the Fock states
- SPF brings sizable QED correction to ${}^3S_1^{[1]}$, but it is forbidden for ${}^1S_0^{[1]}$
- SGF makes ${}^3S_1^{[8]}$ large and considerable
- For ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$, charm-quark fragmentation is the only production channel, so that QED and QCD differ by a universal factor
- EW correction can be large since Z is closed to its mass shell

Standard Model results (III)

Charmonium transverse momentum distribution



Transverse momentum distribution for the free charm quark



VMD Process?

$H \to J/\psi + \gamma$

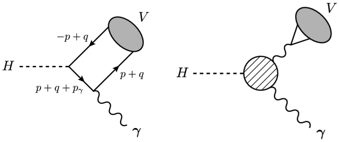
- Small decay rate

$$\mathrm{BR}(H \to J/\psi + \gamma) \simeq 2.8 \times 10^{-6}$$

- Insensitive to $Hc\bar{c}$ coupling

$$\Rightarrow \kappa_c \leq 100$$

"Vector meson dominance" (VMD)

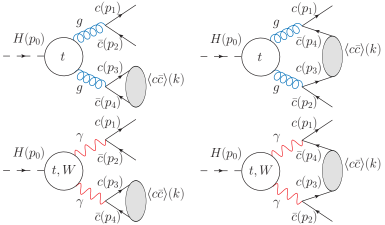


• $\gamma^* \to J/\psi$ dominates over $Hc\bar{c}$
~ 2 orders of magnitude larger.

[1306.5770]

$H \to J/\psi + c\bar{c}$

- Larger decay rate
  $$\mathrm{BR}(H \to J/\psi + c\bar{c}) \simeq 2 \times 10^{-5}$$
- Sensitive to $Hc\bar{c}$ coupling
  QCD and QED dominates
- Other diagrams
  $$H \to g^* g^* / \gamma^* \gamma^* \to J/\psi + c\bar{c}$$

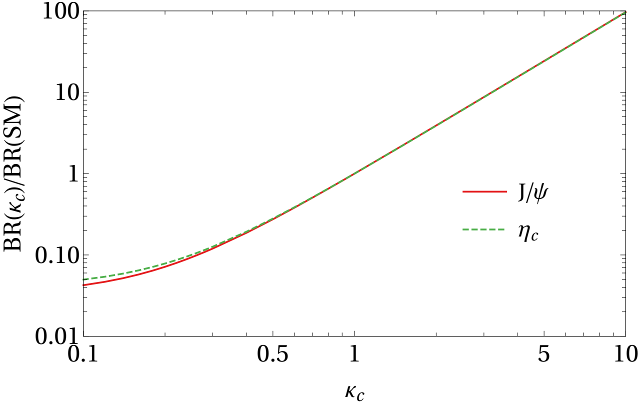


$\mathrm{BR}(g^* g^*) \sim 2.5 \times 10^{-6}$, $\mathrm{BR}(\gamma^* \gamma^*) < 2 \times 10^{-7}$

• No need to worry about VMD

Probe the $Hc\bar{c}$ coupling (I)

Use the κ framework $y_c = \kappa_c y_c^{\mathrm{SM}},\ \mathrm{BR} \approx \kappa_c^2\ \mathrm{BR}^{\mathrm{SM}}$

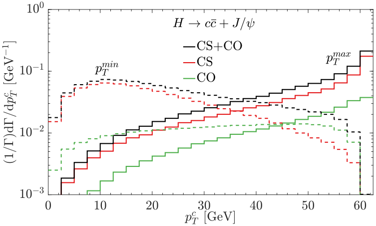


Probe the $Hc\bar{c}$ coupling (II)

Some rough analysis:

- Higgs production cross section at LHC $\sigma_H \sim 50$ pb
- Expect HL-LHC $L \sim 3\ \mathrm{ab}^{-1}$ at ATLAS and CMS and $L \sim 0.3\ \mathrm{ab}^{-1}$ at LHCb
- Detection efficiency ε for the final state $c\bar{c} + \ell^+\ell^-$
- $\mathrm{BR}(J/\psi \to \ell^+\ell^-) \sim 12\%$, $\mathrm{BR}(H \to J/\psi + c\bar{c}) \sim 2 \times 10^{-5}$
- Event number $N = L\sigma_H\ \varepsilon\ \mathrm{BR}(H \to c\bar{c} + \ell^+\ell^-) \approx 12\ \kappa_c^2 \times \frac{L}{\mathrm{ab}^{-1}} \times \frac{\varepsilon}{10\%}$
- Considering the statistical error only $\delta N \sim \sqrt{N}$ gives

$$\Delta\kappa_c \approx 15\% \times (\frac{L}{\mathrm{ab}^{-1}} \times \frac{\varepsilon}{10\%})^{-1/2}$$

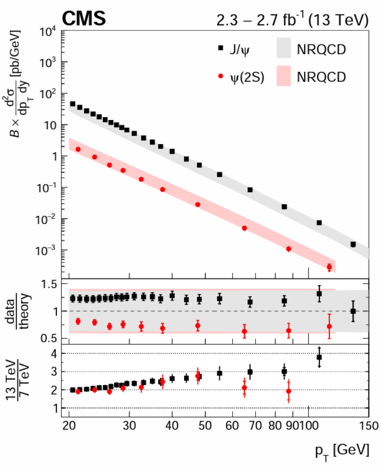


Detection efficiency ε:

- Double charm-tagging $(40\%)^2 \sim 16\%$
- Kinematic acceptance 50%
- Assume $\varepsilon \sim 10\%$
  $\Rightarrow \Delta\kappa_c \sim 15\%$ per ab^{-1}

