Measuring the $HQ\bar{Q}$ Couplings in $H \to V\gamma$

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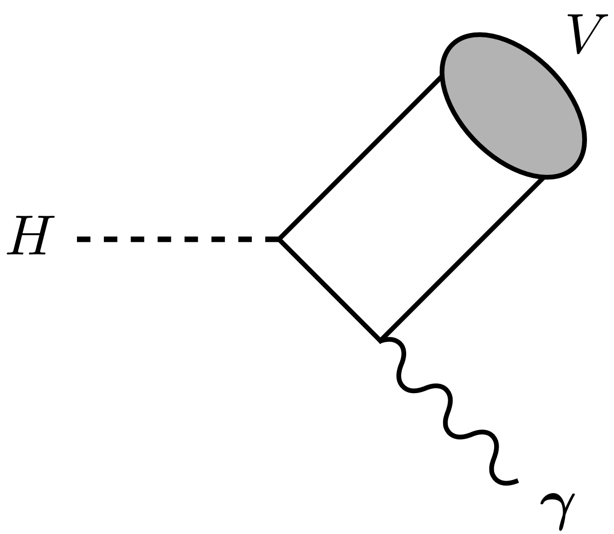
(GTB, F. Petriello, S. Stoynev, M. Velasco, Phys. Rev. D **88**, 053003 (2013))

(GTB, H.S. Chung, J.-H. Ee, J. Lee, F. Petriello arXiv:1407.6695)

- Measuring the $Hc\bar{c}$ Coupling
- $\Gamma[H \to J/\psi + \gamma]$
- Indirect Amplitude
- Direct Amplitude
- Estimated Uncertainties
- Numerical Results for $H \to J/\psi + \gamma$
- Observability of $H \to J/\psi + \gamma$ at the LHC
- Numerical results for $H \to \Upsilon(nS) + \gamma$
- Observability of $H \to \Upsilon(nS) + \gamma$ at the LHC
- Summary

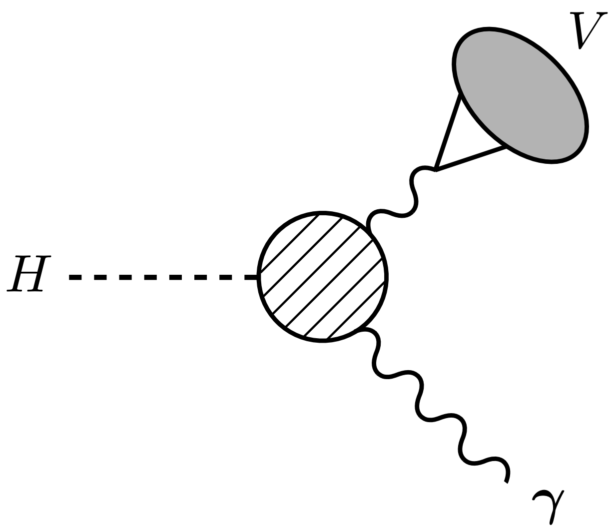
Measuring the $Hc\bar{c}$ Coupling

- Higgs couplings to vector bosons, τ leptons, and b quarks have been measured.
- The coupling to t quarks is known implicitly from loop contributions to decay processes.
- However, the couplings to first- and second-generation quarks are *terra incognita*.
- One could hope to measure the $Hc\bar{c}$ coupling in direct decays to $J/\psi + \gamma$:



- The channel $J/\psi \to \ell^+\ell^-$, when combined with the m_H and $m_{J/\psi}$ mass constraints, provides a clean experimental signal.

- The direct amplitude was computed many years ago.
  (Keung, PRD 27, 2762 (1983))
  - It is proportional to the $H\bar{c}c$ coupling.
  - But, the corresponding decay width is far too small to be observed at the LHC.
- However, there is also a (newly identified) indirect process for producing a vector quarkonium plus a photon:



Dominated by t quarks and W bosons in the loop.

- For J/ψ, the indirect amplitude is about an order of magnitude larger than the direct amplitude.
- The interference between the direct and indirect amplitudes is large enough to be measured at the LHC.
- Requires knowing the theoretical prediction for the indirect amplitude with good precision.

$\Gamma[H \to J/\psi + \gamma]$

- Parametrize deviations from the standard-model $Hc\bar{c}$ coupling with a factor κ_c:

$$g_{Hc\bar{c}} = \kappa_c \, g_{Hc\bar{c}}^{\mathrm{SM}} \, .$$

- Then, the decay rate is

$$\Gamma[H \to J/\psi + \gamma] = \left| \sqrt{\Gamma_{\mathrm{indirect}}^{\mathrm{SM}}} - \kappa_c \sqrt{\Gamma_{\mathrm{direct}}^{\mathrm{SM}}} \right|^2 .$$

- The indirect and direct amplitudes interfere destructively (aside from a small phase (0.005) that we neglect).
- The rate depends on both the magnitude and the phase of $g_{Hc\bar{c}}$.

