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

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Why Higgs charm coupling?

Higgs is special

- Higgs provides masses to all other elementary particles.
- Higgs is the only know elementary particle with spion 0.

Determine the Higgs fermion couplings

- Directly test whether the SM Higgs mechanism generates the masses.
  Or is it a mixture of two (or more) mechanisms?
- All third generation Yukawa couplings are observed at 5σ.
  The values of y_τ, y_t, and y_b are consistent with the SM.
- It is time to look into second generation fermions.
  Is the SM mass-generation mechanism applies only to heavy particles ?
  Or is it also valid for the 1st/2nd generations ?

Current status of charm Yukawa coupling

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

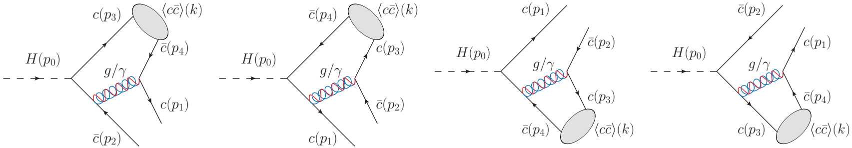
- κ framework: $y_c = \kappa_c y_c^{\mathrm{SM}}$
- $pp \to VH(c\bar{c})$
  - Need c-tagging.
  - Latest result: At LHC Run 2: $\kappa_c \leq 8.5$ for latest ATLAS Run 2. [ATLAS-CONF-2021-021]
  - Future HL-LHC: $\kappa_c \leq 3$. [ATL-PHYS-PUB-2018-016, 1808.08865, 1912.01662]
- Production of $c\bar{c}$ 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 via fragmentation mechanism

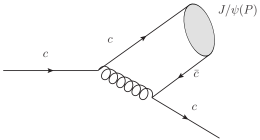
Nonrelativistic QCD frame work

$$\Gamma = \sum_n \hat{\Gamma}_n (H \to (Q\bar{Q})[n] + X) \times \langle \mathscr{O}^h[n] \rangle,$$

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

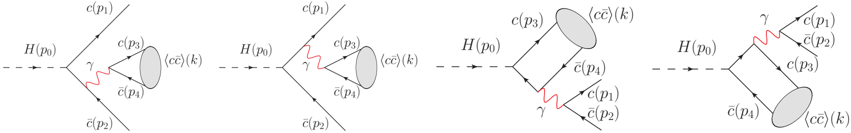


There is enhancement from charm fragmentation

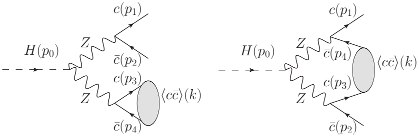


QED and EW corrections

Pure QED diagrams: sizable correction to ${}^3S_1^{[1]}(J/\psi)$ production
Enhancement from single photon fragmentation (SPF)



Electroweak correction from the HZZ diagrams
One of the Z can be on shell $\Rightarrow$ resonance enhancement



Charmonium productiuon via color octet states

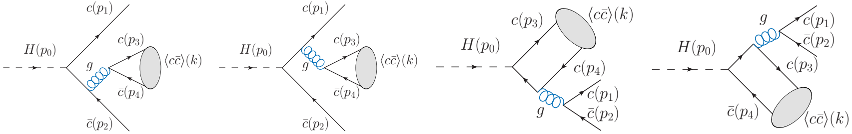
A key property of NRQCD

- A quarkonium can also be produced through color-octet $Q\bar{Q}$ Fork states
- New states involved: ${}^3S_1^{[8]}$, ${}^1S_0^{[8]}$, ${}^3P_J^{[8]}$
- The long distance matrix elements 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 ${}^3S_1^{[8]}$

Enhancement from single gluon fragmentation (SGF)



