

Higgs boson decays to quarkonia and the $H\bar{c}c$ coupling

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In this paper we discuss decays of the Higgs boson to quarkonia in association with a photon. We identify a new mechanism for producing such final states in Higgs decays that leads to predictions for the decay rates that differ by an order of magnitude from previous estimates. Although the branching ratios for these processes are still small, the processes are experimentally clean, and the $H \rightarrow J/\psi \gamma$ decay should be observable at a 14 TeV LHC. We point out that quantum interference between two different production mechanisms makes the decay rates sensitive to the $H\bar{Q}Q$ couplings. Consequently, measurements of the $H \rightarrow J/\psi \gamma$ decay rate would allow one to probe the Higgs-charm coupling directly at the LHC. We discuss the experimental prospects for the observation of these decays and for the direct measurement of the $H\bar{c}c$ coupling.

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I. INTRODUCTION

With the discovery of a new spin-zero boson by the ATLAS and CMS collaborations at the LHC now firmly established [1–4], attention has shifted to understanding the couplings of this particle in order to determine whether it is the Standard Model (SM) Higgs boson. Current studies indicate no significant deviation from SM predictions in any measured channel [5,6], and extracted values of the couplings in well-measured modes, such as $\gamma\gamma$, WW and ZZ , have errors approaching 10–20%.

In addition to improving the measurements of these channels, the future LHC program will study rare and difficult-to-reconstruct decay modes. One example is the decay $H \rightarrow \gamma f\bar{f}$, where f denotes any SM fermion. This final state can be produced via $H \rightarrow \gamma(\gamma^*, Z)$ followed by the decay $(\gamma^*, Z) \rightarrow \bar{f}f$. If the mass of the final-state fermion is large enough, then there is also a significant contribution from the process in which the H couples directly to $\bar{f}f$ and one of the fermions emits a photon. When the final-state fermion is either an electron or muon, then the decay $H \rightarrow \gamma l^+ l^-$, although rare, offers a very clean experimental signature. The observability may be enhanced further by the resonant production processes $H \rightarrow \gamma V$, where V denotes a vector meson, such as the J/ψ or the $Y(1S)$, with the subsequent decay $V \rightarrow l^+ l^-$.

These channels are promising experimentally: a high- p_T photon that is back-to-back to a dilepton pair that reconstructs to a resonance is simple to distinguish from background.

In this paper, we study the exclusive decays $H \rightarrow V\gamma$, where $V = J/\psi$ or $Y(1S)$. We distinguish two separate production mechanisms for the quarkonium state:

- (i) *direct production*, which proceeds through the $h\bar{Q}Q$ coupling, where Q denotes either the charm quark (in the case of the J/ψ) or bottom quark [in the case of the $Y(1S)$];
- (ii) *indirect production*, which proceeds through $H \rightarrow \gamma\gamma^*$, with the subsequent transition $\gamma^* \rightarrow V$.

The possibility of direct quarkonium production in Higgs decays was first pointed out in Ref. [7]. However, to our knowledge the indirect mechanism has not been studied previously.¹ We find that, in the case of the J/ψ , the indirect mechanism leads to SM decay rates that are much larger than the previously estimated direct decay rate. The most promising mode for LHC observation is $H \rightarrow J/\psi \gamma$, followed by the decay $J/\psi \rightarrow \mu^+ \mu^-$. This mode should be evident as a clear peak above the continuum background in a 14 TeV, high-luminosity LHC run. Interestingly, the quantum interference with the larger indirect amplitude enhances the effect of the direct-production amplitude and potentially allows the $H\bar{c}c$ coupling to be constrained directly by measurement of the

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branching ratio for $H \rightarrow J/\psi\gamma$. The $H\bar{c}c$ coupling is otherwise very difficult to access directly at the LHC. In the SM, the interference effect leads to a shift of approximately 30% in the branching ratio, which is potentially observable experimentally. Deviations from SM predictions for the $H\bar{c}c$ coupling can lead to larger shifts and can be either observed or constrained by a measurement of the $H \rightarrow J/\psi\gamma$ branching ratio. A determination of the $H\bar{c}c$ coupling would test whether the observed Higgs boson couples to second-generation quarks with the strength that is predicted in the SM. It had been expected that only third-generation quark couplings would be accessible to measurements at the LHC. Since the decay mode $H \rightarrow J/\psi\gamma$ can only be accessed with high statistics, the possibility of using it to measure the $H\bar{c}c$ coupling motivates a high-luminosity run of the LHC. We note that the $H \rightarrow V\gamma$ modes will also fulfill an important role at future high-luminosity e^+e^- machines. Measurements of the $H\bar{c}c$ and $H\bar{b}b$ couplings via the direct decays $H \rightarrow \bar{c}c$, $\bar{b}b$ leave the overall signs of the couplings undetermined. This ambiguity is resolved by the interference that is present in $H \rightarrow V\gamma$, providing us with important additional information about the properties of the Higgs.²

This paper is organized as follows. We present in detail the calculation of the direct- and indirect-production amplitudes in Sec. II. We pay careful attention to the theoretical uncertainties that enter the prediction. In particular, we point out that the indirect amplitude can be calculated very accurately within the SM and has theoretical uncertainties at the few-percent level, allowing deviations that are due to the direct-production amplitude to be observed reliably. We present numerical results and study the effect on the $H \rightarrow J/\psi\gamma$ and $H \rightarrow Y(1S)\gamma$ branching ratios of deviations of the $H\bar{c}c$ and $H\bar{b}b$ couplings from SM values. In Sec. III, we study the experimental prospects for the observation of the $J/\psi\gamma$ mode at the LHC. Careful estimates of the acceptances and sensitivities are performed for the case of the 14 TeV LHC. Finally, we summarize our conclusions in Sec. IV.