Probe the $Hc\bar{c}$ coupling (III)

Background: $pp \to J/\psi + X$

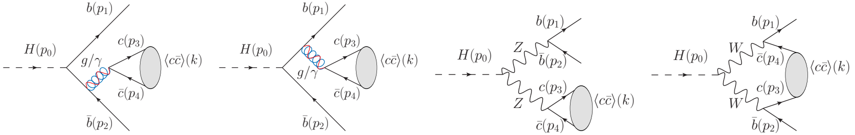


[1710.11002]

- Prompt J/ψ production $\mathrm{BR}(J/\psi \to \mu^+\mu^-) \times \sigma(pp \to J/\psi) \simeq 860$ pb
- Estimate 75000 events for $pp \to J/\psi + c\bar{c}$ a $3\ \mathrm{ab}^{-1}$ HL-LHC $\sim 25\ \mathrm{fb}$ [2012.14161].
- Charm-tagging is needed. • Some kinematic cut may help.

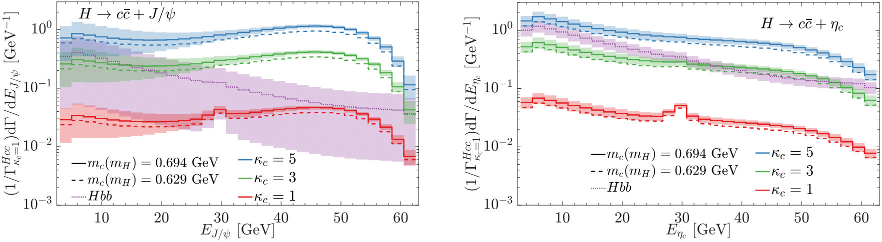
Probe the $Hc\bar{c}$ coupling (IV)

Background: $H \to J/\psi + b\bar{b}$ Color-octet contribution dominates



Charmonium energy distributions

Take the color-octet LDME uncertainty for error estimation



- Charm-tagging is needed.
- More work on LDME fitting is needed.

Probe the $Hc\bar{c}$ coupling (V)

- **If there were no background:** $\Delta\kappa_c \sim 15\%$
- **However, background still exist in the real world (e.g. $pp \to J/\psi + X$):**

- Assume 10,000 background events after cuts at the HL-LHC
- Assume the detection efficiency $\varepsilon \sim 10\%$
- the signal event number is given by

$$N = L\sigma_H \ \varepsilon \ \mathrm{BR}(H \to c\bar{c} + \ell^+\ell^-) \approx 12 \ \kappa_c^2 \times \frac{L}{\mathrm{ab}^{-1}} \times \frac{\varepsilon}{20\%}$$

- Sensitivity $S \simeq N_{simgnal}/\sqrt{N_{background}}$
  $\Rightarrow$ It is possible to reach 2σ for $\kappa_c \approx 2.4$.
- Theoretical uncertainty $\sim 25\%$ and EW contamination $\sim 16\%$ (HZZ 3% and $H \to g^* g^* / \gamma^* \gamma^*$ 13%)

Conclusion

- **Higgs is special and important**
  - Testing the SM mass generation mechanism helps BSM physics searches.
  - The Yukawa couplings of the 3rd generation fermions are well measured.
    $\Rightarrow$ Next target is Charm quark.
- **Current determination of Charm-Higgs coupling**
  - $pp \to VH(c\bar{c})$, c-tagging is challenging.
    ATLAS: $\kappa_c < 8.5$, CMS: $1.1 < |\kappa_c| < 5.5$, future $3\ \mathrm{ab}^{-1}$ HL-LHC: $\kappa_c < 3$
  - $H \to J/\psi + \gamma$, no need for c-tagging but insensitive to κ_c
    ATLAS: $\kappa_c < 100$
- **$H \to J/\psi + c\bar{c}$ is another possible approach**
  - The rate is larger due to the fragmentation enhancements
  - There are both color-singlet and color-octet contributions
  - The QED and EW corrections can be sizable, so need to be included
  - The SM prediction gives $BR \sim 2 \times 10^{-5}$
  - For possible $3\ \mathrm{ab}^{-1}$ HL-LHC, with a 10% final state detection rate
    $\Delta\kappa_c \sim 10\%$
  - Assume 10,000 background events $\Rightarrow 2\sigma$ for $\kappa_c \approx 2.4$
- **More work in progress**
  - Background analysis, detector/systematic effects . . .
  - Better LDMEs, Higher order calculations/resummation . . .

Backups

The SM Yukawa coupling at the scale of the Higgs boson mass is

$$y_c^{\mathrm{SM}} = \frac{\sqrt{2} m_c(m_H)}{v} \approx 3.986 \times 10^{-3},$$

which gives a branching fraction $\mathrm{BR}(H \to c\bar{c}) = 2.9\%$.

Table: Color factors of different Feynman diagrams for the color-singlet (CS) and color-octet (CO) short-distance coefficients. The pure QCD contribution, pure QED contribution and the QCD/QED interference are represented as QCD, QED, and QCD×QED, respectively.

	Fig. 1			Fig. 2	Fig. 4
	QCD	QED	QCD× QED	QED	QCD
CS	$16/9$	1	$4/3$	9	-
CO	$2/9$	8	$-4/3$	-	2

Table: Color factors of the HZZ diagrams for the color-singlet (CS) and color-octet (CO) short-distance coefficients.

	Fig. 3(a)	Fig. 3(b)
CS	9	1
CO	-	8