Higgs decay to charmonia and the charm-quark Yukawa coupling

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A lot of particle physics is missing in the Standard Model

- Why Electroweak Symmetry Breaking occurs?
  What is the history of the Electroweak Phase Transition?
- The reason for the Hierarchy in Fermion Masses and their Flavor Structure
- The Nature of Dark Matter
- The origin of the Matter-Antimatter Asymmetry
- The generation of Neutrino Masses
- The cause of the Universe's accelerated expansion - Dark Energy
- What are the quantum properties of Gravity?
- What caused Cosmic Inflation after the Big Bang?

The SM is silent about all above, BSM physics is at the core of it all

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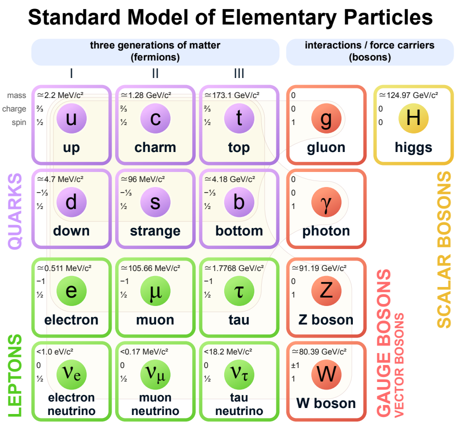
Why Higgs?

A well understood and well tested model

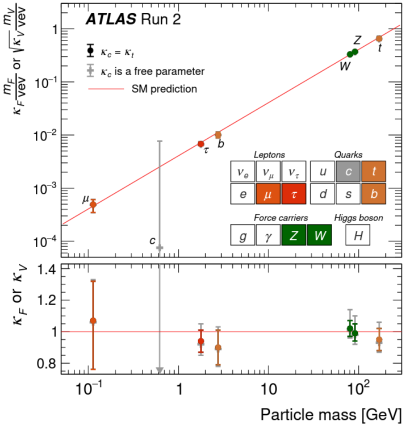


- Model doesn't make sense without Higgs or something like it
- The Higgs is a scalar particle whose interactions with other particles are predicted in terms of the Higgs mass
- It provides masses to all other elementary particles

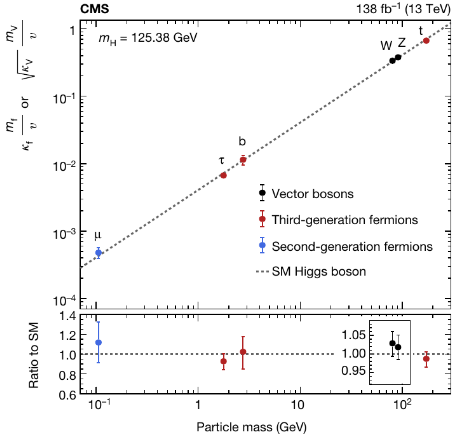
Higgs physics: A portal to new physics

- LHC has gone from discovery to precision
- A telescope to high scale physics
- Interplay of theory and experiment is important

Measure the Higgs couplings



[Nature 607 (2022) 52]



[Nature 607 (2022) 60]

Higgs to light fermion couplings are to be measured $\Rightarrow$ The next task is charm quark

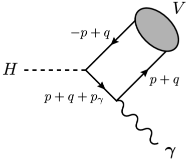
Measure the Charm-Higgs coupling: current status

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 $y_c^{\mathrm{SM}} = \sqrt{2}m_c/v$, set $y_c = \kappa_c y_c^{\mathrm{SM}}$
- $pp \to VH(c\bar{c})$: Need c-tagging
  - LHC Run 2: ATLAS $\kappa_c \leq 8.5$ [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]



Higgs decay to charmonia in Non-relativistic QCD (NRQCD)

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):**

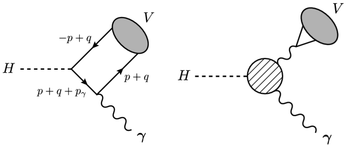
$$d\hat{\Gamma}_{\mathbb{N}} = \frac{1}{2m_H} \frac{|\mathcal{M}|^2}{\langle \mathcal{O}^{Q\bar{Q}} \rangle} d\Phi_3$$

