MEASURING THE HIGGS-CHARM COUPLING WITH HEAVY QUARKONIA

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Based on
Geoffrey T. Bodwin, Frank Petriello, Stoyan Stoynev, Mayda Velasco, PRD88, 053003 (2013)
Geoffrey T. Bodwin, HSC, June-Haak Ee, Jungil Lee, Frank Petriello, arXiv:1407.6695 [hep-ph]

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OUTLINE

- Higgs-charm coupling and $H \to J/\psi + \gamma$
- Observability at LHC
- Summary

HIGGS COUPLING TO CHARM QUARK

- Higgs couplings to first- and second-generation quarks are ***terra incognita***.
- Higgs-charm coupling $g_{Hc\bar{c}}$ can deviate significantly from SM in new physics theories.
- For example, Higgs-dependent Yukawa couplings can lead to large enhancements to the Higgs-fermion coupling.

Giudice and Lebedev, PLB665, 79 (2008)

HIGGS COUPLING TO CHARM QUARK

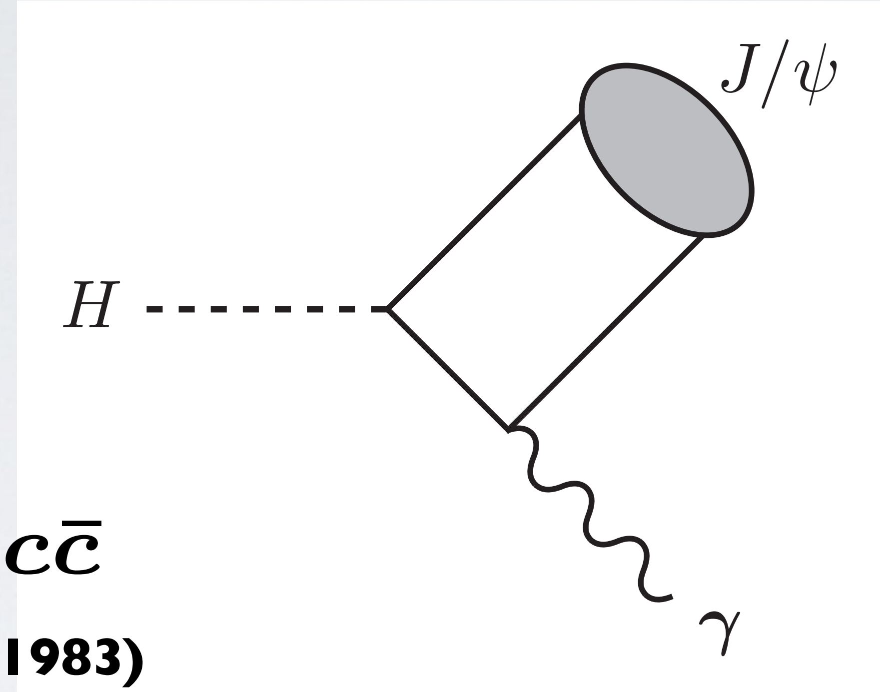
- $H \to \mathrm{charmonium} + \gamma$ is sensitive to the Higgs-charm coupling through H decay into $c\bar{c}$.

- The vector charmonium J/ψ provides a clean signal through $J/\psi \to \ell^+\ell^-$, which has been measured accurately

- $H \to J/\psi + \gamma$ would appear as a resonance above $H \to \ell^+\ell^-\gamma$, where $\ell^+\ell^-$ and γ are back-to-back in the H rest frame