Indirect Amplitude

- It is essential to predict the indirect amplitude very precisely in order to measure the direct amplitude.
- Can be computed from $H \to \gamma\gamma^*$, followed by $\gamma^* \to J/\psi$.
- $H \to \gamma\gamma^*$ can be approximated by $H \to \gamma\gamma$, up to corrections of order $m_{J/\psi}^2/m_H^2$.
  - The amplitude for $H \to \gamma\gamma$ has been computed to high precision.

    (Dittmaier *et al.*, arXiv:1101.0593, arXiv:1201.3084)
- Extract the amplitude for $\gamma^* \to J/\psi$ from the measured rate for $J/\psi \to \ell^+\ell^-$.
  - Both amplitudes are proportional to the coupling of the J/ψ to the EM current.
  - This approach effectively includes QCD and relativistic corrections to all orders—greatly reducing uncertainties.

Direct Amplitude

- We used nonrelativistic QCD (NRQCD) to compute the direct amplitude to all orders in v^2 for the $Q\bar{Q}$ Fock state.
  - NRQCD nonperturbative long-distance matrix elements (LDMEs) at leading and subleading orders in v^2 from $\Gamma[J/\psi \to e^+e^-]$ and a potential-model.

    (GTB, Chung, Kang, Lee, Yu, PRD 77, 094017 (2008))
- We also computed the direct amplitude through order v^2 using the light-cone formalism.

  (Jia, Yang, NPB 814, 217 (2009))
  - Accurate up to corrections of order m_c^2/m_H^2.
  - Allowed us to make contact with an existing light-cone calculation of one-loop corrections at leading order in v^2.
  - Allowed us to sum leading logs of m_H^2/m_c^2.

- The light-cone amplitude $i\mathcal{M}$ involves an integration over the longitudinal momentum fraction x of the Q in the quarkonium:

$$i\mathcal{M} = f_V \int_{-1}^{+1} dx\, T_H(x)\phi(x).$$

- The decay constant f_V has an NRQCD expansion (sum of short-distance coefficients times LDMEs).
- The hard-scattering kernel T_H can be calculated in perturbation theory. At leading order in α_s

$$T_H(x) \propto 1/(1-x^2) = 1 + x^2 + \ldots.$$

  - The "1" term and the order-v^0 part of f_V give the v^0 contribution.
  - The "x^2" term and the order-v^2 part of f_V give the corrections of order v^2.
  - Complete order-α_s corrections are known for the "1" term.

    (Shifman, Vysotsky, NPB 186, 475 (1981))

- Light-cone distribution amplitude (LCDA) $\phi(x)$ is nonperturbative and depends on the factorization scale.
  - Initially, choose the scale to be m_c.
  - Compute the x moments of the LCDA at the scale m_c by using the relations between the moments of the LCDA and the NRQCD LDMEs.

    (Braguta, PRD 75, 094016 (2007); Braguta, Likhoded, Luchinsky, PLB646, 80 (2007))
  - Evolution of the LCDA moments from the scale m_c to the scale m_H incorporates logs of m_H^2/m_c^2.

    (Brodsky, Lepage, PRD 22, 2157 (1980))
- The evolution equation is usually solved by expanding in Gegenbauer polynomials.
  - We used this method to resum leading logs for the "1" term.

    (Shifman, Vysotsky, NPB 186, 475 (1981))
  - For the "x^2" term, the Gegenbauer expansion diverges.
  - Instead, we solved the evolution equation perturbatively through relative order α_s^2.

    (Jia, Wang, NPB 814, 217, (2009))

Estimated Uncertainties

- Indirect Process: 2% uncertainty
  - Uncertainties in m_t and m_W
  - Uncalculated corrections of higher orders in α_s
  - Uncertainty in the J/ψ leptonic width
- Direct Process: 13% uncertainty
  - Uncertainties in LDMEs
  - Uncalculated corrections of order α_s^2, $\alpha_s v^2$, v^4
  - Our new calculation of order-v^2 corrections reduced the uncertainty by a factor of 3.3.
- SM Higgs total width: 5% uncertainty