- **Long distance matrix element (LDME)**
  Related to the wave function at origin

$$\langle \mathcal{O}^{J/\psi}[^3S_1^{[1]}] \rangle = \frac{3N_c}{2\pi}|R(0)|^2, \ \langle \mathcal{O}^{\eta_c}[^1S_0^{[1]}] \rangle = \frac{N_c}{2\pi}|R(0)|^2,$$
$$\langle \mathcal{O}^{Q\bar{Q}} \rangle = 6N_c, \text{ for } {}^3S_1^{[1]}, \ \langle \mathcal{O}^{Q\bar{Q}} \rangle = 2N_c, \text{ for } {}^1S_0^{[1]}$$

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,
  $\Gamma_{\text{SM}} \simeq 1.00 \times 10^{-8}$ GeV [1306.5770, 1407.6695]

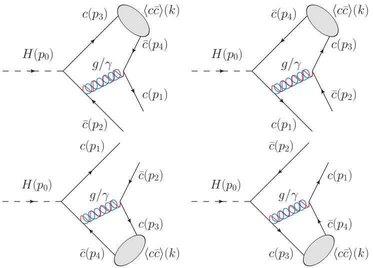


Our idea: Look for a process with higher rate

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

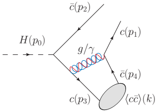
Main contribution (Color-singlet):

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

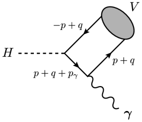


[T.Han, A.Leibovich, YM, and X.Tan, 2202.08273]

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



VS



- Enhancement from the quark fragmentation $\Rightarrow$ **Larger rate**
- The $Hc\bar{c}$ channel dominates $\Rightarrow$ **More sensitive to κ_c**

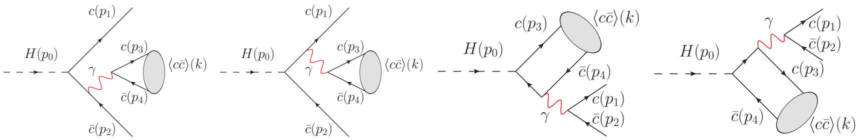
More to calculate

- Corrections from QED and EW
- The color-octet mechanism

More corrections from QED and EW sector

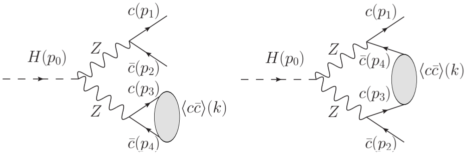
Pure QED diagrams: sizable correction to $^3S_1^{[1]}(J/\psi)$ production

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



Electroweak correction from the HZZ diagrams

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



- Sizable for $^1S_0^{[1]}(\eta_c)$ due to the larger axial $Zc\bar{c}$ coupling.

Charmonium productiuon via color octet states

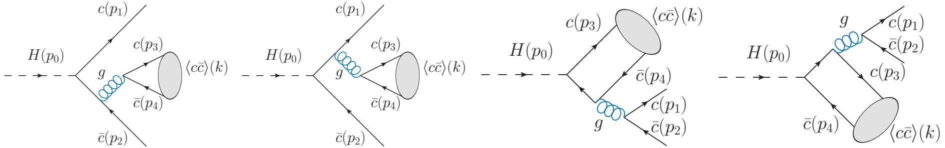
A key property of NRQCD

- 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 $\langle \mathcal{O}^h[{}^{2S+1}L_J^{[\text{color}]}]\rangle$ need to be fitted from experimental data

Reference	$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}]\rangle$	$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{[8]}]\rangle$	$\langle \mathcal{O}^{J/\psi}[{}^3P_0^{[8]}]\rangle/m_c^2$
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 ${}^3S_1^{[8]}$

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



Color-singlet VS color-octet: Why is color-octet sizable

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

The color-octet LDMEs are suppressed

In higher orders of v

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

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

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

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 appear new diagrams:
  The SGF diagrams result in large ${}^3S_1^{[8]}$ SDC ⇒ **Sizable color-octet contribution (mainly from ${}^3S_1^{[8]}$)**

Standard Model results (I): The overall picture

Numerical parameters

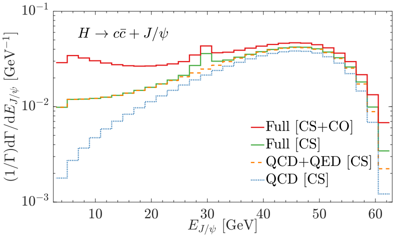
$$\alpha = 1/132.5,\ \alpha_s(2m_c) = 0.235,\ m_c^{\text{pole}} = 1.5\,\text{GeV},\ m_c(m_H) = 0.694\,\text{GeV},\ m_H = 125\,\text{GeV},$$

