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

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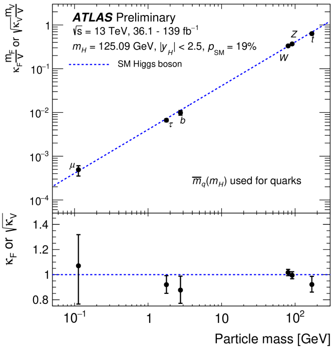
Why Charm-Higgs coupling?

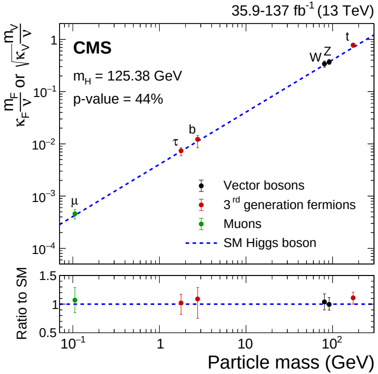
Higgs is special

- 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.

Measure the Higgs couplings



[ATLAS-CONF-2021-053]



[2009.04363]

Higgs to light fermion couplings are to be measured

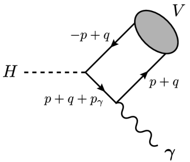
Measuring Charm-Higgs coupling: current status

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

- Smaller mass $\Rightarrow$ Smaller branching fraction: BR$(H \to c\bar{c}) \simeq 2.9\%$
- Large QCD background at hadron colliders $\Rightarrow$ Need c-tagging
- **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], CMS $1.1 < |\kappa_c| < 5.5$ [CMS-PAS-HIG-21-008]
  - Future HL-LHC: $\kappa_c \leq 3$. [2201.11428, ATL-PHYS-PUB-2021-039]
- **To avoid c-tagging** $\Rightarrow$ Higgs decay to J/ψ
  - Clean final states $J/\psi \to \mu^+\mu^-$, may avoid c-tagging
  - Use an addition photon as trigger: $H \to J/\psi + \gamma$
  - 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 charmonia (I)

The Nonrelativistic QCD framework

- The Higgs decay width in NRQCD factorization

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

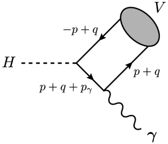
- Long distance matrix element (LDME) are related to the wave function at origin

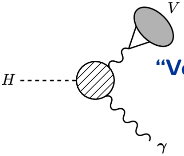
$$\langle \mathscr{O}^{J/\psi}[{}^3S_1^{[1]}] \rangle = \frac{3N_c}{2\pi} |R(0)|^2, \quad \langle \mathscr{O}^{\eta_c}[{}^1S_0^{[1]}] \rangle = \frac{N_c}{2\pi} |R(0)|^2$$

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

Higgs decay to J/ψ and a photon

- $Hc\bar{c}$ diagram is suppressed $\Rightarrow$ Small branching fraction
- The dominant contribution is from $H\gamma\gamma$ diagram $\Rightarrow$ Less sensitive to κ_c
  $\Gamma_{H\gamma\gamma^*} \simeq 1.32 \times 10^{-8}$ GeV, $\Gamma_{\mathrm{SM}} \simeq 1.00 \times 10^{-8}$ GeV [1306.5770, 1407.6695]





"Vector meson dominance" (VMD)

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

Higgs decay to charmonia (II)

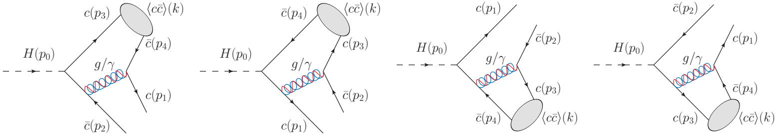
Our idea

- Take advantage of the clean $J/\psi \to \mu^+\mu^-$ decay
- Look for a process

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

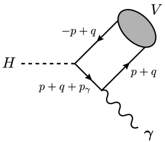
  - The rate is larger than that of $H \to J/\psi + \gamma$
  - The $Hc\bar{c}$ channel dominates over possible contaminations

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



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

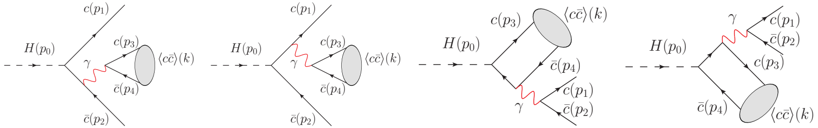
- Enhancement from the quark fragmentation
  $\Rightarrow$ Larger rate
- The decay width is more sensitive to κ_c



