Charm and bottom Yukawa couplings via quarkonia production at HL-LHC

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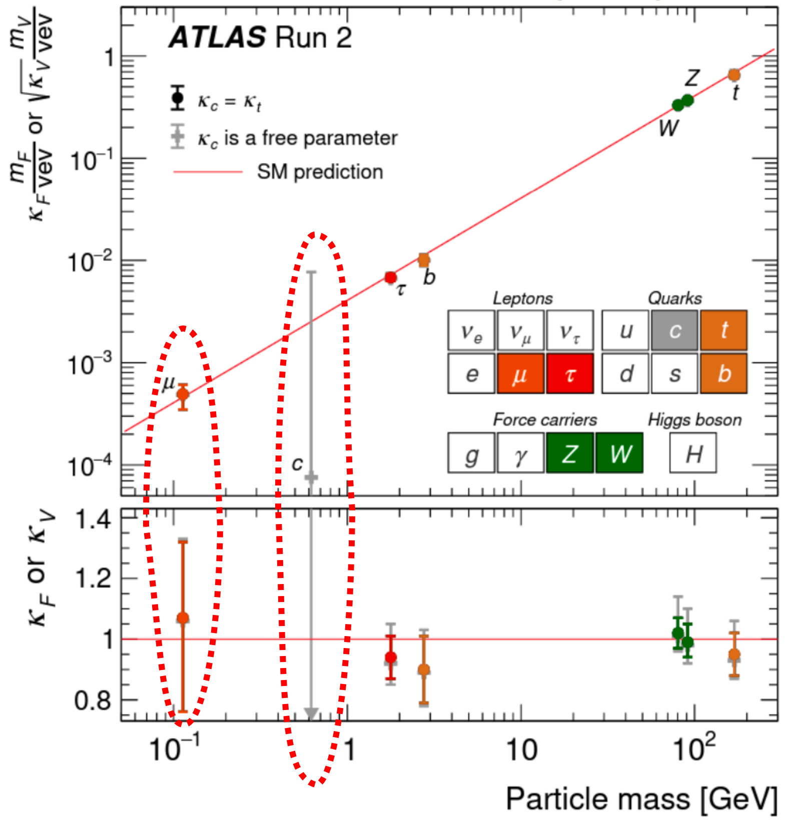
Measure the Higgs couplings

Nature 607 (2022) 52



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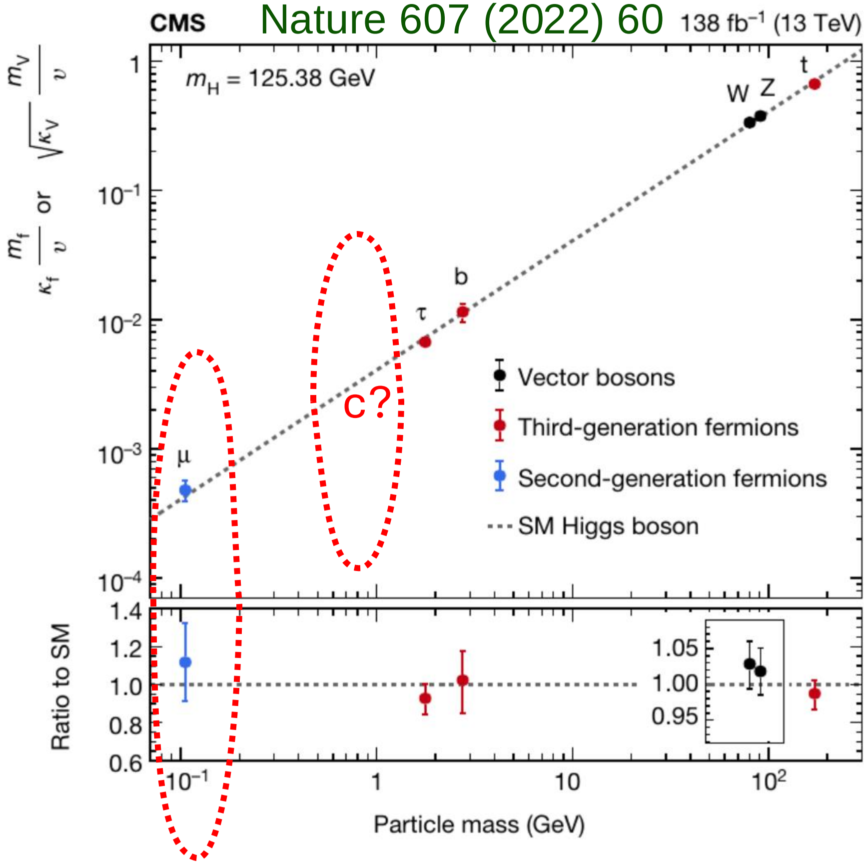


The next target is the 2nd generation fermions: c, s, μ

See my 2nd talk at 3:20pm for Higgs-muon interaction

Measuring the charm quark Yukawa

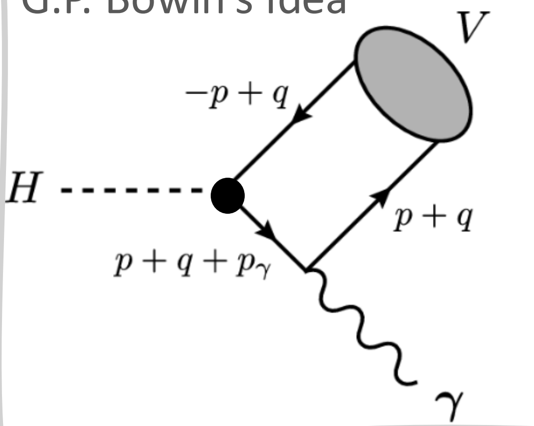
Measuring $Hc\bar{c}$ coupling is not easy

