Higgs decay to quarkonia and the Yukawa couplings

Yang Ma

INFN Bologna

November 28, 2023

Higgs 2023, IHEP

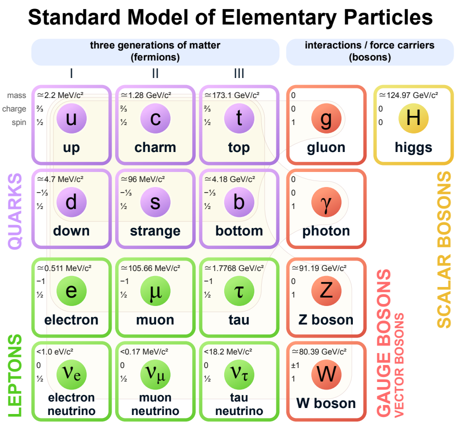
INFN Istituto Nazionale di Fisica Nucleare

Theory and Phenomenology of Fundamental Interactions

UNIVERSITY AND INFN · BOLOGNA

Why Higgs?

A well understood and well tested model

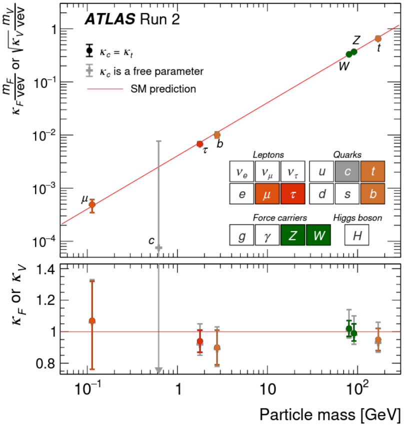


- Model doesn't make sense without Higgs or something like it
- The Higgs is a scalar particle whose interactions with other particles are predicted in terms of the Higgs mass
- It provides masses to all other elementary particles

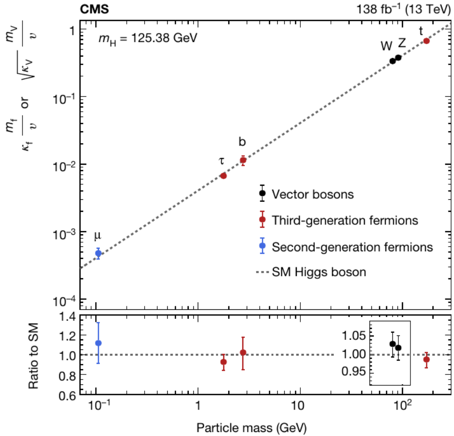
Higgs physics: A portal to new physics

- 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 the 2nd generation

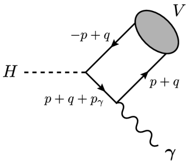
Measure the Charm-Higgs coupling: current status

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]



Quarkonia: From the Standard Model to beyond

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

Non-relativistic QCD (NRQCD) framework

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)**

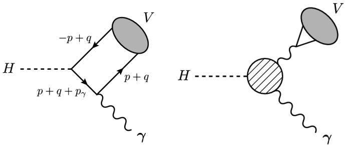
  Related to the wave function at origin

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

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

$$\Gamma_{H\gamma\gamma^*} \simeq 1.32 \times 10^{-8}\,\mathrm{GeV},$$
$$\Gamma_{\mathrm{SM}} \simeq 1.00 \times 10^{-8}\,\mathrm{GeV}$$ [1306.5770, 1407.6695]



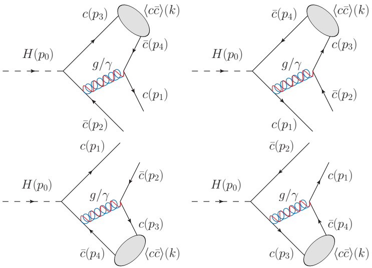
Our idea: Look for a process with higher rate

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

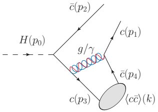
Main contribution (Color-singlet):

Charm quark fragmentation to charmonia:

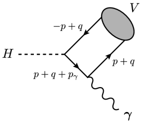
${}^3S_1^{[1]}(J/\psi)$ and ${}^1S_0^{[1]}(\eta_c)$