More corrections from QED and EW sector

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

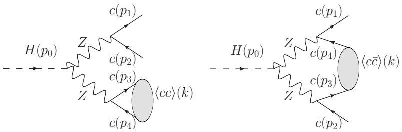
The photon propagator $1/q^2 = 1/m_{J/\psi}^2$



Single photon fragmentation (SPF) $\Rightarrow$ **logarithmic enhancement**

Electroweak correction from the HZZ diagrams

This may be the contamination for Charm-Higgs coupling determination



One of the Z can be on shell $\Rightarrow$ **resonance enhancement**

- The resonance peak can be seen in the $J/\psi(\eta_c)$ energy distribution.
- Sizable for ${}^1S_0^{[1]}(\eta_c)$ due to the larger axial $Zc\bar{c}$ coupling.

Charmonia productiuon via color-octet states

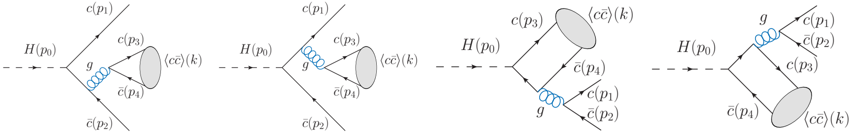
A key property of NRQCD: color-octet states also contribute

- 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 $\langle \mathscr{O}^h[{}^{2S+1}L_J^{[\mathrm{color}]}]\rangle$ 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 ${}^3S_1^{[8]}$

Similar to the SPF: The gluon propagator $1/q^2 = 1/m_{J/\psi}^2$



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

Standard Model results (I)

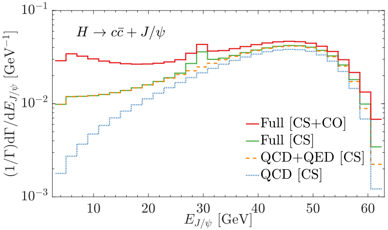
Numerical parameters

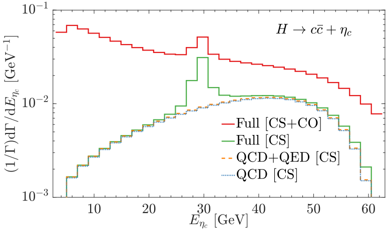
$$\alpha = 1/132.5, \quad \alpha_s(2m_c) = 0.235, \quad m_c^{\mathrm{pole}} = 1.5 \text{ GeV}, \quad m_c(m_H) = 0.694 \text{ GeV},$$
$$m_H = 125 \text{ GeV}, \quad m_W = 80.419 \text{ GeV}, \quad m_Z = 91.188 \text{ GeV}, \quad v = 246.22 \text{ GeV}.$$
$$y_c^{\mathrm{SM}} = \frac{\sqrt{2} m_c(m_H)}{v}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

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}

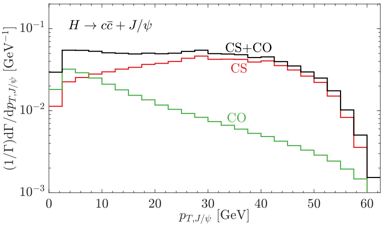
Charmonium energy distributions

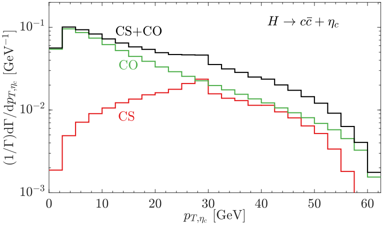




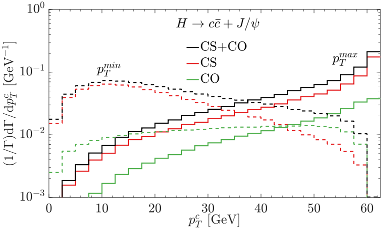
Standard Model results (II)

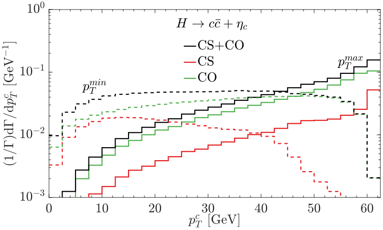
Charmonium transverse momentum distribution