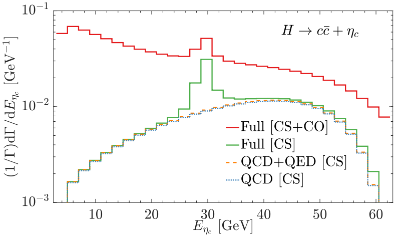
$$m_W = 80.419\,\text{GeV},\ m_Z = 91.188\,\text{GeV},\ v = 246.22\,\text{GeV},\ y_c^{\text{SM}} = \frac{\sqrt{2}m_c(m_H)}{v} \approx 3.986\times10^{-3}.$$

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): Who is contributing?

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}

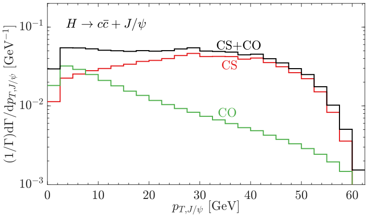
Contributions with respect to QCD

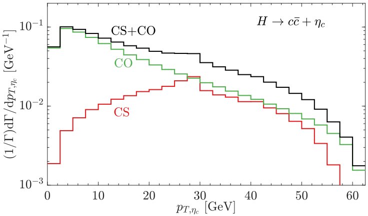
$\hat{\Gamma}_{\mathbb{N}}/\hat{\Gamma}_{\mathbb{N}}^{\mathrm{QCD}}$	${}^1S_0^{[1]}$	${}^3S_1^{[1]}$	${}^1S_0^{[8]}$	${}^3S_1^{[8]}$	${}^1P_1^{[8]}$	${}^3P_0^{[8]}$	${}^3P_1^{[8]}$	${}^3P_2^{[8]}$
QCD	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
QED	1.1×10^{-4}	0.077	0.0073	1.1×10^{-5}	0.0068	0.0073	0.0073	0.0073
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

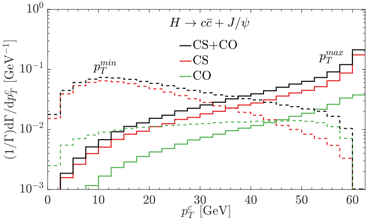
Standard Model results (III): Transverse momentum (p_T) distributions

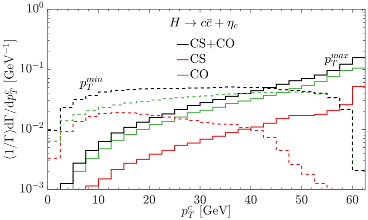
Charmonium p_T distributions





Free charm quark p_T distributions



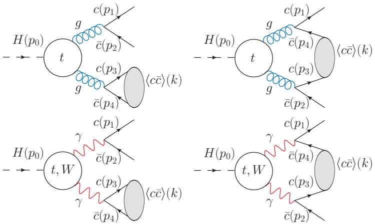


Worry about VMD ?

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

- Larger decay rate: $\mathrm{BR} \simeq 2 \times 10^{-5}$
- Sensitive to $Hc\bar{c}$ coupling: QCD dominates
- Other diagrams

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



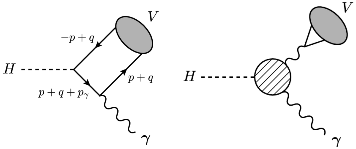
$\mathrm{BR}(g^* g^*) \sim 2.5 \times 10^{-6}$, $\mathrm{BR}(\gamma^* \gamma^*) < 2 \times 10^{-7}$

• No need to worry about VMD

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

- Small decay rate: $\mathrm{BR} \simeq 2.8 \times 10^{-6}$
- Insensitive to $Hc\bar{c}$ coupling
  $\Rightarrow \kappa_c \lesssim 100$

VMD dominates



• $\gamma^* \to J/\psi$ dominates over $Hc\bar{c}$

Two orders of magnitude larger.