- Small mass $\Rightarrow$ Small branching fraction BR($H \to c\bar{c}$) $\simeq 2.8\%$
- Large QCD background at hadron colliders $\Rightarrow$ Need c-tagging
- c-tagging is challenging

Current experimental searching

- κ framework: For $y_c^{\rm SM} = \sqrt{2}m_c/v$, set $y_c = \kappa_c y_c^{\rm SM}$
- $pp \to VH(c\bar{c})$: Need c-tagging
  - LHC Run 2: ATLAS $\kappa_c \leq 8.5$ [2201.11428], CMS $1.1 < |\kappa_c| < 5.5$ [2205.05550]
  - Future HL-LHC: $\kappa_c \leq 3.$ [2201.11428]
- 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]

G.P. Bowin's idea



Recall the history a bit...

Charmonium used to be the new physics

- **The "Standard Model" in the 1960s:** "up", "down", "strange"
- **November Revolution:** The discovery of J/ψ in 1974 $\Rightarrow$ "charm"
  Richter and Ting explored the new energy regimes, not just to test the GIM mechanism.

Nowadays quarkonium physics

- For over 20 years, we have been working the Standard Model with better precision
- With no doubt, it provides an ideal platform to study the QCD theory
- There may also be chance to see the hint of new physics beyond the Standard Model

and Higgs

Non-relativistic QCD (NRQCD)

Generate a $Q\bar{Q}$ pair and then hadronized it into the bound state (quarkonia)

Separate the physics into two parts

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

- **Short distance coefficient (SDC):**

$$d\hat{\Gamma}_{\mathbb{N}} = \frac{1}{2m_H} \frac{|\mathcal{M}|^2}{\langle \mathcal{O}^{Q\bar{Q}} \rangle} d\Phi_3$$

- **Long distance matrix element (LDME)**

  Related to the wave function at origin

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

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

$${}^{2s+1}L_J^{[\text{color}]}$$

The color-octet LDMEs are suppressed

In higher orders of v

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

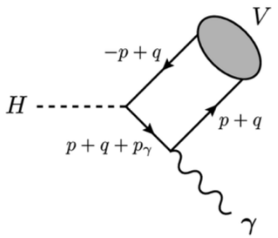
$$\frac{\langle \mathcal{O}^{J/\psi}({}^3P_J^{[8]}) \rangle}{\langle \mathcal{O}^{J/\psi}({}^3S_1^{[1]}) \rangle} \sim \mathcal{O}(v^4), \quad \frac{\langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle}{\langle \mathcal{O}^{\eta_c}({}^1S_0^{[1]}) \rangle} \sim \mathcal{O}(v^3),$$

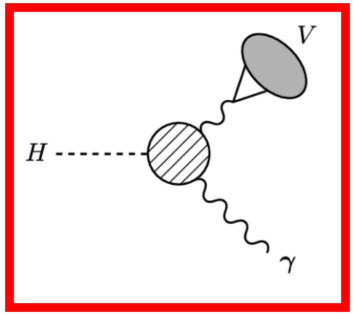
$$\frac{\langle \mathcal{O}^{\eta_c}({}^1P_1^{[8]}) \rangle}{\langle \mathcal{O}^{\eta_c}({}^1S_0^{[1]}) \rangle} \sim \mathcal{O}(v^4)$$

Color-octet can be enhanced by kinematics

Look for a proper process

Why Bodwin's process does not work well?





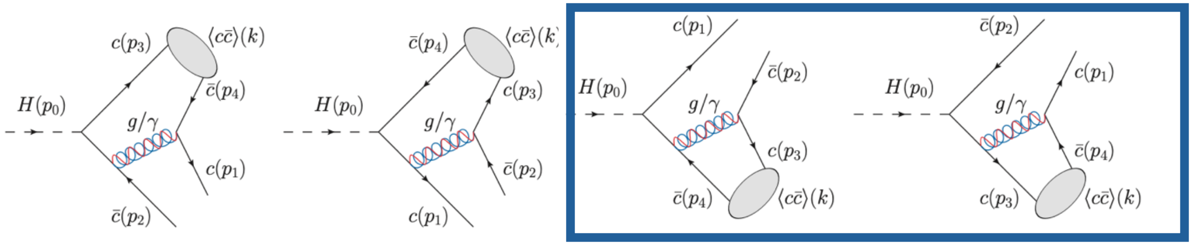
Dominated by "vector meson dominance" (VMD)

$$\Gamma_{H\gamma\gamma^*} \simeq 1.32 \times 10^{-8}\,\text{GeV},$$
$$\Gamma_{\text{SM}} \simeq 1.00 \times 10^{-8}\,\text{GeV}$$

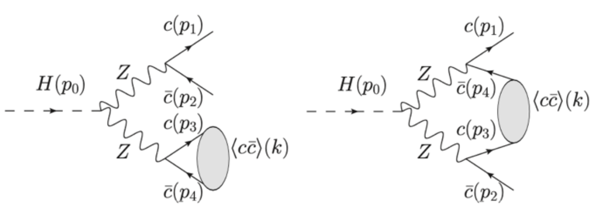
More details to consider:

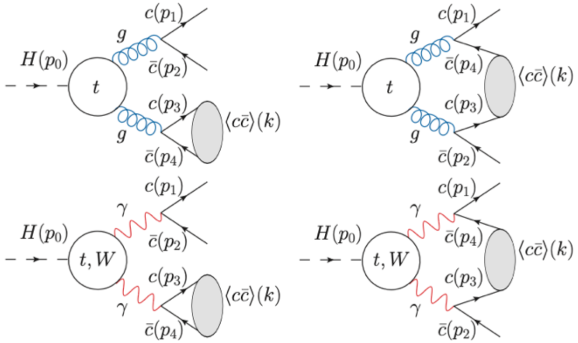
- Apart from Hcc, there are also Hzz, Hgg, and Hγγ diagrams
- Include both color-singlet and color-octet
- Consider both QCD and QED contributions

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



- **Enhanced by charm fragmentation**
- **Hcc diagrams dominate**





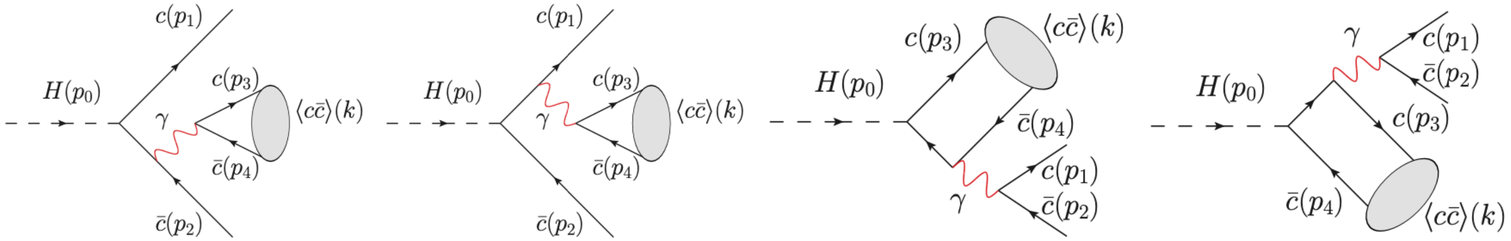
T. Han, A. K. Leibovich, YM and X.-Z. Tan, 2202.08273

More fragmentations

Single photon fragmentation (SPF)

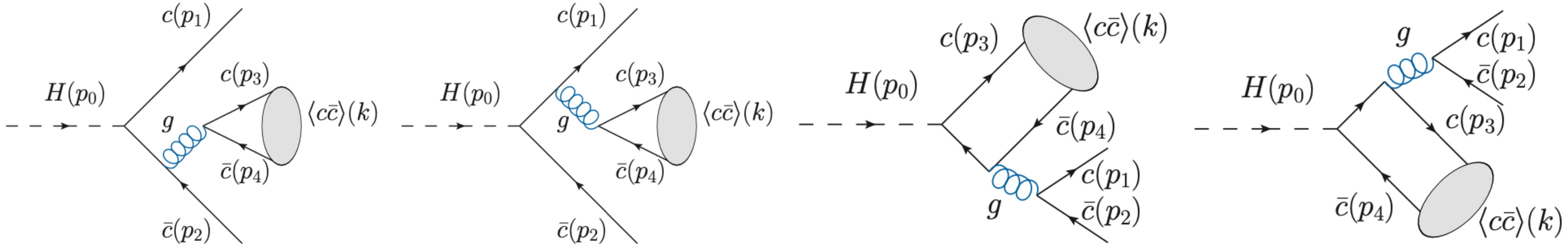
Pure QED diagrams: sizable correction to ${}^3S_1^{[1]}(J/\psi)$ production

Single photon fragmentation (SPF): $1/q^2 = 1/m^2_{J/\psi} \Rightarrow$ **logarithmic enhancement**



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

Single gluon fragmentation (SGF): $1/q^2 = 1/m^2_{J/\psi} \Rightarrow$ **logarithmic enhancement**