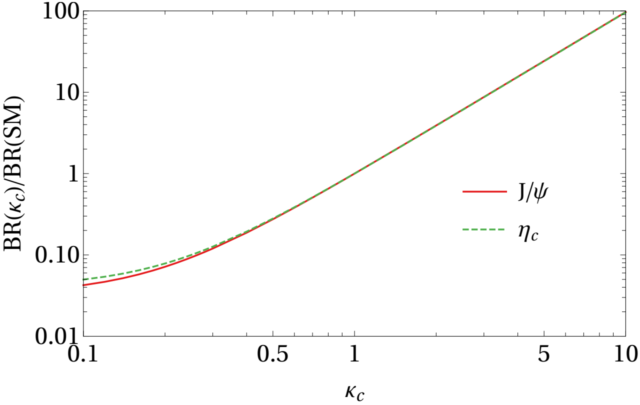
Transverse momentum distribution for the free charm quark





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

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



Note there are small contaminations:

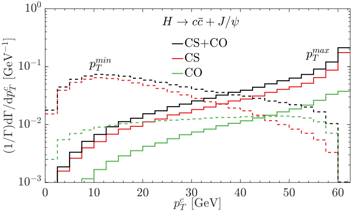
- HZZ diagrams
- The $H \to g^* g^* / \gamma^* \gamma^* \to J/\psi + c\bar{c}$ channel

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

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

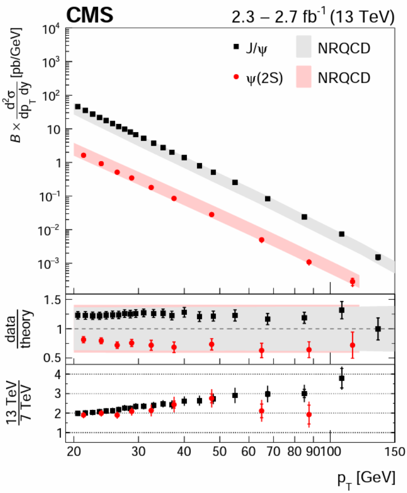


Detection efficiency ε:

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

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

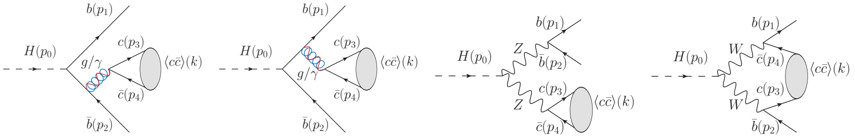
Background: $pp \to J/\psi + X$



- Prompt J/ψ production $\mathrm{BR}(J/\psi \to \mu^+\mu^-) \times \sigma(pp \to J/\psi) \simeq 860$ pb [1710.11002]
- Estimate 75000 events for $pp \to J/\psi + c\bar{c} \Rightarrow \sim 25$ fb for a $3\ \mathrm{ab}^{-1}$ HL-LHC [2012.14161]
- Charm-tagging is needed. • Some kinematic cuts may help.

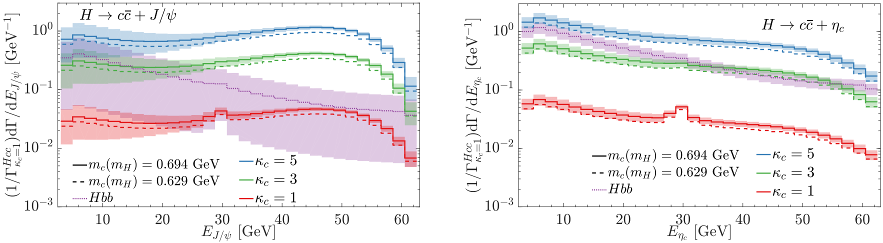
Probe the $Hc\bar{c}$ coupling (IV)

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



Charmonium energy distributions

Take the ${}^3S_1^{[8]}$ LDME uncertainty for error estimation



- Need to determine charm from bottom $\Rightarrow$ Charm-tagging is needed.
- Large uncertainty from LDME $\Rightarrow$ More work on LDMEs fitting is needed.

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

- **If there were no background:** $\Delta\kappa_c \sim 15\%$
- **However, there is background in the real world:**
  - Assume 10,000 background events after the election cuts at the HL-LHC
  - Assume the detection efficiency $\varepsilon \sim 10\%$
  - The signal event number is given by

$$N = L\sigma_H \; \varepsilon \; \mathrm{BR}(H \to c\bar{c}\ell^+\ell^-) \approx 12 \; \kappa_c^2 \times \frac{L}{\mathrm{ab}^{-1}} \times \frac{\varepsilon}{10\%}$$

  - Sensitivity $S \simeq N_{\mathrm{signal}}/\sqrt{N_{\mathrm{Background}}}$
    $\Rightarrow$ It is possible to reach 2σ for $\kappa_c \approx 2.4$.
  - systematic effect $N_{\mathrm{signal}}/N_{\mathrm{Background}} = 2\%$ for $\kappa_c \approx 2.4$.