Standard Model results

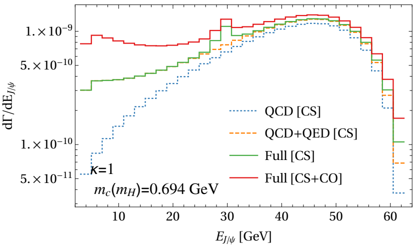
Numerical parameters

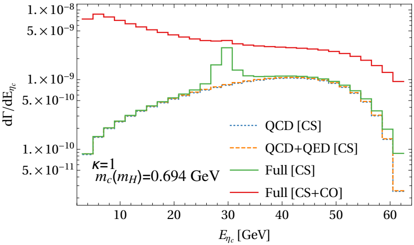
$$\alpha = 1/132.5, \quad \alpha_s(2m_c) = 0.235, \quad m_c^{\text{pole}} = 1.5\ \text{GeV}, \quad m_c(m_H) = 0.694\ \text{GeV},$$
$$m_H = 125\ \text{GeV}, \quad m_W = 80.419\ \text{GeV}, \quad m_Z = 91.188\ \text{GeV}, \quad v = 246.22\ \text{GeV}.$$

Decay width and branching fraction

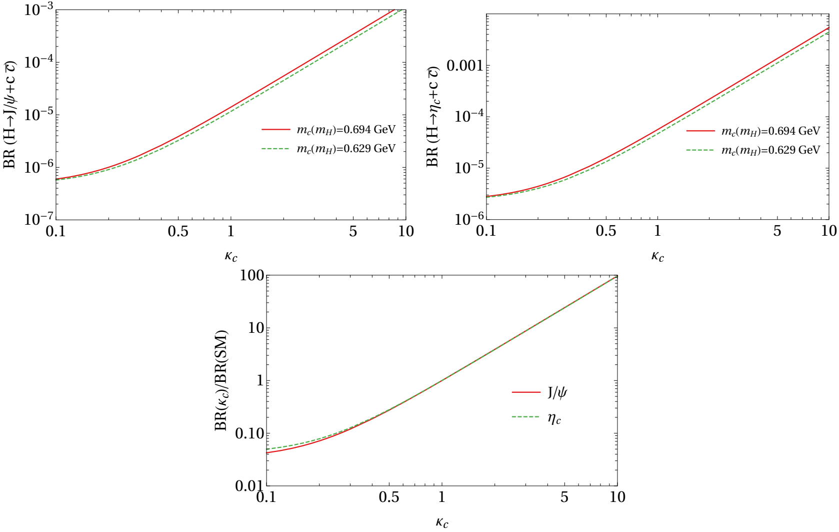
	QCD [CS]	QCD+QED [CS]	Full [CS]	Full [CO]	Full [CS+CO]
$\Gamma(H \to c + \bar{c} + J/\psi)$ (GeV)	4.763×10^{-8}	5.815×10^{-8}	6.059×10^{-8}	2.166×10^{-8}	8.226×10^{-8}
$\text{BR}(H \to c + \bar{c} + J/\psi)$	1.165×10^{-5}	1.423×10^{-5}	1.482×10^{-5}	5.299×10^{-6}	2.012×10^{-5}
$\Gamma(H \to c + \bar{c} + \eta_c)$ (GeV)	4.946×10^{-8}	5.053×10^{-8}	6.255×10^{-8}	1.843×10^{-7}	2.469×10^{-7}
$\text{BR}(H \to c + \bar{c} + \eta_c)$	1.210×10^{-5}	1.236×10^{-5}	1.530×10^{-5}	4.509×10^{-5}	6.039×10^{-5}

Charmonium energy distributions





Probe the $Hc\bar{c}$ coupling



Conclusion

- The Higgs sector is the portal giving access to new physics.
  As the Yukawa couplings of the 3rd generation fermions are precisely tested, next target is to test the SM mass generation mechanism for the 1st/2nd generation fermions.
- For the charm Yukawa determination
  - $pp \to VH(c\bar{c})$, c-tagging is challenging
  - $H \to J/\psi + \gamma$, the rate is too low
- $H \to J/\psi + c + \bar{c}$ is another possible approach.
  - The rate is larger due to the fragmentation mechanism
  - There is color-octet contributions
  - The QED and EW corrections are also considered
  - The SM prediction gives $BR \sim 2 \times 10^{-5}$