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

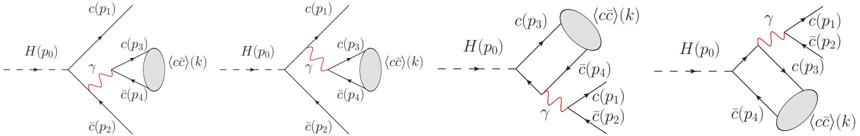
- Corrections from QED and EW
- The color-octet mechanism

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

More corrections from QED and EW sector

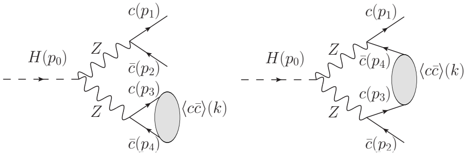
Pure QED diagrams: sizable correction to ${}^3S_1^{[1]}(J/\psi)$ production

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

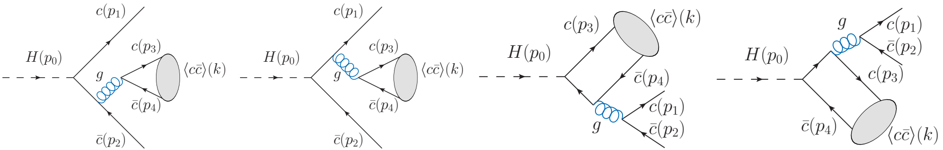
A key property of NRQCD

- 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**



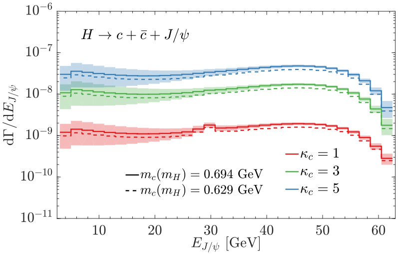
Standard Model predictions

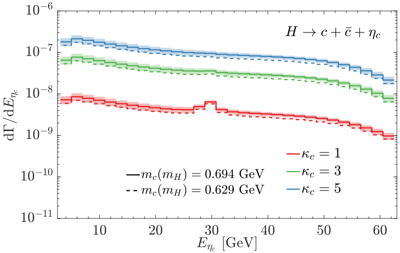
Color-octet contributions: $^3S_1^{[8]}$ dominates

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

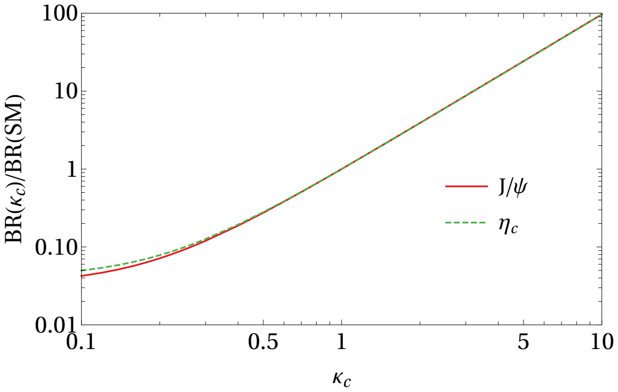
$$\mathrm{BR}(H \to c\bar{c} + J/\psi) = (2.0 \pm 0.5) \times 10^{-5}, \quad \mathrm{BR}(H \to c\bar{c} + \eta_c) = (6.0 \pm 1.0) \times 10^{-5}.$$





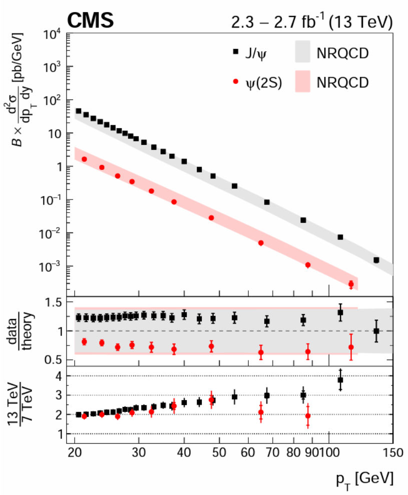
Probe the $Hc\bar{c}$ coupling

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

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.