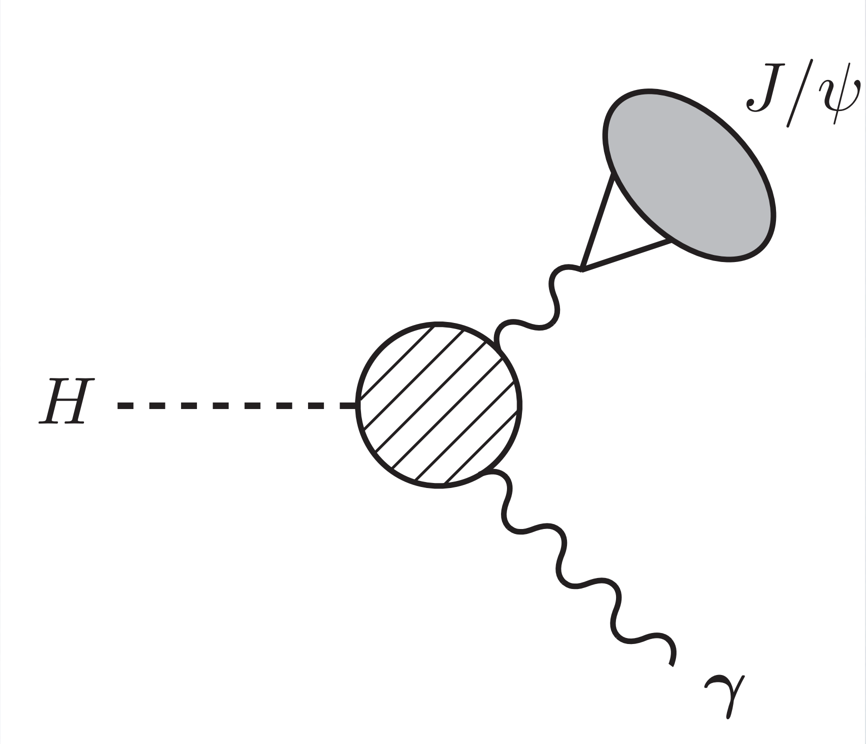
$H \to J/\psi + \gamma$ PROCESS

- ***Direct process***
  - H decays into $c\bar{c}$, which emits a photon and forms J/ψ
  - Amplitude proportional to $g_{Hc\bar{c}}$



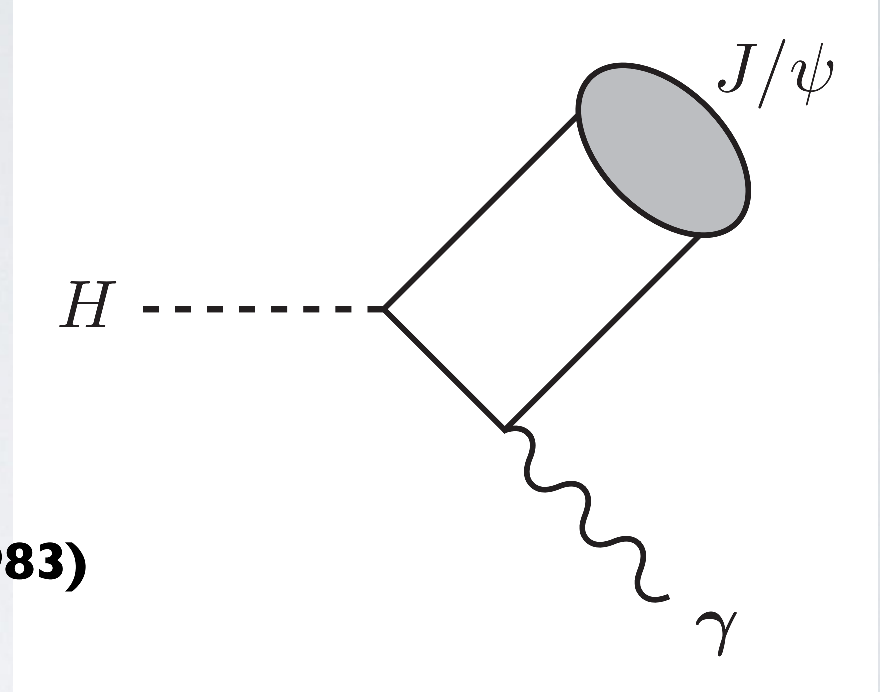
Keung, PRD27, 2762 (1983)

- ***Indirect process***
  - H decays into two photons, one of which decays into J/ψ
  - Process is dominated by top and W loops