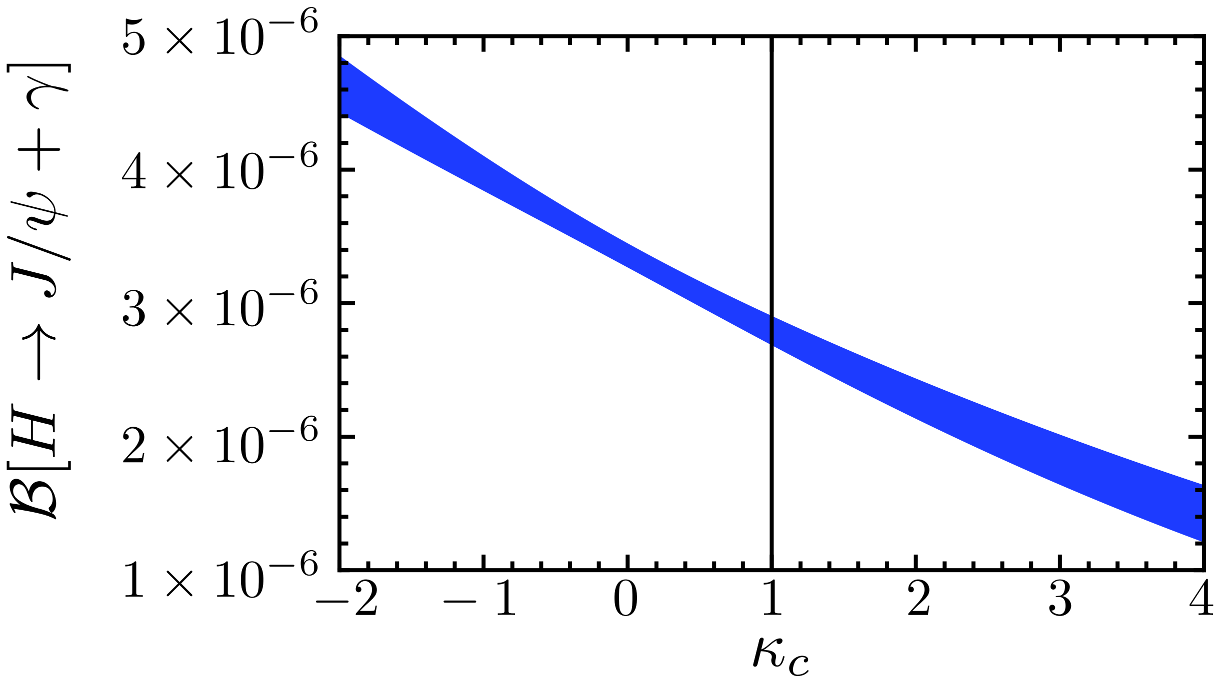
Numerical Results for $H \to J/\psi + \gamma$

$$g_{Hc\bar{c}} = \kappa_c \, g_{Hc\bar{c}}^{\rm SM}$$

$$\Gamma[H \to J/\psi + \gamma] = |(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c|^2 \times 10^{-10}\ {\rm GeV}.$$

$$\Gamma_{\rm SM}[H \to J/\psi+\gamma] = 1.17^{+0.05}_{-0.05}\times 10^{-8}\ {\rm GeV}. \qquad \mathcal{B}_{\rm SM}[H \to J/\psi+\gamma] = 2.79^{+0.16}_{-0.15}\times 10^{-6}.$$

- The width is sensitive to deviations from the Standard Model value of the $H\bar{c}c$ coupling:



- $+42\%$ for $\kappa_c = -1$.
- $+20\%$ for $\kappa_c = 0$.
- -18% for $\kappa_c = 2$.
- Interference allows us to determine the sign of κ_c.

Observability of $H \to J/\psi + \gamma$ at the LHC

- The branching fraction through $J/\psi + \gamma$ to $\mu^+\mu^-$ is

$$\mathcal{B}_{\rm SM} \times \mathcal{B}_{J/\psi \to \mu^+\mu^-} = 1.66^{+0.09}_{-0.09} \times 10^{-7}.$$

- This is comparable to the branching fraction to the continuum background

$$\mathcal{B}_{H \to \mu^+\mu^-\gamma} = 2.3 \times 10^{-7}$$

$$(m_{J/\psi} - 0.05 \text{ GeV} < m_{\mu^+\mu^-} < m_{J/\psi} + 0.05 \text{ GeV})$$

(Firan, Stroynowski, PRD 76, 057301 (2007))

- Combined ATLAS and CMS e^+e^- and $\mu^+\mu^-$ events:
  - 8 TeV LHC: 0.3 events
  - 14 TeV high luminosity LHC ($\mathcal{L} = 3000 \text{ fb}^{-1}$): 113 events
    157 background events
  - Expected acceptance/efficiency is about 50%.
  - $S/\sqrt{B}$ is significantly greater than one.

