Order v^4 corrections to $H \to J/\psi + \gamma$

N. Brambilla, H. S. Chung, W. K. Lai, V. Shtabovenko and A. Vairo
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Light-Cone Distribution Amplitudes of Hadrons in QCD and their Applications

Mainz Institute for Theoretical Physics
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Outline

- Motivation: probing Higgs-charm coupling via $H \to J/\psi + \gamma$

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- Summary and Outlook

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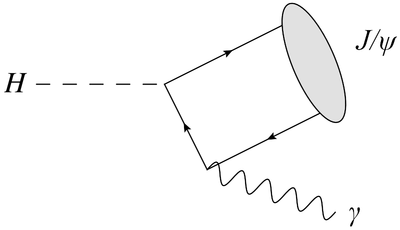
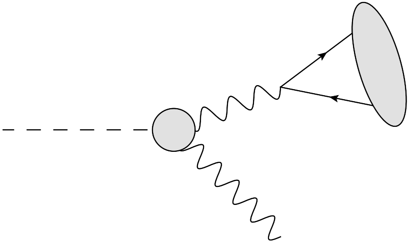
    Advantage: large rate
    Disadvantage: c-tagging challenging, sign of coupling degenerate
  - Exclusive observable: $H \to J/\psi + \gamma$
    Advantage: clean signal ($J/\psi \to l^+ l^-$), sensitive to both magnitude and sign of coupling
    Disadvantage: small rate

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

Direct amplitude:

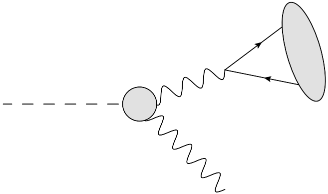


Indirect amplitude:



- $J/\psi \to l^+l^-$ gives clear final states.
- Direct amplitude $\mathcal{M}_{\rm dir}$: proportional to y_c
  Indirect amplitude $\mathcal{M}_{\rm ind}$: independent of y_c
  $\Gamma(H \to J/\psi + \gamma) \sim |\kappa_c \mathcal{M}_{\rm dir} + \mathcal{M}_{\rm ind}|^2$, sensitive to both the magnitude and sign of κ_c.

Indirect amplitude

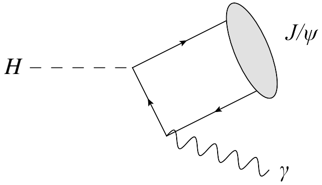


- $\mathcal{M}_{\text{ind}} \sim \mathcal{M}(H \to \gamma\gamma) \times f_V^{\parallel}$, where $f_V^{\parallel} = -\frac{1}{m_V}\langle V|\bar{Q}\not{\epsilon}Q|0\rangle$, $V = J/\psi$.
- $\mathcal{M}(H \to \gamma\gamma)$ was computed with 1% uncertainty.

  Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables [arXiv:1101.0593 [hep-ph]]
- $f_V^{\parallel}$ was measured precisely in $J/\psi \to l^+l^-$ (uncertainty $< 3\%$).

  M. Tanabashi et al. (Particle Data Group), PRD98 (2018) 030001
- $\mathcal{M}_{\text{ind}}$ can be computed with uncertainty $< 2\%$.

Direct amplitude



- NRQCD factorization (utilize $m \equiv m_Q \gg mv$):

$$i\mathcal{M}_{\rm dir} = \sum_n \frac{c_n}{m^{d_n-3}} \langle V|O_n|0\rangle$$

- $\mathcal{O}(v^0)$ in NRQCD, LL resummation:
  Bodwin, Petriello, Stoynev, Velasco, PRD88 (2013) 053003
- $\mathcal{O}(v^2)$ in NRQCD, NLL resummation:
  Bodwin, Chung, Ee, Lee, Petriello, PRD90 (2014) 113010
  M. König and M. Neubert, JHEP 1508, 012 (2015)
  Bodwin, Chung, Ee, Lee, PRD95 (2017) 054018, PRD96 (2017) 116014
- $\mathcal{O}(v^4)$ in NRQCD, NLL resummation:
  Brambilla, Chung, **WKL**, Shtabovenko, Vairo, PRD100 (2019) 054038

$H \to J/\psi + \gamma$ TO $\mathcal{O}(v^4)$

To relative order v^4,

$$i\mathcal{M}_{\rm dir} = \phi_0 \left(c_0 + c_{\mathbf{D}^2}\langle v_S^2\rangle + c_{\mathbf{D}^4}\langle v_S^4\rangle + c_{\mathbf{D}^{(i}\mathbf{D}^{j)}}\langle v_D^2\rangle + c_B\langle B\rangle + c_{DE_0}\langle DE_0\rangle \right.$$
$$\left. + c_{DE_1}\langle DE_1\rangle\right)$$

We use conservative power counting from Brambilla, Mereghetti, Vairo, JHEP 0608, 039 (2006), PRD79 (2009) 074002.