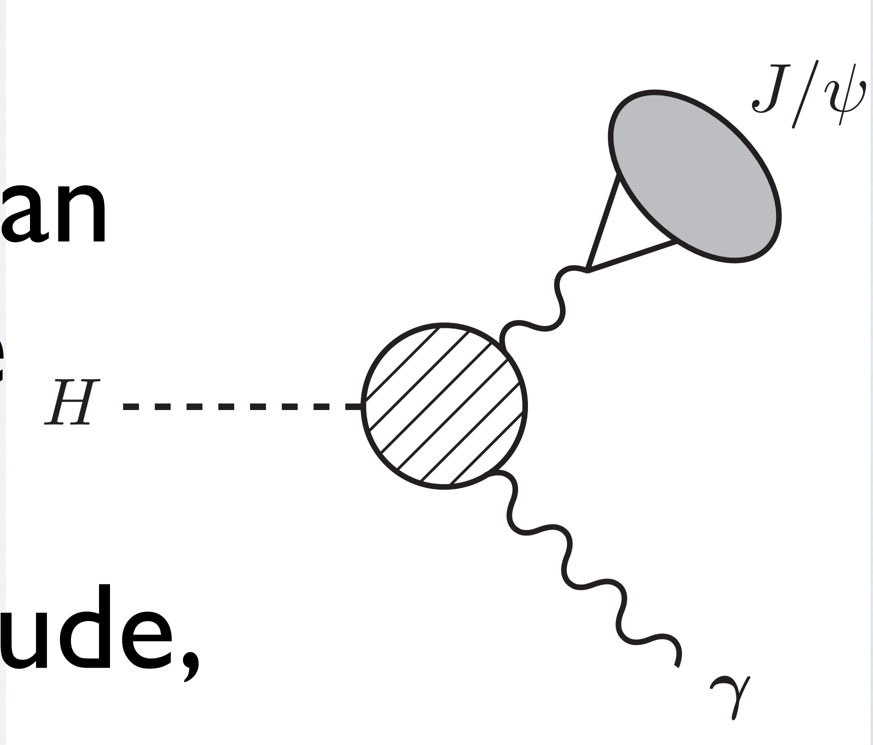
$H \to J/\psi + \gamma$ PROCESS

- ***Direct process***
  - Known for many years
  - Decay width too small to be observed at LHC



Keung, PRD27, 2762 (1983)

- ***Indirect process***
  - *Newly identified*
  - *An order of magnitude larger* than the direct amplitude, giving large enhancement
  - Interferes with the direct amplitude, gives sensitivity to $g_{Hc\bar{c}}$



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

- If $g_{Hc\bar{c}}$ deviates from SM,

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

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

- Indirect amplitude interferes destructively with the direct amplitude (we neglect a small phase)
- Depends on both the *size* and the *phase* of $g_{Hc\bar{c}}$
- *In order to have sensitivity to $g_{Hc\bar{c}}$ it is essential to have small uncertainty in the indirect amplitude*

DIRECT PROCESS

- Nonrelativistic QCD (NRQCD) is used to compute the direct amplitude with relativistic corrections of order v^2 ($v^2 \approx 0.25$ for J/ψ)

  Bodwin, Braaten, Lepage, PRD51, 1125 (1995)

- QCD 1-loop correction is known and included

  Vysotsky, PLB97, 159 (1980)

- Nonperturbative matrix elements are extracted from the J/ψ leptonic decay rate

  Bodwin, HSC, Kang, Lee, Yu, PRD77, 094017 (2008)

- We use the light-cone method to compute leading logarithms of m_H^2/m_c^2

  Lepage and Brodsky, PRD22, 2157 (1980)

DIRECT PROCESS

- We also calculate the direct amplitude using the light-cone method

Hard-scattering kernel (perturbative)

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

decay constant (nonperturbative)

Light-cone distribution amplitude (nonperturbative)

- f_V and $\phi(x)$ can be determined from the NRQCD matrix elements; $T(x)$ is calculated using perturbative QCD
- Relativistic corrections come from f_V and $\phi(x)$
- This reproduces the NRQCD calculation with relativistic corrections at leading order in $1/m_H$

DIRECT PROCESS

- $\phi(x)$ is scale dependent
- The evolution equation for $\phi(x)$ can be solved formally in terms of the Gegenbauer polynomials
- We use this to resum leading logarithms at leading order in v^2 **Shifman and Vysotsky, NPB186, 475 (1981)**
- At order v^2, the Gegenbauer expansion leads to a diverging series
- Instead we solve the evolution equation perturbatively to order α_s^2
- The perturbation series converges rapidly.