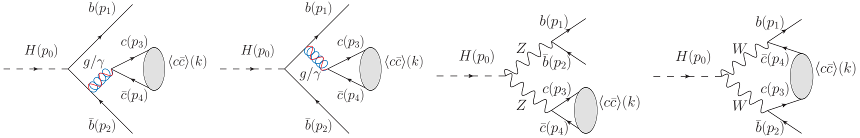
- Estimate 75000 events for $pp \to J/\psi + c\bar{c}$ at a $3\,\mathrm{ab}^{-1}$ HL-LHC

  Corresponding to a $25\,\mathrm{fb}$ cross section

  Some kinematic cut may help.

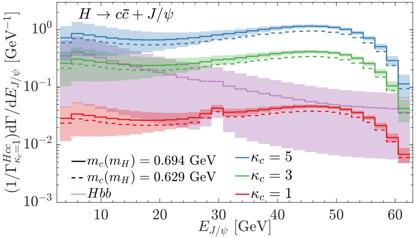
Background from $H \to J/\psi + b\bar{b}$

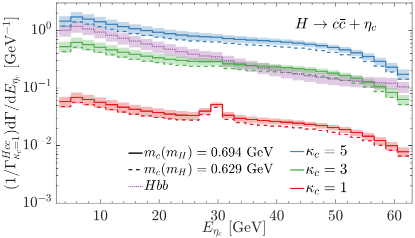
Color-octet contribution dominates



Charmonium energy distributions

Take the color-octet LDME uncertainty for error estimation





Some rough discussions

- $\mathrm{BR}(J/\psi \to \ell^+\ell^-) \sim 12\%, \mathrm{BR}(H \to J/\psi + c\bar{c}) \sim 2 \times 10^{-5}$
- Higgs production cross section at LHC $\sigma_H \sim 50$ pb, HL-LHC luminosity $L \sim 3\,\mathrm{ab}^{-1}$
- Assume the detection efficiency $\epsilon \sim 10\%$
- The signal event number is given by

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

- Assume 10,000 background events after the election cuts at the HL-LHC
- 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 $\kappa_c \approx 2.4$.

INFN
Istituto Nazionale di Fisica Nucleare

The bottom quark case

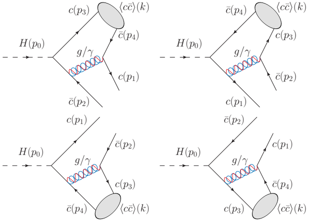
- New processes could verify the bottom quark Yukawa coupling measurements
- Learn lessons for the charm quark case

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

• Replace c by b in $H \to J/\psi + c\bar{c}$

Charm quark fragmentation

$$BR \sim BR(H \to J/\psi + c\bar{c})$$

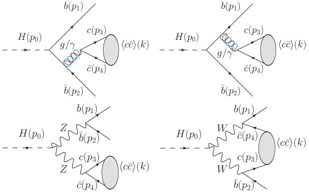


$$H \to J/\psi + b\bar{b}$$

• The $Hb\bar{b}$ background in the $Hc\bar{c}$ case

Color-octet dominates

$$BR \sim 4BR(H \to J/\psi + c\bar{c})$$



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
  $\Rightarrow$ The 2nd generation is the next target.

There is chance to look at the Yukawa couplings from quarkonia production processes

- Benefit from the clean decay of J/ψ or Υ $\Rightarrow$ Look for processes with higher rate
- In the NRQCD framework, these processes are perturbatively calculable
- The QCD channel dominates, but there is also QED (SPF) and EW (HZZ or $Ht\bar{t}$)
- For the $H \to J/\psi + c\bar{c} \Rightarrow 2\sigma$ for $\kappa_c \simeq 2.4$
  - The SM prediction gives $BR \sim 2 \times 10^{-5}$
  - Assume a $3\,\mathrm{ab}^{-1}$ HL-LHC, a 10% detection efficiency, and $10,000$ background events

More work in progress:

- Background analysis, detector/systematic effects
- Better LDMEs fittings, higher order calculations/resummation . . .

Numerical parameters

Standard Model parameters

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

Choose the color-octet LDMEs

- Different fitting strategies lead to different LDME values.