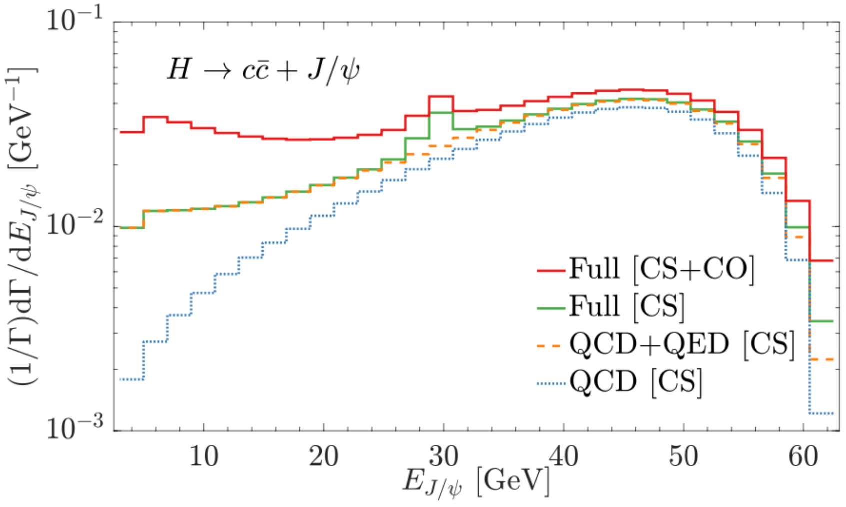


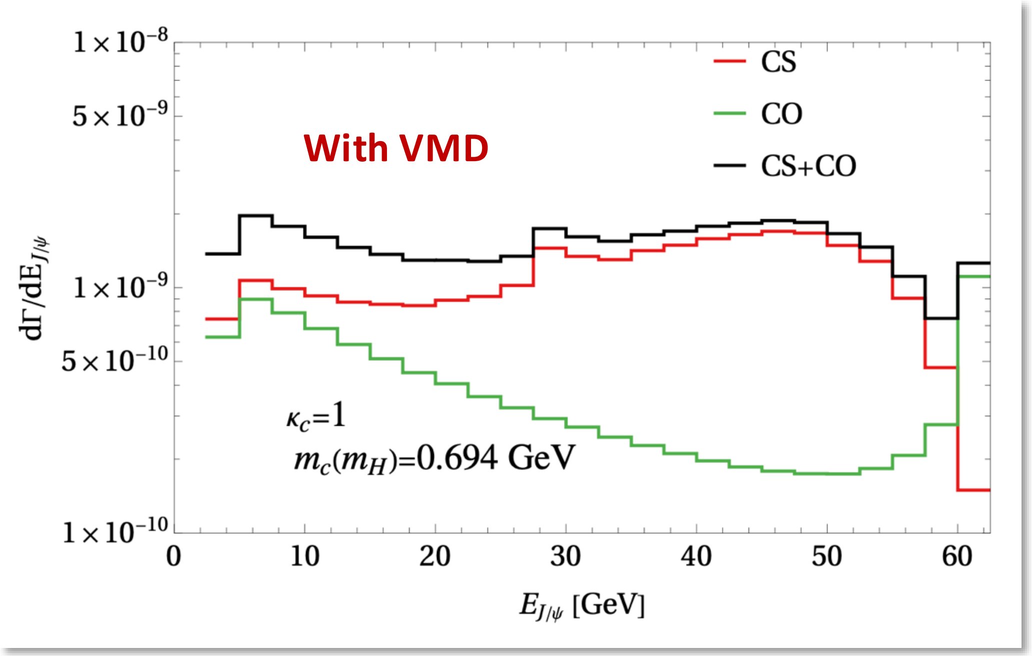
SM Results

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





Who is contributing?

$^{2s+1}L_J^{[\text{color}]}$

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}

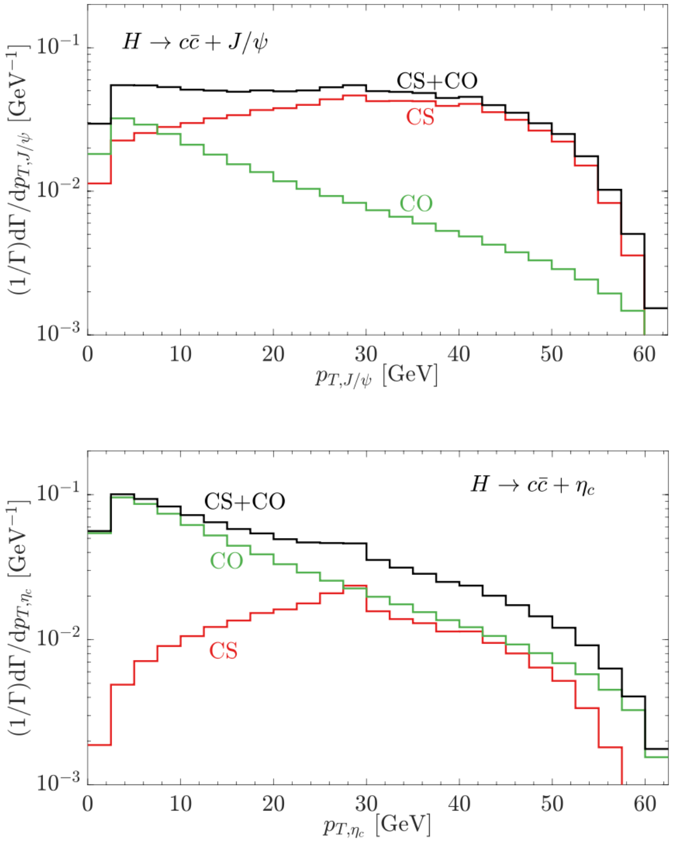
Contributions with respect to QCD

$\hat{\Gamma}_{\mathbb{N}}/\hat{\Gamma}_{\mathbb{N}}^{\mathrm{QCD}}$	$^1S_0^{[1]}$	$^3S_1^{[1]}$	$^1S_0^{[8]}$	$^3S_1^{[8]}$	$^1P_1^{[8]}$	$^3P_0^{[8]}$	$^3P_1^{[8]}$	$^3P_2^{[8]}$
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