INDIRECT PROCESS

- Indirect process can be computed from $H \to \gamma\gamma^*$ followed by $\gamma^* \to J/\psi$
- Because J/ψ is much lighter than H, $H \to \gamma\gamma^*$ can be approximated by $H \to \gamma\gamma$, which has been computed to high accuracy

Dittmaier et al, arXiv:1101.0593
Dittmaier et al, arXiv:1201.3084

- $\gamma^* \to J/\psi$ can be extracted from the J/ψ leptonic decay rate, rather than using NRQCD
- *This approach effectively includes QCD radiative and relativistic corrections to all orders, and leads to greatly reduced uncertainties*

ESTIMATED UNCERTAINTIES

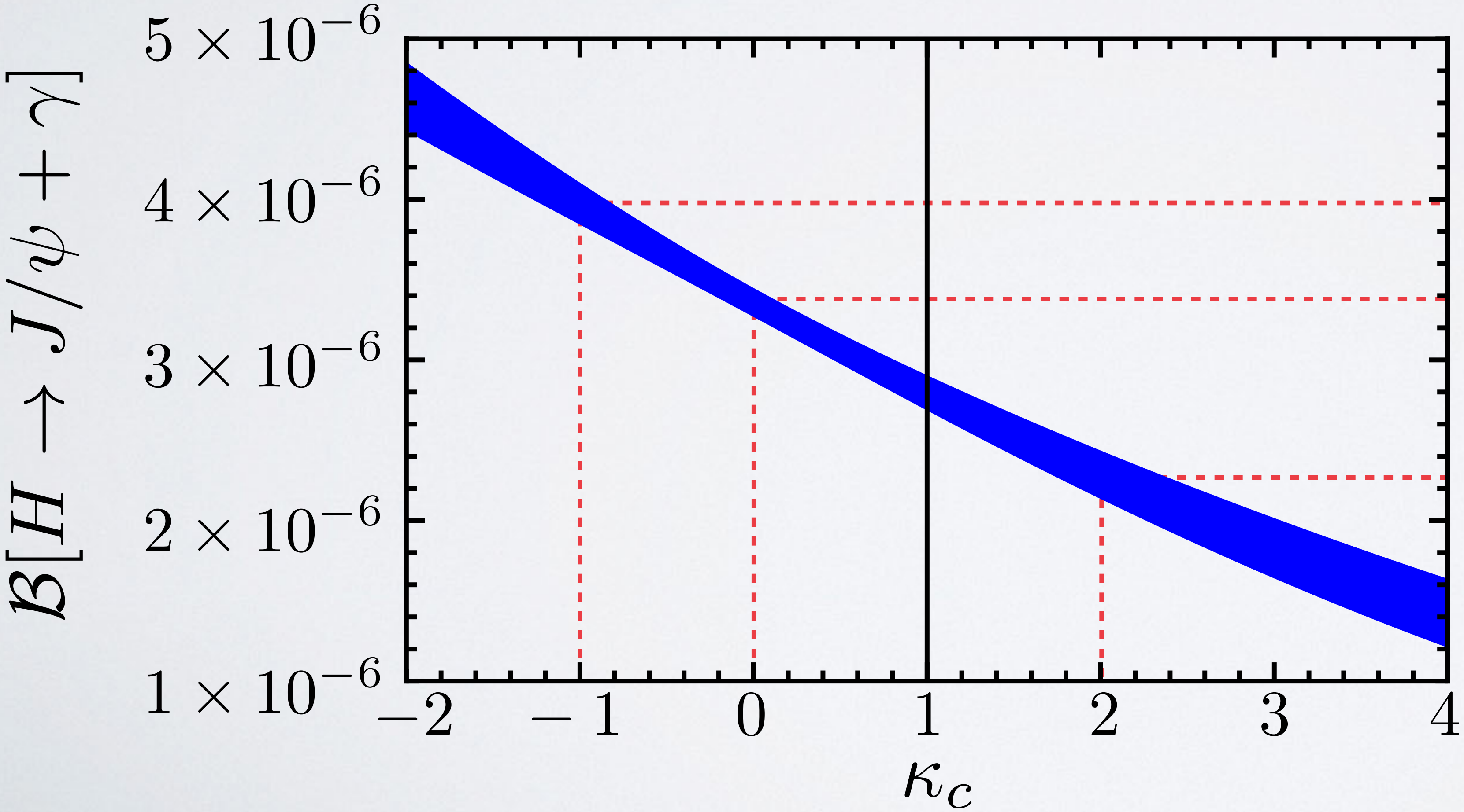
- ***Direct process : 13% uncertainty from***
  - nonperturbative matrix elements
  - uncalculated corrections of order $\alpha_s^2, \alpha_s v^2, v^4$
  - Uncertainty is reduced by a factor of 2.7 by including relativistic corrections
- ***Indirect process : 2% uncertainty from***
  - top quark and W boson masses, uncalculated higher-order corrections, J/ψ leptonic decay rate
  - Uncertainty is greatly reduced by using the measured leptonic decay rate
- ***5% uncertainty in the SM decay rate***