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,	$(5.66\pm 4.7)\times 10^{-2}$	$(1.77\pm 0.58)\times 10^{-3}$	$(3.42\pm 1.02)\times 10^{-3}$

- We take Bodwin's LDME fitting from CMS and CDF high p_T data.
- Use heavy quark spin symmetry (HQSS) to obtain the LDMEs for η_c

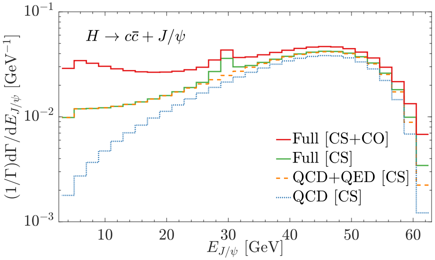
$$\langle \mathcal{O}^{\eta_c}[^1S_0^{[1,8]}]\rangle = \frac{1}{3}\langle \mathcal{O}^{J/\psi}[^3S_1^{[1,8]}]\rangle,\ \langle \mathcal{O}^{\eta_c}[^3S_1^{[8]}]\rangle = \langle \mathcal{O}^{J/\psi}[^1S_0^{[8]}]\rangle,\ \langle \mathcal{O}^{\eta_c}[^1P_1^{[8]}]\rangle = 3\langle \mathcal{O}^{J/\psi}[^3P_0^{[8]}]\rangle,$$

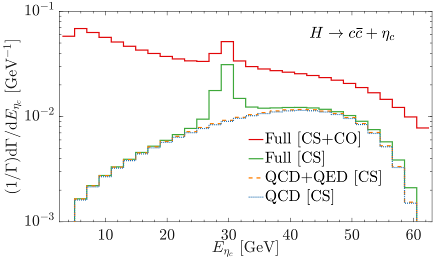
Standard Model results (I): The overall picture

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



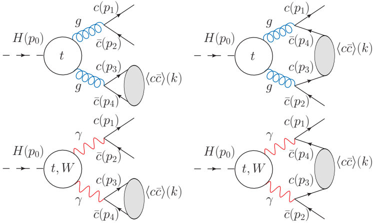


Worry about VMD ?

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

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

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



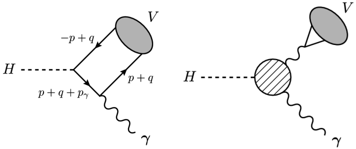
$\mathrm{BR}(g^*g^*) \sim 2.5 \times 10^{-6}$, $\mathrm{BR}(\gamma^*\gamma^*) < 2 \times 10^{-7}$

• 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



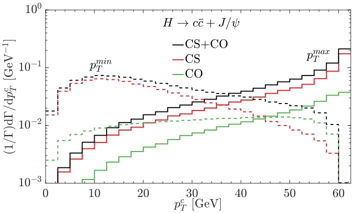
• $\gamma^* \to J/\psi$ dominates over $Hc\bar{c}$

Two orders of magnitude larger.

Some rough analysis (assume no background)

- 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

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

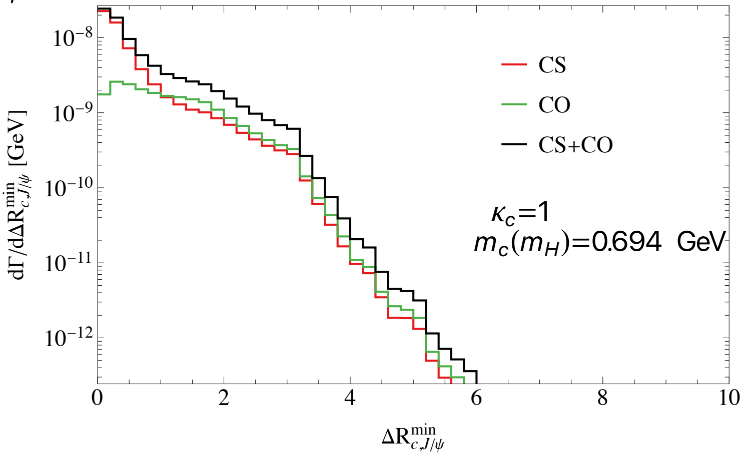


Detection efficiency ϵ:

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

More about the final state

$$H \to c\bar{c} + \mu^+\mu^-$$



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:

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

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

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

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

INFN Istituto Nazionale di Fisica Nucleare

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

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

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

Fragmentation functions

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

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

INFN Istituto Nazionale di Fisica Nucleare