LDME (abbrev.)	LDME	relative order
ϕ_0	$\langle V\vert\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\chi\vert 0\rangle$	1
$\langle v_S^2\rangle$	$\frac{1}{m^2\phi_0}\langle V\vert\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(-\frac{i}{2}\overleftrightarrow{\mathbf{D}})^2\chi\vert 0\rangle$	v^2
$\langle B\rangle$	$\frac{1}{m^2\phi_0}\langle V\vert\psi^\dagger g\mathbf{B}\cdot\boldsymbol{\epsilon}\chi\vert 0\rangle$	v^3
$\langle v_S^4\rangle$	$\frac{1}{m^4\phi_0}\langle V\vert\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(-\frac{i}{2}\overleftrightarrow{\mathbf{D}})^4\chi\vert 0\rangle$	v^4
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$\langle DE_0\rangle$	$\frac{1}{m^3\phi_0}\langle V\vert\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}\frac{1}{3}(\overleftrightarrow{\mathbf{D}}\cdot g\mathbf{E}+g\mathbf{E}\cdot\overleftrightarrow{\mathbf{D}})\chi\vert 0\rangle$	v^4
$\langle DE_1\rangle$	$\frac{1}{m^3\phi_0}\langle V\vert\psi^\dagger\frac{1}{2}[\boldsymbol{\sigma}\times(\overleftrightarrow{\mathbf{D}}\times g\mathbf{E}-g\mathbf{E}\times\overleftrightarrow{\mathbf{D}})]\cdot\boldsymbol{\epsilon}\vert 0\rangle$	v^4

- Color-singlet S-wave LDME's can be calculated from potential models.
- Color-octet LDME's are sensitive to $\vert Q\bar{Q}g\rangle$ Fock state.
- $\langle B\rangle$ and $\langle DE_0\rangle$ can be expressed in terms of other LDME's using Gremm-Kapustin relations.
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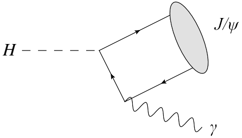
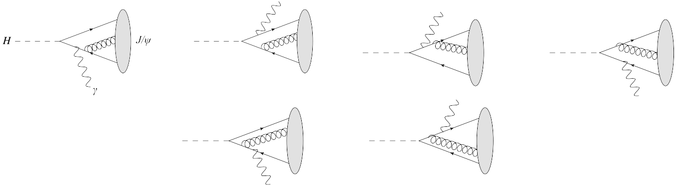
- Computation requires matching with nonrelativistic partonic $|Q\bar{Q}\rangle$ and $|Q\bar{Q}g\rangle$ states.
  With $|Q\bar{Q}\rangle$:



With $|Q\bar{Q}g\rangle$:



- The computation is very tedious, but is managable thanks to the FeynCalc package **FeynOnium** [N. Brambilla, H. S. Chung, V. Shtabovenko and A. Vairo, TUM-EFT 92/17, in preparation], a great tool for nonrelativistic EFT calculation which can deal with nonrelativistic spinors, Pauli matrices, Cartesian tensor reduction, etc.

- The matching coefficients are found to be

$$
\begin{aligned}
c_0 &= -i\frac{ee_Q y_Q}{m}\boldsymbol{\epsilon}_\gamma^* \cdot \boldsymbol{\epsilon}^*(\lambda) \\
c_{\boldsymbol{D}^2} &= i\frac{ee_Q y_Q}{m}\frac{3-7r}{6(1-r)}\boldsymbol{\epsilon}_\gamma^* \cdot \boldsymbol{\epsilon}^*(\lambda) \\
c_{\boldsymbol{D}^{(i}\boldsymbol{D}^{j)}} &= -i\frac{ee_Q y_Q}{m}\frac{3+17r}{10(1-r)}\boldsymbol{\epsilon}_\gamma^* \cdot \boldsymbol{\epsilon}^*(\lambda), \\
c_{\boldsymbol{D}^4} &= -i\frac{ee_Q y_Q}{m}\frac{43-110r+147r^2}{120(1-r)^2}\boldsymbol{\epsilon}_\gamma^* \cdot \boldsymbol{\epsilon}^*(\lambda), \\
c_B &= -i\frac{ee_Q y_Q}{m}\boldsymbol{\epsilon}_\gamma^* \cdot \boldsymbol{\epsilon}^*(\lambda), \\
c_{DE_0} &= i\frac{ee_Q y_Q}{m}\frac{3-6r+5r^2}{4(1-r)^2}\boldsymbol{\epsilon}_\gamma^* \cdot \boldsymbol{\epsilon}^*(\lambda), \\
c_{DE_1} &= i\frac{ee_Q y_Q}{m}\frac{3-4r+5r^2}{8(1-r)^2}\boldsymbol{\epsilon}_\gamma^* \cdot \boldsymbol{\epsilon}^*(\lambda),
\end{aligned}
$$