NUMERICAL RESULTS FOR $H \to J/\psi + \gamma$

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

$$\Gamma = \left| (11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c \right|^2 \times 10^{-10} \ \text{GeV}$$

$$\Gamma_{\rm SM} = 1.17^{+0.05}_{-0.05} \times 10^{-8} \ \text{GeV} \qquad \mathcal{B}_{\rm SM} = 2.79^{+0.16}_{-0.15} \times 10^{-6}$$



+42% for $\kappa_c = -1$

+20% for $\kappa_c = 0$

−18% for $\kappa_c = 2$

Interference allows us to determine the sign

OBSERVABILITY AT LHC

- $\mathcal{B}_{\rm SM} \times \mathcal{B}_{J/\psi \to \ell^+ \ell^-} = 1.66^{+0.09}_{-0.09} \times 10^{-7}$ is comparable to the continuum background $\mathcal{B}_{H \to \mu^+ \mu^- \gamma} = 2.3 \times 10^{-7}$ **Firan and Stroynowski, PRD76, 057301 (2007)**
  $(m_{J/\psi} - 0.05 \text{ GeV} < m_{\mu^+\mu^-} < m_{J/\psi} + 0.05 \text{ GeV})$
- Combined number of events for ATLAS+CMS electron+muon final states for $\kappa_c = 1$:
  - 0.3 events at 8 TeV LHC
  - ***113 events at 14 TeV high-luminosity LHC (157 events from the background)***
- Expected acceptance/efficiency is about 50%

$H \to \Upsilon(1S) + \gamma$

- We can do the same calculation for Υ

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

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

$$\Gamma_{\rm SM}(H \to \Upsilon(1S) + \gamma) = 2.56^{+7.30}_{-2.56} \times 10^{-12}\ {\rm GeV}$$

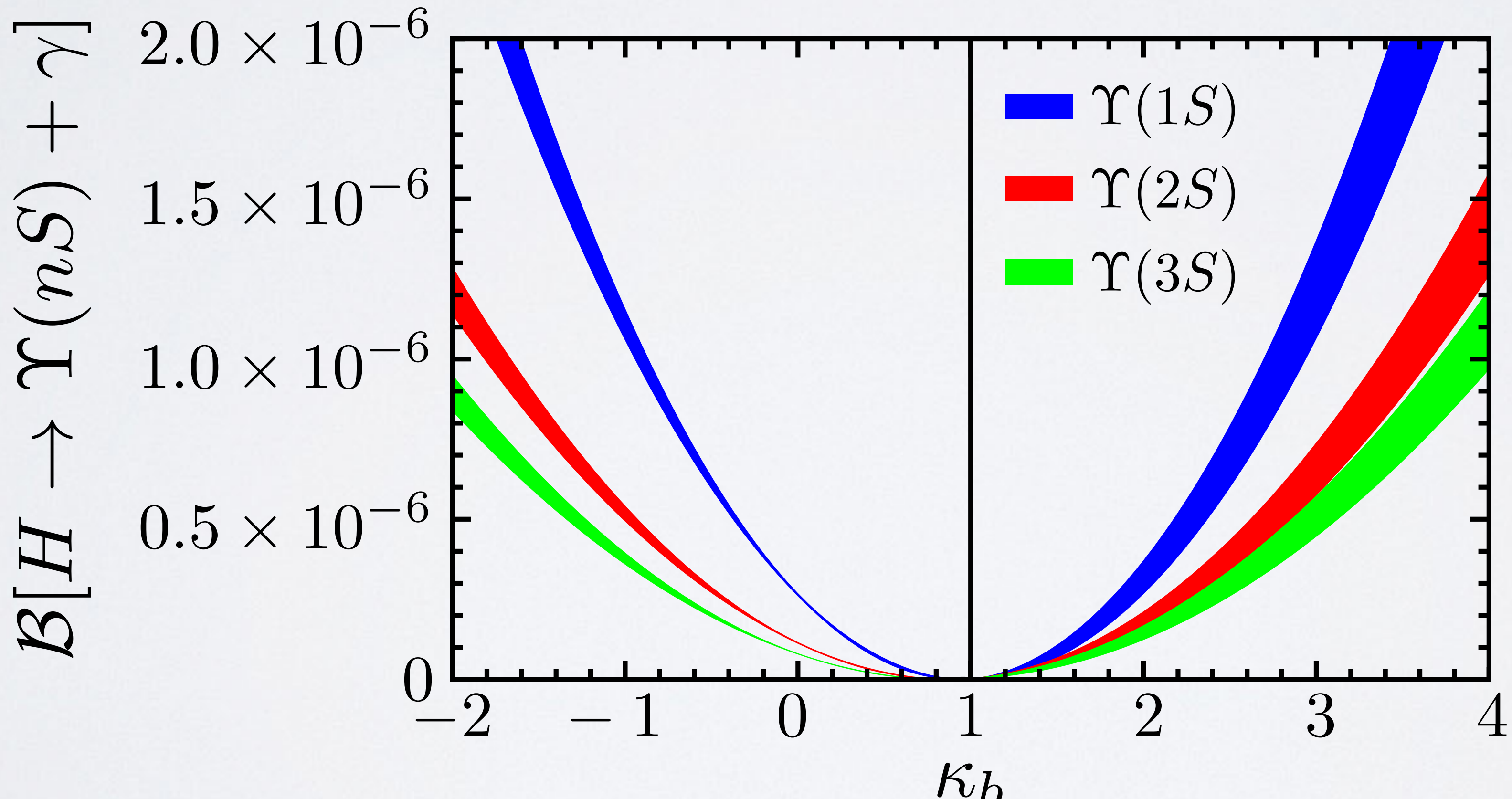
$$\mathcal{B}_{\rm SM}(H \to \Upsilon(1S) + \gamma) = 6.11^{+17.41}_{-6.11} \times 10^{-10}$$