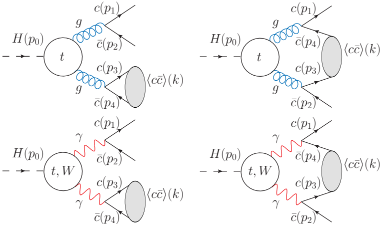
Conclusion

- **Higg is special and important**
  - The Higgs sector is the portal to new physics beyond SM.
  - Testing the SM mass generation mechanism helps BSM physics searches.
  - The Yukawa couplings of the 3rd generation fermions are precisely measured $\Rightarrow$ Charm quark is the next target.
- **For the current determination of the 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: $\kappa_c < 100$
- **Another possible approach:** $H \to J/\psi + c\bar{c}$
  - 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 a possible $3\ \mathrm{ab}^{-1}$ HL-LHC, with a 10% final state detection efficiency
    $\Rightarrow \Delta\kappa_c \sim 10\%$
  - Assume there are 10,000 background events $\Rightarrow$ 2σ for $\kappa_c \simeq 2.4$
- **More work in progress:**
  - Background analysis, detector/systematic effects
  - Better LDMEs fittings, higher order calculations/resummation ...

Worry about VMD ?

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

- 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
  $H \to g^* g^* / \gamma^* \gamma^* \to J/\psi + c\bar{c}$



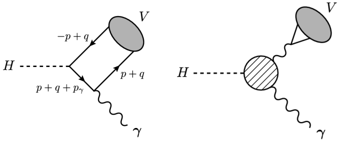
$\mathrm{BR}(g^* g^*) \sim 2.5 \times 10^{-6}$, $\mathrm{BR}(\gamma^* \gamma^*) < 2 \times 10^{-7}$

- **No need to worry about VMD**

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

- Small decay rate
  $\mathrm{BR}(H \to J/\psi + \gamma) \simeq 2.8 \times 10^{-6}$
- Insensitive to $Hc\bar{c}$ coupling
  $\Rightarrow \kappa_c \leq 100$

VMD dominates



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

Color-singlet VS color-octet

Recall the NRQCD factorization formalism

$$\Gamma = \sum_{\mathbb{N}} \hat{\Gamma}_{\mathbb{N}}(H \to (Q\bar{Q})[\mathbb{N}] + X) \times \langle \mathscr{O}^h[\mathbb{N}] \rangle$$

Long distance: the color-octet LDMEs are suppressed

They are in higher orders of v than the color-singlet one

$$\frac{\langle \mathscr{O}^{J/\psi}({}^1S_0^{[8]}) \rangle}{\langle \mathscr{O}^{J/\psi}({}^3S_1^{[1]}) \rangle} \sim \mathscr{O}(v^3), \quad \frac{\langle \mathscr{O}^{J/\psi}({}^3S_1^{[8]}) \rangle}{\langle \mathscr{O}^{J/\psi}({}^3S_1^{[1]}) \rangle} \sim \mathscr{O}(v^4), \quad \frac{\langle \mathscr{O}^{J/\psi}({}^3P_J^{[8]}) \rangle}{\langle \mathscr{O}^{J/\psi}({}^3S_1^{[1]}) \rangle} \sim \mathscr{O}(v^4),$$

$$\frac{\langle \mathscr{O}^{\eta_c}({}^3S_1^{[8]}) \rangle}{\langle \mathscr{O}^{\eta_c}({}^1S_0^{[1]}) \rangle} \sim \mathscr{O}(v^3), \quad \frac{\langle \mathscr{O}^{\eta_c}({}^1P_1^{[8]}) \rangle}{\langle \mathscr{O}^{\eta_c}({}^1S_0^{[1]}) \rangle} \sim \mathscr{O}(v^4)$$

Short distance coefficient (SDC)

- The color factors are different for color-singlet and color-octet states

	Charm fragmentation			SPF	SGF
	QCD	QED	QCD×QED	QED	QCD
CS	16/9	1	4/3	9	-
CO	2/9	8	-4/3	-	2

- There may appear new diagrams for color-octet state production
  The SGF diagrams result in large ${}^3S_1^{[8]}$ SDC
  $\Rightarrow$ Sizable color-octet contribution (mainly from ${}^3S_1^{[8]}$)

Standard Model results: some details

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 ${}^3S_1^{[8]}$ super large
- 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 is large since Z is closed to its mass shell

