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

Yang Ma

Pittsburgh Partcile-physics, Astrophysics, and Cosmology Center,
Department of Physics and Astronomy,
University of Pittsburgh, PA 15260, USA

May 9, 2022

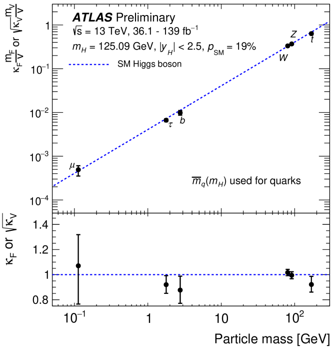
2202.08273, in collaboration with
T. Han, A. Leibovich (PITT), X. Tan (HIT)

Why Charm-Higgs coupling?

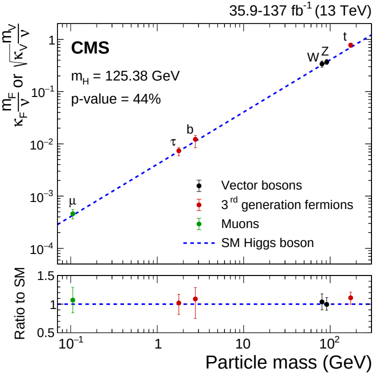
Higgs is special

- 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

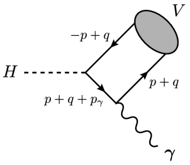
Measuring Charm-Higgs coupling: current status

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

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

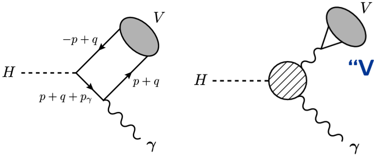
- Long distance matrix element (LDME) are related to the wave function at origin

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

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

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)

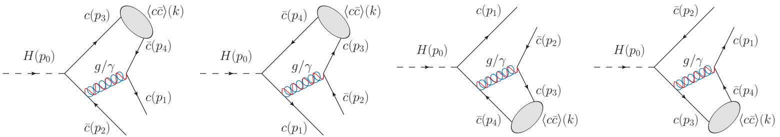
Our idea

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

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

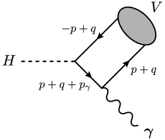
  - The rate is larger than that of $H \to J/\psi + \gamma$
  - The $Hc\bar{c}$ channel dominates over possible contaminations

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



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

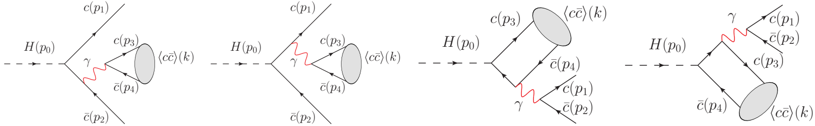
- Enhancement from the quark fragmentation
  $\Rightarrow$ Larger rate
- The decay width is more sensitive to κ_c



More corrections from QED and EW sector

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

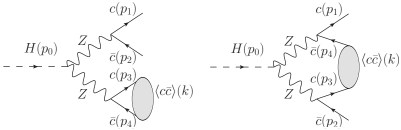
The photon propagator $1/q^2 = 1/m_{J/\psi}^2$



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

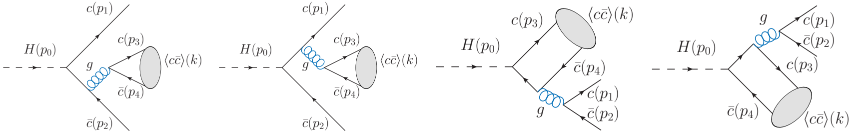
A key property of NRQCD: color-octet states also contribute

- 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,	$(9.9 \pm 2.2) \times 10^{-2}$	$(1.1 \pm 1.0) \times 10^{-2}$	$(4.89 \pm 4.44) \times 10^{-3}$
K.T. Chao,	$(8.9 \pm 0.98) \times 10^{-2}$	$(3.0 \pm 1.2) \times 10^{-3}$	$(5.6 \pm 2.1) \times 10^{-3}$
Y. Feng,	$(5.66 \pm 4.7) \times 10^{-2}$	$(1.77 \pm 0.58) \times 10^{-3}$	$(3.42 \pm 1.02) \times 10^{-3}$