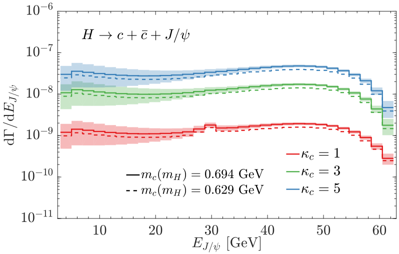
Color-octet uncertainties from the LDMEs

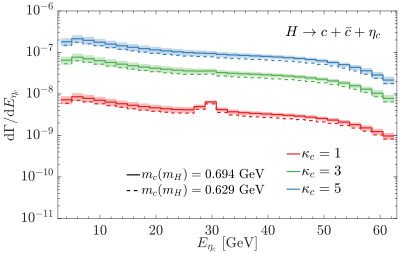
Color-octet contributions: ${}^3S_1^{[8]}$ dominates

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

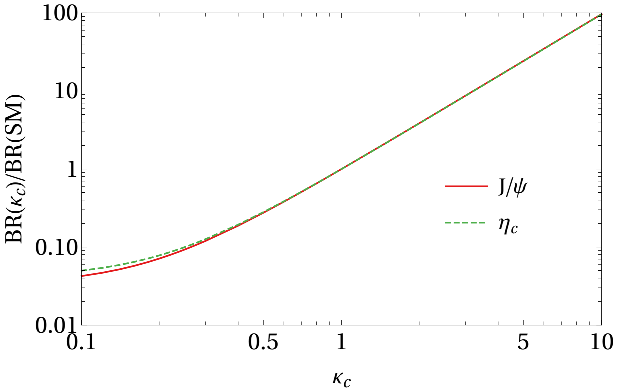
$$\mathrm{BR}(H \to c\bar{c} + J/\psi) = (2.0 \pm 0.5) \times 10^{-5}, \quad \mathrm{BR}(H \to c\bar{c} + \eta_c) = (6.0 \pm 1.0) \times 10^{-5}.$$





Probe the $Hc\bar{c}$ coupling

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



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

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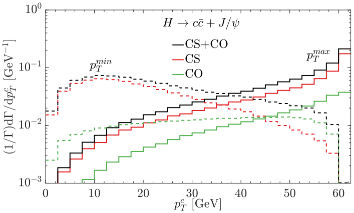
Some rough analysis

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

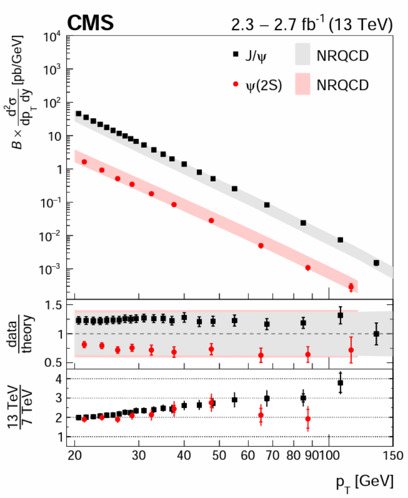
$$\Delta\kappa_c \approx 15\% \times \left(\frac{L}{\text{ab}^{-1}} \times \frac{\epsilon}{10\%}\right)^{-1/2}$$



Detection efficiency ϵ:

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

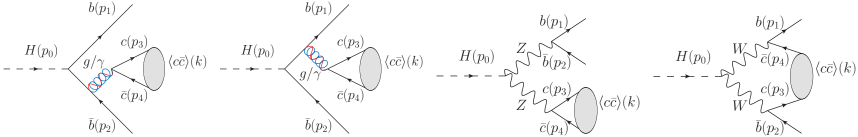
Background from $pp \to J/\psi + X$



- 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.

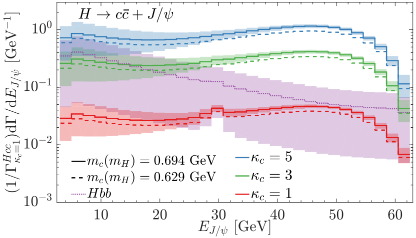
Background from $H \to J/\psi + b\bar{b}$

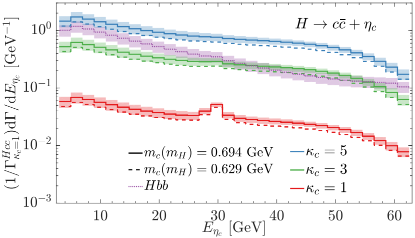
Color-octet contribution dominates



Charmonium energy distributions

Take the color-octet LDME uncertainty for error estimation





More realistic discussions

- **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 $\epsilon \sim 10\%$
  - 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 $\kappa_c \approx 2.4$.

Summary and prospects

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.

New approach to determine the Charm-Higgs coupling: $H \rightarrow J/\psi + c\bar{c}$

- 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 …

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