- In the SM, direct and indirect amplitudes cancel in the 5% level

- *Dramatic sensitivity to deviations from the SM*

$H \to \Upsilon(nS) + \gamma$

- If $\kappa_b = -1$, we expect 19, 7, and 6 events at HL-LHC for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ (52 events from the background $H \to \ell^+ \ell^- \gamma$ $m_\Upsilon - 0.05 \text{ GeV} < m_{\ell^+\ell^-} < m_\Upsilon + 0.05 \text{ GeV}$)



This may help to discriminate between $\kappa_b = \pm 1$

SUMMARY

- Owing to interference in $H \to J/\psi + \gamma$, the magnitude and phase of the Higgs-charm coupling may be measurable at the LHC
- $H \to \Upsilon(nS) + \gamma$ may help to determine the phase of the Higgs-bottom coupling

SUPPLEMENTARY

$H \to \Upsilon(nS) + \gamma$

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

$$\Gamma(H \to \Upsilon(2S) + \gamma) = \left|(2.18 \pm 0.03) - (2.48 \pm 0.11)\kappa_b\right|^2 \times 10^{-10}\ \text{GeV},$$

$$\Gamma(H \to \Upsilon(3S) + \gamma) = \left|(1.83 \pm 0.02) - (2.15 \pm 0.10)\kappa_b\right|^2 \times 10^{-10}\ \text{GeV}.$$

$$\Gamma_{\text{SM}}(H \to \Upsilon(1S) + \gamma) = 2.56^{+7.30}_{-2.56} \times 10^{-12}\ \text{GeV},$$

$$\Gamma_{\text{SM}}(H \to \Upsilon(2S) + \gamma) = 8.46^{+7.79}_{-5.35} \times 10^{-12}\ \text{GeV},$$

$$\Gamma_{\text{SM}}(H \to \Upsilon(3S) + \gamma) = 10.25^{+7.33}_{-5.45} \times 10^{-12}\ \text{GeV}.$$

$$\mathcal{B}_{\text{SM}}(H \to \Upsilon(1S) + \gamma) = 6.11^{+17.41}_{-6.11} \times 10^{-10},$$

$$\mathcal{B}_{\text{SM}}(H \to \Upsilon(2S) + \gamma) = 2.02^{+1.86}_{-1.28} \times 10^{-9},$$

$$\mathcal{B}_{\text{SM}}(H \to \Upsilon(3S) + \gamma) = 2.44^{+1.75}_{-1.30} \times 10^{-9}.$$