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

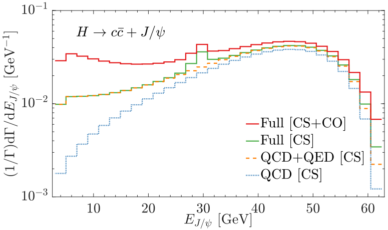
$$\alpha = 1/132.5, \quad \alpha_s(2m_c) = 0.235, \quad m_c^{\text{pole}} = 1.5\ \text{GeV}, \quad m_c(m_H) = 0.694\ \text{GeV},$$
$$m_H = 125\ \text{GeV}, \quad m_W = 80.419\ \text{GeV}, \quad m_Z = 91.188\ \text{GeV}, \quad v = 246.22\ \text{GeV}.$$

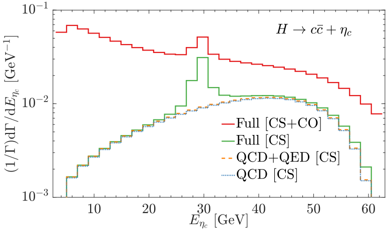
$$y_c^{\text{SM}} = \frac{\sqrt{2} m_c(m_H)}{v} \approx 3.986 \times 10^{-3},$$

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}
$\text{BR}(H \to c\bar{c} + J/\psi)$	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}
$\text{BR}(H \to c\bar{c} + \eta_c)$	1.2×10^{-5}	1.2×10^{-5}	1.5×10^{-5}	4.5×10^{-5}	6.0×10^{-5}

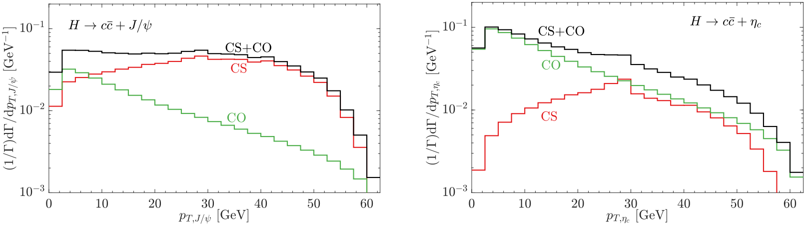
Charmonium energy distributions



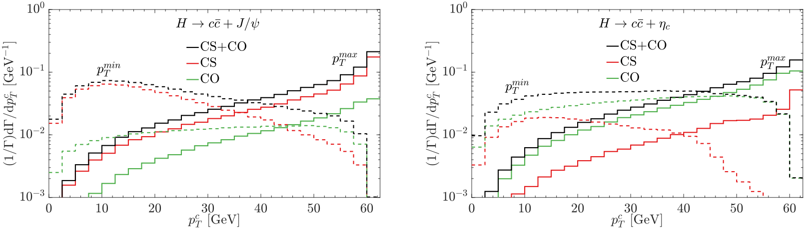


Standard Model results (II)

Charmonium transverse momentum distribution

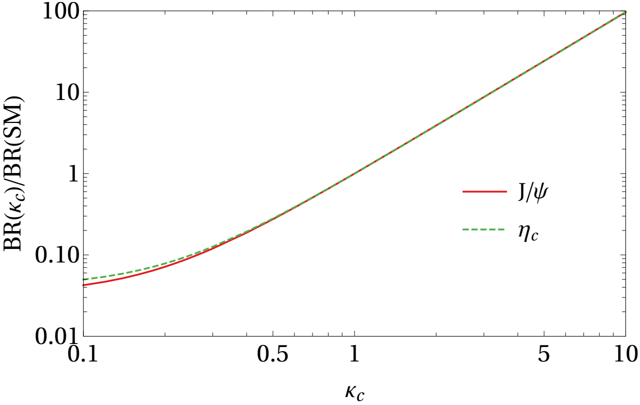


Transverse momentum distribution for the free charm quark



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

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



Note there are small contaminations:

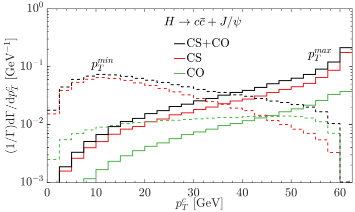
- HZZ diagrams
- The $H \to g^* g^* / \gamma^* \gamma^* \to J/\psi + c\bar{c}$ channel

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

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

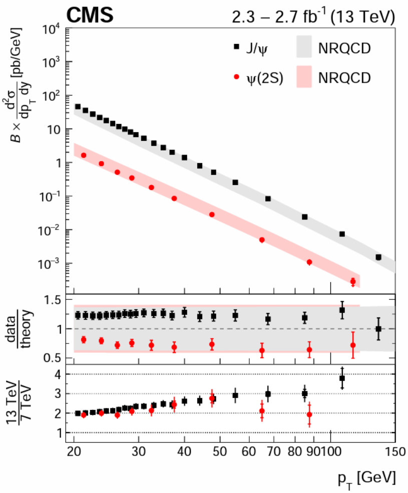


Detection efficiency ε:

- 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)

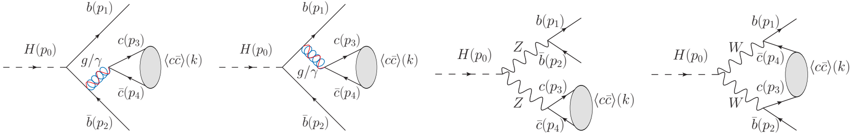
Background: $pp \to J/\psi + X$



- 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.

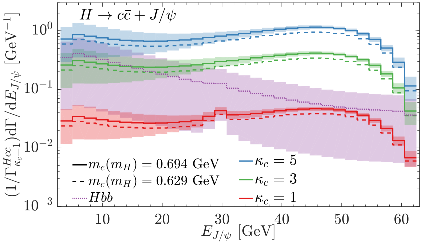
Probe the $Hc\bar{c}$ coupling (IV)

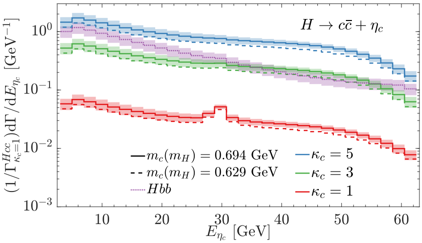
Background: $H \to J/\psi + b\bar{b}$ Color-octet contribution dominates



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 $\kappa_c \approx 2.4$.

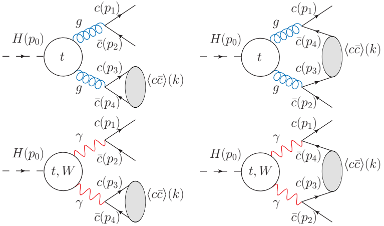
Conclusion

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



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

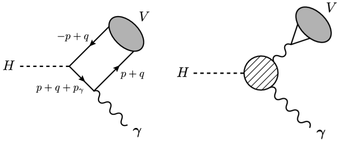
- **No need to worry about VMD**

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

- 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

  ⇒ 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

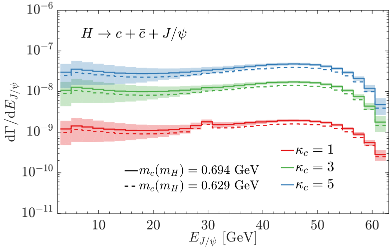
Color-octet uncertainties from the LDMEs

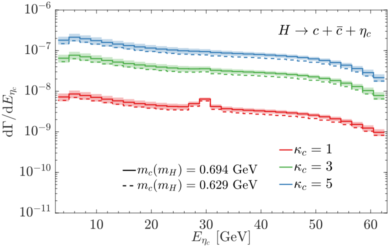
Color-octet contributions: ${}^3S_1^{[8]}$ dominates

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

$$\mathrm{BR}(H\to c\bar{c}+J/\psi)=(2.0\pm0.5)\times10^{-5},$$
$$\mathrm{BR}(H\to c\bar{c}+\eta_c)=(6.0\pm1.0)\times10^{-5}.$$





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:

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

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

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

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

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