  where $r \equiv \frac{4m^2}{m_H^2}$

- Note that $r = \frac{4m_c^2}{m_H^2} \sim 0.0005$ is negligible.
- On the other hand, in higher-order α_s corrections, $\log \frac{m_H^2}{m_{J/\psi}^2} \sim 7.5$ is large, needs to be resummed.

Resummation of $\log(m_H^2/m_{J/\psi}^2)$

Collinear factorization

$$i\mathcal{M}_{\rm dir}(H \to V + \gamma) = \frac{i}{2} e e_Q y_Q \epsilon_\gamma^* \cdot \epsilon^*(\lambda) f_V^\perp(\mu) \int_0^1 dx\, T_H(x,\mu) \phi_V^\perp(x,\mu)$$

$$f_V^\perp(\mu) \epsilon_\perp^{*\,\alpha}(\lambda) \phi_V^\perp(x,\mu) = \langle V | \mathcal{Q}^\alpha(x) | 0 \rangle$$

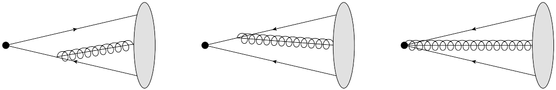
$$\mathcal{Q}^\alpha(x) = \int \frac{d\omega}{2\pi} e^{-i(x-1/2)\omega \bar{n}\cdot P} (\bar{Q} W_n)(\omega\bar{n}/2) \not{\bar{n}} \gamma_\perp^\alpha (W_n^\dagger Q)(-\omega\bar{n}/2)$$

- $T_H(x,\mu)$: perturbative hard part
  $\phi_V^\perp(x,\mu)$: nonperturbative LCDA, normalized to $\int_0^1 dx\, \phi_V^\perp(x,\mu) = 1$
- Consider the rest frame of the Higgs:
  n: lightlike vector in the direction of $V = J/\psi$
  $\bar{n}$: lightlike vector in the direction of the photon
  P: momentum of V
- Collinear Wilson line: $W_n(x) = \mathcal{P} \exp\left[-ig \int_{-\infty}^0 ds\, \bar{n} \cdot A(x + s\bar{n})\right]$

NRQCD factorization of LCDA to $\mathcal{O}(v^4)$

$$f_V^\perp(\mu)\phi_V^\perp(x,\mu) = \phi_0 \left[\tilde{c}_0(x) + \tilde{c}_{\mathbf{D}^2}(x)\langle v_S^2\rangle + \tilde{c}_{\mathbf{D}^4}(x)\langle v_S^4\rangle + \tilde{c}_{\mathbf{D}^{(i}\mathbf{D}^{j)}}(x)\langle v_D^2\rangle + \tilde{c}_B(x)\langle B\rangle + \tilde{c}_{DE_0}(x)\langle DE_0\rangle + \tilde{c}_{DE_1}(x)\langle DE_1\rangle\right]$$

- Again, the matching calculation is tedious, and involves nonrelativistic partonic $|Q\bar{Q}\rangle$ and $|Q\bar{Q}g\rangle$ states.
  With $|Q\bar{Q}g\rangle$, the relevant LCDA diagrams are:



  Again, we use the FeynCalc package **FeynOnium** for the calculation.
  First calculation of matching an collinear operator to LDME's with $|Q\bar{Q}g\rangle$!
- Result of matching:

$$\begin{aligned}
\tilde{c}_0(x) &= \frac{1}{2m}\delta(x-1/2) \\
\tilde{c}_{\boldsymbol{D}^2}(x) &= \frac{1}{m}\left[-\frac{5}{12}\delta(x-1/2)+\frac{1}{48}\delta^{(2)}(x-1/2)\right] \\
\tilde{c}_{\boldsymbol{D}^{(i}\boldsymbol{D}^{j)}}(x) &= \frac{1}{m}\left[\frac{1}{4}\delta(x-1/2)-\frac{1}{80}\delta^{(2)}(x-1/2)\right] \\
\tilde{c}_{\boldsymbol{D}^4}(x) &= \frac{1}{m}\left[\frac{19}{48}\delta(x-1/2)-\frac{19}{480}\delta^{(2)}(x-1/2)+\frac{1}{3840}\delta^{(4)}(x-1/2)\right] \\
\tilde{c}_B(x) &= \frac{1}{2m}\delta(x-1/2) \\
\tilde{c}_{DE_0}(x) &= \frac{1}{m}\left[-\frac{7}{16}\delta(x-1/2)+\frac{1}{128}\delta^{(2)}(x-1/2)\right] \\
\tilde{c}_{DE_1}(x) &= \frac{1}{m}\left[-\frac{1}{8}\delta(x-1/2)-\frac{1}{128}\delta^{(2)}(x-1/2)\right]
\end{aligned}$$

- $i\mathcal{M}_{\rm dir}$ calculated using $\tilde{c}_n(x)$ without RG running **completely agrees** with $r\to 0$ limit of fixed-order NRQCD result.

Method

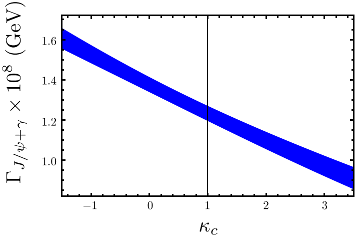
- We use $T_H(x)$ to $\mathcal{O}(\alpha_s)$ available in X.-P. Wang, D. Yang, JHEP 1406 (2014) 121.
- We include $\mathcal{O}(v^0\alpha_s)$ correction in the LCDA, computed in X.-P. Wang, D. Yang, JHEP 1406 (2014) 121. So for the LCDA at $\mu \sim m$, we include contributions of order v^0, $v^0\alpha_s$, v^2, and v^4.
- We perform the resummation to NLL. Special care has been taken for convergence of series of convolutions of highly singular distributions. We use the method of Abel sum and Padé approximants introduced in Bodwin, Chung, Ee, Lee, PRD95 (2017) 054018, PRD96 (2017) 116014.
- Leading-order LDME $\langle V|\psi^\dagger \boldsymbol{\sigma} \cdot \boldsymbol{\epsilon}\chi|0\rangle$ is eliminated by expressing $f_V^{\parallel}$ in terms of LDME's. Other color-singlet S-wave LDME's are obtained from potential models [Bodwin, Chung, Kang, Lee, Yu, PRD77 (2008) 094017].
- LDME's with unknown values, $\langle v_D^2\rangle$ and $\langle DE_1\rangle$, are estimated using velocity-scaling rules.
- We obtain $\Gamma(H \to V + \gamma)$ for $V = J/\psi$ and $\Upsilon(nS)$, $n = 1, 2, 3$.

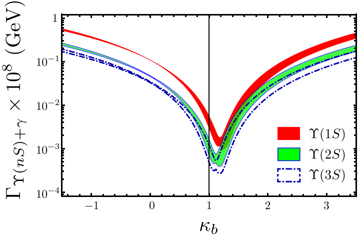
Result on $\Gamma(H \to V + \gamma)$

$\mathcal{A}_{\rm dir}$ and $\mathcal{A}_{\rm ind}$ are normalized such that $\Gamma(H \to V + \gamma) = |\kappa_Q \mathcal{A}_{\rm dir} + \mathcal{A}_{\rm ind}|^2$

V	$\mathcal{A}_{\rm ind} \times 10^5$ (GeV$^{1/2}$)	$\mathcal{A}_{\rm dir} \times 10^5$ (GeV$^{1/2}$)
J/ψ	$-(11.73^{+0.16}_{-0.16})$	$(0.631^{+0.071}_{-0.080}) + (0.065^{+0.015}_{-0.012})i$
$\Upsilon(1S)$	$(3.288^{+0.033}_{-0.033})$	$-(2.719^{+0.136}_{-0.142}) - (0.291^{+0.055}_{-0.040})i$
$\Upsilon(2S)$	$(2.158^{+0.026}_{-0.026})$	$-(1.896^{+0.101}_{-0.104}) - (0.197^{+0.037}_{-0.027})i$
$\Upsilon(3S)$	$(1.808^{+0.022}_{-0.022})$	$-(1.614^{+0.090}_{-0.093}) - (0.164^{+0.031}_{-0.023})i$