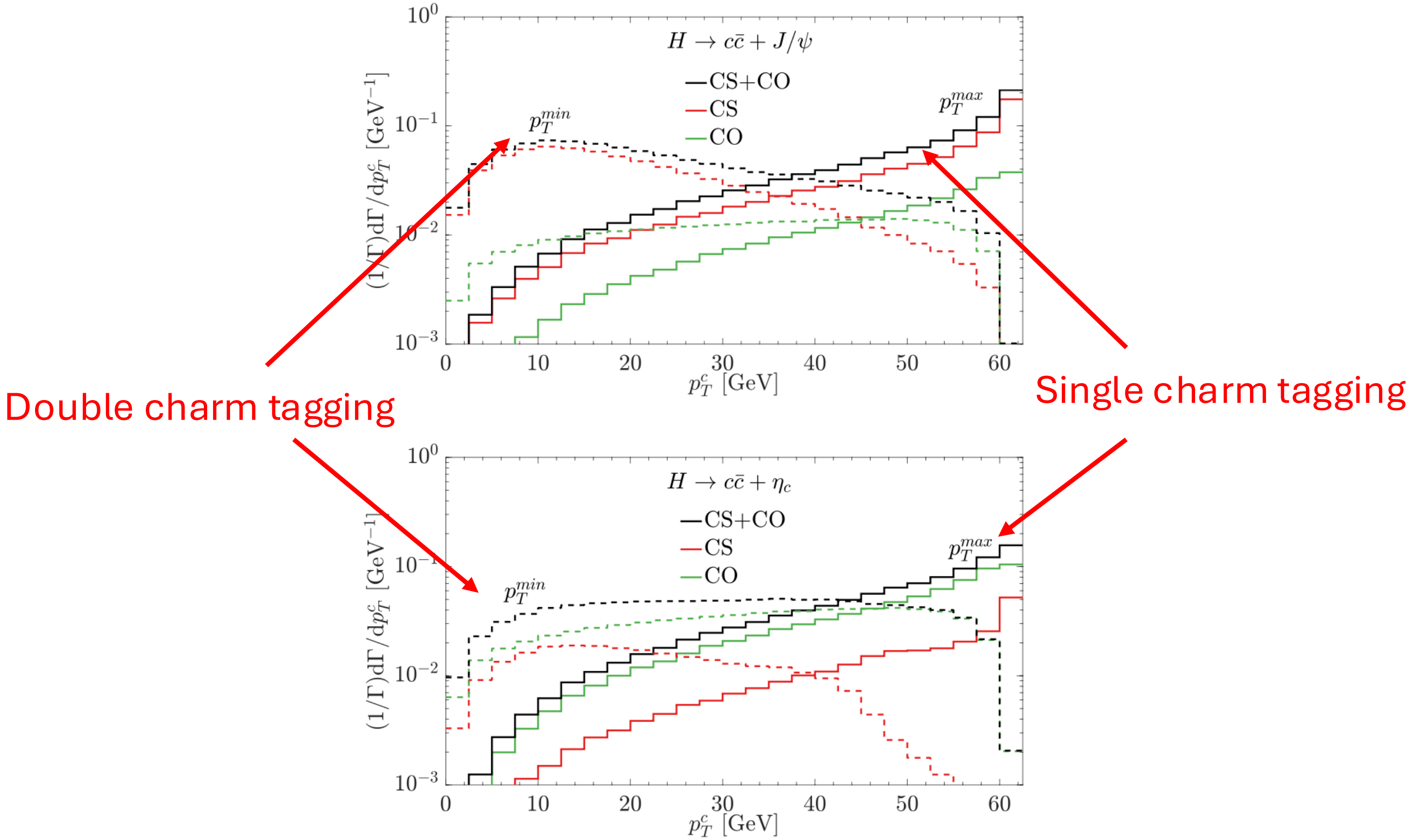
- QCD is dominant in most of the Fock states
- SPF brings sizable QED correction to $^3S_1^{[1]}$, but it is forbidden for $^1S_0^{[1]}$
- SGF makes $^3S_1^{[8]}$ super large
- For $^1S_0^{[8]}$ and $^3P_J^{[8]}$, only quark fragmentation contributions $\Rightarrow$ QED and QCD differ by a constant
- EW correction is large since Z is closed to its mass shell