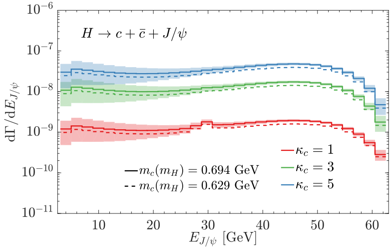
Color-octet uncertainties from the LDMEs

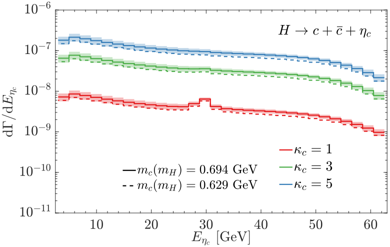
Color-octet contributions: ${}^3S_1^{[8]}$ dominates

	${}^3S_1^{[8]}$	${}^1S_0^{[8]}$	${}^1P_1^{[8]}$	${}^3P_J^{[8]}$	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}

Take the ${}^3S_1^{[8]}$ LDME for the uncertainty estimation

$$\mathrm{BR}(H \to c\bar{c} + J/\psi) = (2.0 \pm 0.5) \times 10^{-5},$$
$$\mathrm{BR}(H \to c\bar{c} + \eta_c) = (6.0 \pm 1.0) \times 10^{-5}.$$





When is y_c not related to the charm mass?

Higgs Effective Field Theory (HEFT)

$SU(2)$ doublets of the global $SU(2)_{L,R}$ symmetries:

$$Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix}, \quad Q_R \quad = \begin{pmatrix} U_R \\ D_R \end{pmatrix}, \quad L_L = \begin{pmatrix} \nu_L \\ E_L \end{pmatrix}, \quad L_R \quad = \begin{pmatrix} 0 \\ E_R \end{pmatrix}.$$

Define

$$U(x) \equiv \exp(i\boldsymbol{\sigma}_a \boldsymbol{\pi}^a(x)/v)$$

so that the Lagrangian contains

$$\mathscr{L} \supset -\frac{v}{\sqrt{2}} \bar{Q}_L U y_Q(h) Q_R - \frac{v}{\sqrt{2}} \bar{L}_L U y_L(h) L_R + h.c.$$

The functions $y_Q(h)$ and $y_L(h)$ control the Yukawa couplings

$$y_Q(h) \equiv \mathrm{diag}\left(\sum_n y_U^{(n)} \frac{h^n}{v^n}, \sum_n y_D^{(n)} \frac{h^n}{v^n}\right)$$

$$y_L(h) \equiv \mathrm{diag}\left(0, \sum_n y_\ell^{(n)} \frac{h^n}{v^n}\right) L$$

$n = 0$ is for mass term, $n = 1$ is for Yukawa coupling.

Fragmentation formalism

The decay width is written as a convolution

Define $z \equiv 2E_\psi/m_H$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}z}(H \to \psi(z) q\bar{q}) = 2C_q \otimes D_q + C_g \otimes D_g, C \otimes D \equiv \int_z^1 C(y) D(z/y) \frac{\mathrm{d}y}{y}$$

Hard coefficient

$$C_q(\mu^2, z) = \Gamma(H \to q\bar{q}) \delta(1-z)$$

$$C_g(\mu^2, z) = \frac{4\alpha_s}{3\pi} \Gamma(H \to q\bar{q}) \left[\frac{(z-1)^2+1}{z} \log\left(\frac{(1-z) z^2 m_H^2}{\mu^2} \right) - z \right]$$

Fragmentation functions

$$D^{(1)}_{c\to J/\psi}(\mu^2, z) = \frac{128\alpha_s^2}{243 m_{J/\psi}^3} \frac{z(1-z^2)}{(2-z)^6} (16 - 32z + 72z^2 - 32z^3 + 5z^4) \langle \mathscr{O}^{J/\psi}({}^3S_1^{[1]}) \rangle$$

$$D^{(8)}_{q\to\psi}(\mu^2, z) = \frac{2\alpha_s^2}{9 m_\psi^3} \left[\frac{(z-1)^2+1}{z} \log\left(\frac{\mu^2}{m_\psi^2 (1-z)} \right) - z \right] \langle \mathscr{O}^{J/\psi}({}^3S_1^{[8]}) \rangle$$

$$D_{g\to\psi}(\mu^2, z) = \frac{\pi\alpha_s}{3 m_\psi^3} \delta(1-z) \langle \mathscr{O}^{J/\psi}({}^3S_1^{[8]}) \rangle$$