Numerical results for $H \to \Upsilon(nS) + \gamma$

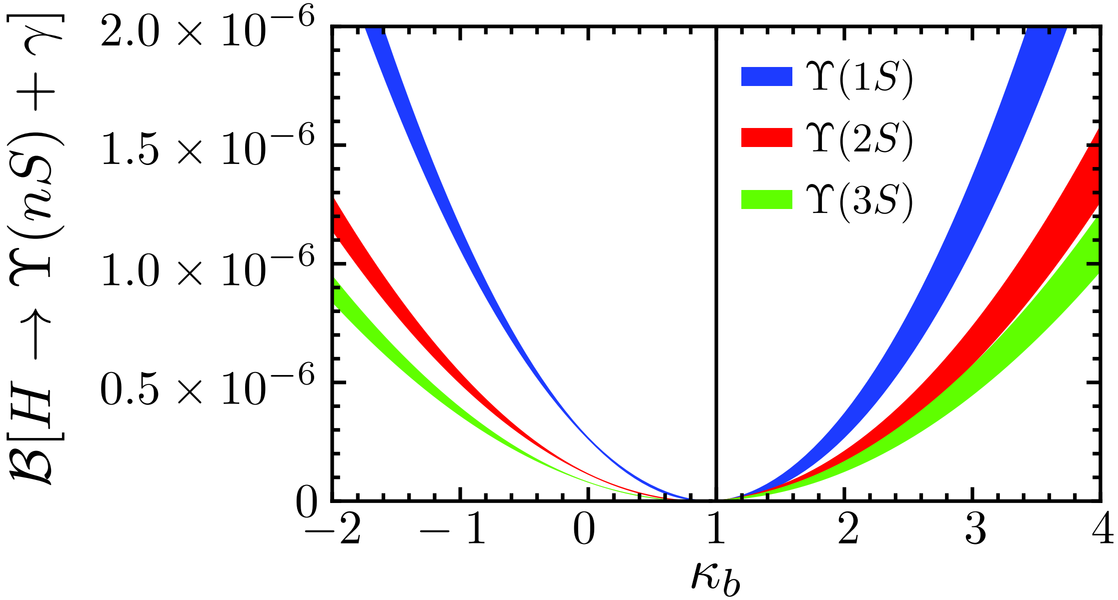
- We do the same calculation for the $\Upsilon(nS)$ states.

$$g_{Hb\bar{b}} = \kappa_b \, g_{Hb\bar{b}}^{\rm SM}$$

$$\Gamma[H \to \Upsilon(1S) + \gamma] = |(3.33 \pm 0.03) - (3.49 \pm 0.15)\kappa_b|^2 \times 10^{-10} \text{ GeV}.$$

$$\Gamma_{\rm SM}[H \to \Upsilon(1S) + \gamma] = 2.56^{+7.30}_{-2.56} \times 10^{-12} \text{ GeV}.$$
$$\mathcal{B}_{\rm SM}[H \to \Upsilon(1S) + \gamma] = 6.11^{+17.41}_{-6.11} \times 10^{-10}.$$

- In the SM, the $\Upsilon(1S)$ direct and indirect amplitudes cancel at the 5% level.



- The SM rates are probably unobservable at the LHC.
- However, there is a dramatic sensitivity to deviations from the SM coupling.

Observability of $H \to \Upsilon(nS) + \gamma$ at the LHC

- If $\kappa_b = -1$, we expect at a high-luminosity LHC ($\mathcal{L} = 3000\ \mathrm{fb}^{-1}$) the following combined ATLAS and CMS e^+e^- and $\mu^+\mu^-$ events:
  $\Upsilon(1S)$: 19 events,
  $\Upsilon(2S)$: 7 events,
  $\Upsilon(3S)$: 6 events.
- Background from $H \to \ell^+\ell^-\gamma$: 52 events
  $(m_\Upsilon - 0.05\ \mathrm{GeV} < m_{\ell^+\ell^-} < m_\Upsilon + 0.05\ \mathrm{GeV})$
- $S/\sqrt{B}$ is of order one.
- There may be some discriminating power for the sign of κ_b.

Summary

- The rare decay $H \to J/\psi + \gamma$ has a clean experimental signature and may be observable at a high-luminosity LHC.
- Owing to the interference between the direct and indirect amplitudes, the rate is sensitive to the $Hc\bar{c}$ coupling.
- It may be possible to determine both the magnitude and the phase of the $Hc\bar{c}$ coupling.
- For $H \to \Upsilon(nS) + \gamma$, there is a dramatic cancellation between the direct and indirect amplitudes at the SM value of the $Hb\bar{b}$ coupling.
- A (non-)measurement of $\Gamma[H \to \Upsilon(nS)+\gamma]$ may have some discriminating power for the sign of the $Hb\bar{b}$ coupling.
- Higgs decays to a quarkonium plus a photon may open a new window on the $HQ\bar{Q}$ couplings.