pT distributions

Charmonium p_T distributions

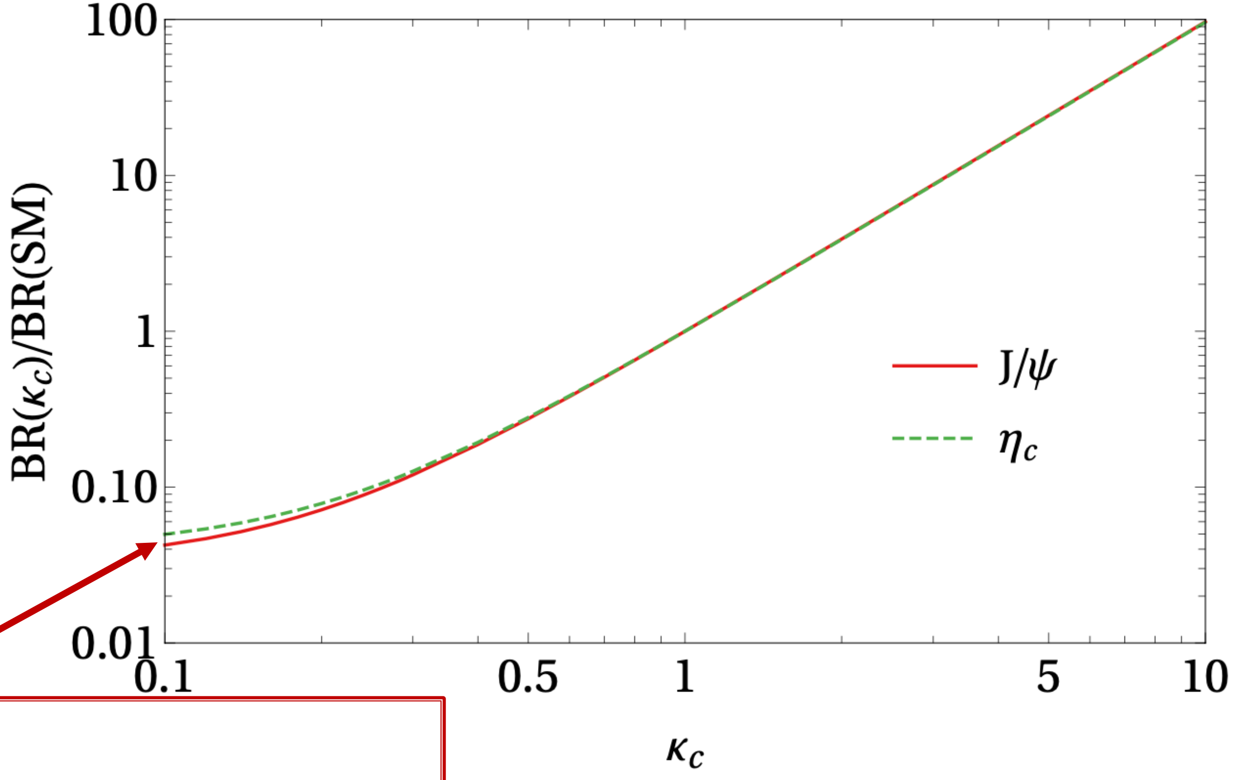


Free charm quark p_T distributions



Probe charm Yukawa with charmonia

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



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

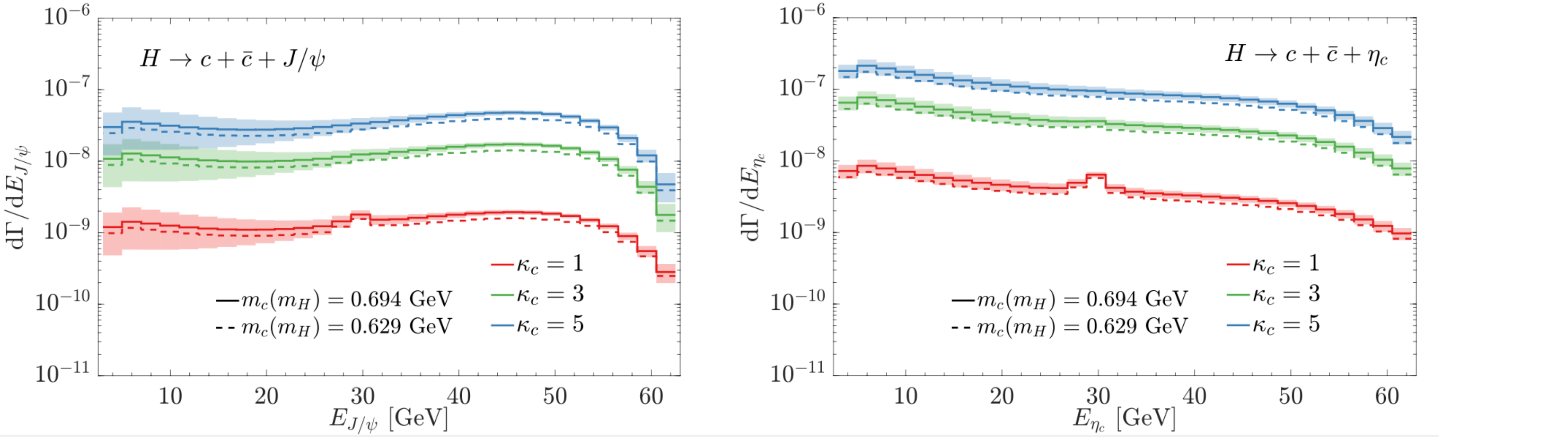
Color-octet uncertainties from the LDMEs

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

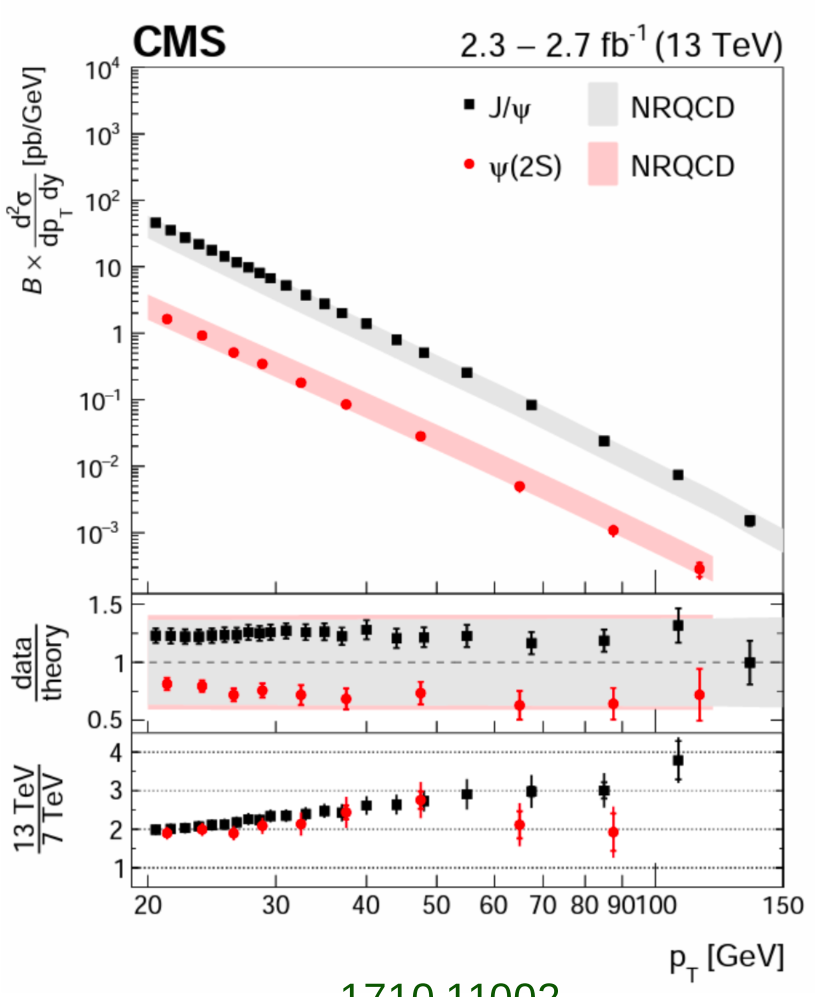
	$^3S_1^{[8]}$	$^1S_0^{[8]}$	$^1P_1^{[8]}$	$^3P_J^{[8]}$	Total
$\Gamma(H \to c\bar{c} + J/\psi)$ (GeV)	2.0×10^{-8}	9.8×10^{-10}	-	2.2×10^{-10}	2.2×10^{-8}
$\mathrm{BR}(H \to c\bar{c} + J/\psi)$	5.0×10^{-6}	2.4×10^{-7}	-	5.3×10^{-8}	5.3×10^{-6}
$\Gamma(H \to c\bar{c} + \eta_c)$ (GeV)	1.8×10^{-7}	3.6×10^{-11}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