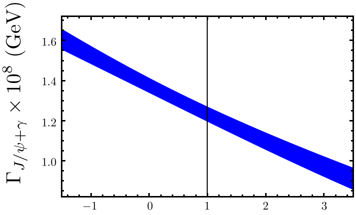
V	$\Gamma_{SM}(H \to V + \gamma)$ (GeV)	${\rm Br}_{SM}(H \to V + \gamma)$
J/ψ	$(1.231^{+0.038}_{-0.037}) \times 10^{-8}$	$(3.01^{+0.15}_{-0.15}) \times 10^{-6}$
$\Upsilon(1S)$	$(4.08^{+1.65}_{-1.23}) \times 10^{-11}$	$(9.97^{+4.04}_{-3.03}) \times 10^{-9}$
$\Upsilon(2S)$	$(1.07^{+0.57}_{-0.37}) \times 10^{-11}$	$(2.62^{+1.39}_{-0.91}) \times 10^{-9}$
$\Upsilon(3S)$	$(0.77^{+0.43}_{-0.28}) \times 10^{-11}$	$(1.87^{+1.05}_{-0.69}) \times 10^{-9}$

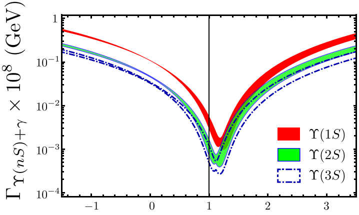




Result on $\Gamma(H \to V + \gamma)$

- $\Gamma(H \to J/\psi + \gamma)$:
  - Resummation effect: -20% for $|\mathcal{A}_{\rm dir}|$, $+3\%$ for $\Gamma(H \to J/\psi + \gamma)$
  - Uncertainty in SM branching fraction: 5%
    (Uncertainty in $\mathcal{A}_{\rm dir}$: 13%)
  - Compatible with previous results but uncertainty is reduced.
  - If $\kappa_c = +6.2\,(-6.2)$, branching fraction would be half (twice) the SM value.
- $\Gamma(H \to \Upsilon(nS) + \gamma)$:
  - Huge cancellation between $\mathcal{A}_{\rm dir}$ and $\mathcal{A}_{\rm ind}$ when $\kappa_b \approx 1$.
  - Resummation effect for $\kappa_b = 1$:
    -10% for $|\mathcal{A}_{\rm dir}|$
    $+100\%(1\text{S}), +30\%(2\text{S}), +600\%(3\text{S})$ for $\Gamma(H \to \Upsilon(nS) + \gamma)$
  - Branching fractions are 2 orders of magnitude larger than the SM values when $\kappa_b \approx -1$.





SUMMARY

- $H \to J/\psi + \gamma$ provides a way to probe the size and sign of the $Hc\bar{c}$ coupling.
- We computed the partial decay width $\Gamma(H \to J/\psi + \gamma)$ to relative order v^4 in NRQCD, and resum $\log \frac{M_H^2}{M_{J/\psi}^2}$ at NLL.
- Theoretical uncertainty is under control (5%).
- We also did a parallel calculation for $H \to \Upsilon(nS) + \gamma$, $n = 1, 2, 3$. The branching fractions are 3 orders of magnitude smaller than that of $H \to J/\psi + \gamma$, but very sensitive to κ_b.

Outlook

- Current upper limit of $\Gamma(H \to J/\psi + \gamma)$ at the LHC is 2 orders of magnitude larger than the SM value.

$$95\%\text{CL upper limit for } \mathrm{Br}(H \to J/\psi + \gamma):$$
ATLAS: $3.5 \times 10^{-4} \approx 110 \times \mathrm{Br}_{\mathrm{SM}}(H \to J/\psi + \gamma)$ PLB 786 (2018) 134
CMS: $7.6 \times 10^{-4} \approx 260 \times \mathrm{Br}_{\mathrm{SM}}(H \to J/\psi + \gamma)$ EPJC 79 (2019) 94

- At HL-LHC, $3000\ \mathrm{fb}^{-1}$ of data is expected to give 95% CL upper limit for $\mathrm{Br}(H \to J/\psi + \gamma)$ of about 15 times the SM value. ATL-PHYS-PUB-2015-043
- Current upper limit from charm-jet tagging via $\sigma(pp \to ZH) \times \mathrm{Br}(H \to c\bar{c})$ is 110 times the SM value. ATLAS, PRL120 (2018) 211802

  HL-LHC is expected to improve the upper limit to 6 times the SM value. ATL-PHYS-PUB-2018-016
- Prospect for direct measurement of the $Hc\bar{c}$ coupling is not bright even at HL-LHC.
- We should consider $H \to J/\psi + \gamma$ seriously in planning on future collider experiments.