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



Background at colliders: $p\ p \to J/\psi$



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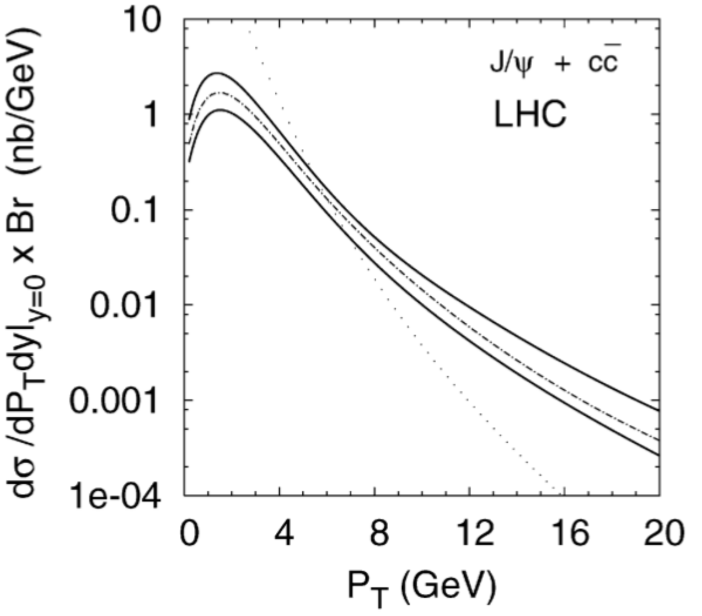


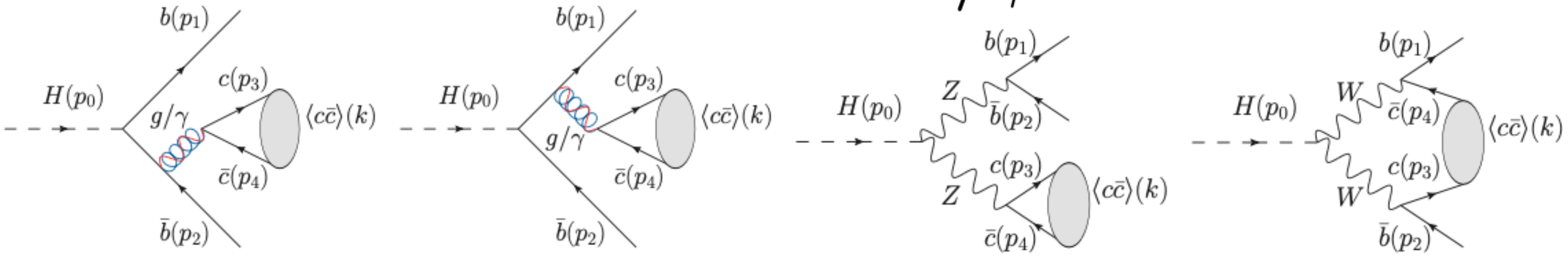
P. Artoisenet, J.P. Lansberg, F. Maltoni, NPB 653, 60-66

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

Background from other channels

Color-octet contribution dominates

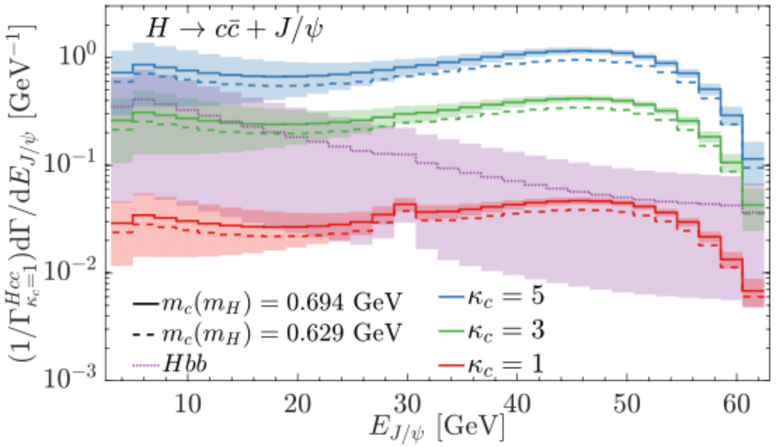
$$H \to J/\psi + b\bar{b}$$

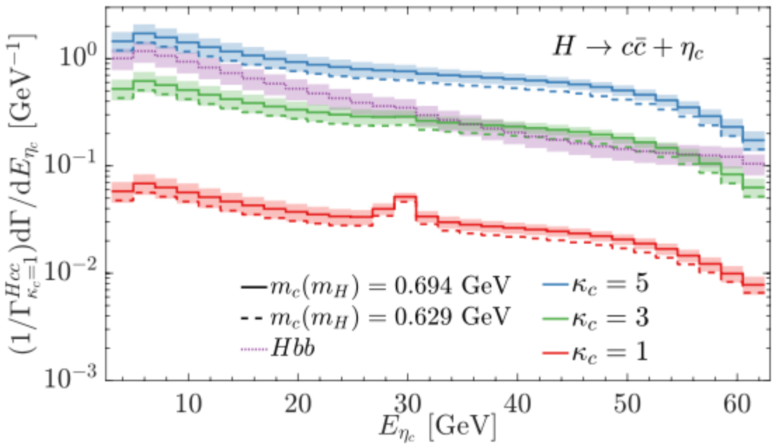


This can be the signal for Bottom quark Yukawa

Charmonium energy distributions

Take the color-octet LDME uncertainty for error estimation





A rough estimate

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

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

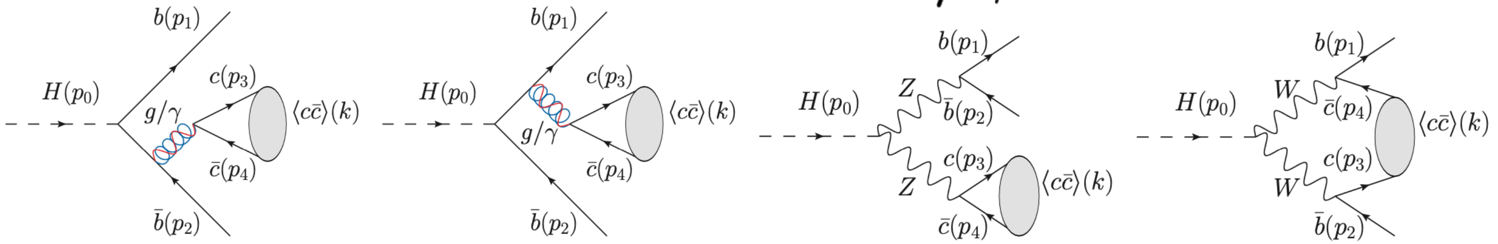
- Sensitivity $S \simeq N_{\mathrm{signal}}/\sqrt{N_{\mathrm{Background}}}$
  $\Rightarrow$ It is possible to reach 2σ for $\kappa_c \approx 2.4$.
- systematic effect $N_{\mathrm{signal}}/N_{\mathrm{Background}} = 2\%$ for $\kappa_c \approx 2.4$.

I shall admit that we are too optimistic on the results...

For bottom Yukawa

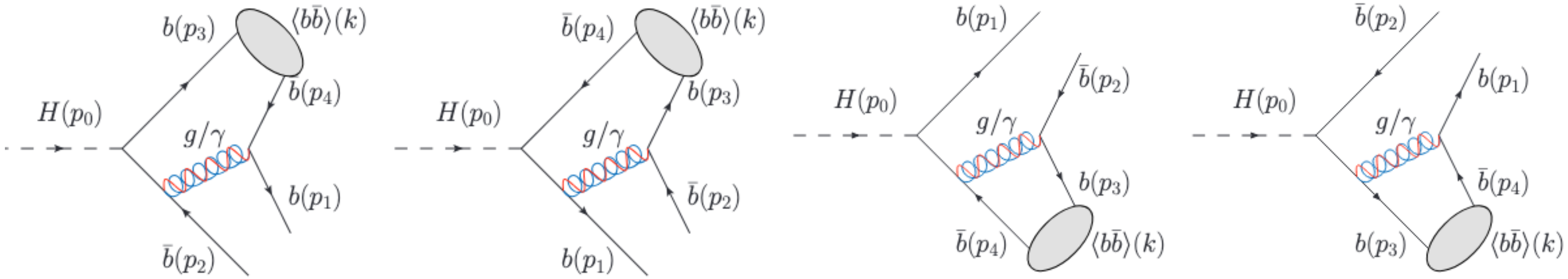
Two channels:

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



Dominated by CO

$$H \to \Upsilon + b\bar{b}$$



Similar to the charm case

T. Han, YM and X.-Z. Tan, coming out soon

Summary

There are chances to measure the Yukawa couplings via quarkonia production

- Benefit from the clean J/ψ and Υ decay
- In NRQCD frame, these processes are perturbatively calculable
- The QCD contribution dominates, but there is also something else

QED, HZZ, VMD

Concerns and the wishlist:

- May not be able to bypass c tagging
- May suffer from the QCD hadron production background
- May receive corrections from higher orders
- Call for the better LDME fitting

Backup: fragmentation functions

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

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

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

Fragmentation functions

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

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

Backup: HEFT for the Yukawa sector

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

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

Define $U(x) \equiv \exp(i\sigma_a \pi^a(x)/v)$, so that the Lagrangian contains

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

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.

More about the final state