II. CALCULATION AND NUMERICAL RESULTS

In this section, we calculate the rate for the exclusive decays of a Higgs to a quarkonium and a photon. We include contributions from both the direct and indirect mechanisms, which are described in Sec. I, including their quantum-mechanical interference. An accounting of the theoretical uncertainties of these predictions is given as well. We also present numerical results for the $H \rightarrow J/\psi\gamma$ and $H \rightarrow Y(1S)\gamma$ branching ratios in the SM and study the impact of deviations of the $H\bar{c}c$ and $H\bar{b}b$ couplings from their SM values.

A. Direct-production amplitude

We begin with the direct production mechanism. This mechanism was first discussed in Ref. [7]. We will allow the heavy-quark Yukawa couplings to deviate from their SM values by factors κ_Q :

$$g_{H\bar{Q}Q} = \kappa_Q(g_{H\bar{Q}Q})_{\text{SM}}, \quad (1)$$

where $Q = c, b$. The amplitude for the direct production process can be computed in the nonrelativistic QCD (NRQCD) factorization framework [9] as an expansion in powers of α_s and v , where v is the heavy-quark or heavy-antiquark velocity in the quarkonium rest frame. The result at leading order in α_s and v is

$$\mathcal{M}_{\text{direct}} = \frac{4\sqrt{3}e_Q e \kappa_Q}{m_H^2 - m_V^2} \left[\frac{G_F m_V}{2\sqrt{2}} \right]^{1/2} \phi_0(V) \{ 2p_\gamma \cdot \epsilon_V^* p_V \cdot \epsilon_\gamma^* - (m_H^2 - m_V^2) \epsilon_\gamma^* \cdot \epsilon_V^* \}, \quad (2)$$

in agreement with Ref. [7]. Here, e_Q is the heavy-quark electric charge in units of e , m_Q is the heavy-quark mass, G_F is the Fermi constant, and ϵ_γ and ϵ_V denote the polarization vectors of the photon and vector meson, respectively. The factor ϕ_0 is the wave function of the quarkonium state at the origin. Numerical values for this factor are [10,11]

$$\begin{aligned} \phi_0^2(J/\psi) &= 0.073_{-0.009}^{+0.011} \text{ GeV}^3, \\ \phi_0^2(Y) &= 0.512_{-0.032}^{+0.035} \text{ GeV}^3. \end{aligned} \quad (3)$$

We note that the next-to-leading-order (NLO) QCD correction to this process has been calculated previously [12] and decreases the direct-production rate by approximately 50%. The large size of this correction is due to large logarithms of the form $\ln(m_H^2/m_V^2)$, which must be resummed in order to obtain a reliable perturbative expansion. There are two sources of such logarithms: the emission of collinear gluons and the running of the $H\bar{Q}Q$ coupling. These logarithms have been resummed in the leading-logarithmic approximation [13], and the resummed result, including the full NLO correction, is smaller than the Born amplitude for direct production by a factor of 0.597 for the $J/\psi\gamma$ final state and by a factor of 0.689 for the $Y(1S)\gamma$ final state. We include this resummed QCD correction in the numerical results that we present.

B. Indirect-production amplitude

Next we calculate the amplitude for indirect production through a virtual photon. Here, following the treatment in Ref. [14], we note that the virtual photon couples to a vector quarkonium through a matrix element of the electromagnetic current. The scattering amplitude that corresponds to this matrix element of the electromagnetic current is

$$i\mathcal{M}_{J_V} = -ie\langle V(\epsilon) | J_V^\mu(x=0) | 0 \rangle = -ieg_{V\gamma} \epsilon^{\mu*}, \quad (4)$$

²We thank Heather Logan for pointing this out to us.

where ϵ is the polarization vector of the quarkonium and J_V is the electromagnetic current,

$$J_V^\mu(x) = \sum_q e_q \bar{q}(x) \gamma^\mu q(x). \quad (5)$$

In Eq. (5), the sum is over all quark flavors, heavy and light. The decay of the quarkonium V to a lepton-antilepton pair through a single virtual photon is mediated by the adjoint of the matrix element in Eq. (4). It follows straightforwardly that

$$\Gamma[V \rightarrow l^+ l^-] = \frac{4\pi\alpha^2 g_{V\gamma}^2}{3m_V^3}. \quad (6)$$

Therefore, the magnitude of the coupling $g_{V\gamma}$ can be determined from Eq. (6). In order to determine the phase of $g_{V\gamma}$, we note that the matrix element of the electromagnetic current in a vector quarkonium state has an expansion in terms of NRQCD operator matrix elements:

$$\langle V(\epsilon) | J_V^\mu(x=0) | 0 \rangle = \sum_n c_n \langle V | \mathcal{O}_n | 0 \rangle, \quad (7)$$

where the short-distance coefficients c_n have an expansion in powers of α_s , and the long-distance matrix elements of the NRQCD operators \mathcal{O}_n scale as known powers of the heavy-quark velocity v . At leading order in α_s and v we have, in the quarkonium rest frame,

$$\begin{aligned} \langle V(\epsilon) | J_V^\mu(x=0) | 0 \rangle &= g_i^\mu e_Q \langle V(\epsilon) | \mathcal{O}^i(^3S_1^{[1]}) | 0 \rangle \\ &= -\sqrt{2N_c} \sqrt{2m_V} \phi_0 e_Q \epsilon^{*\mu}, \end{aligned} \quad (8)$$

from which it follows that

$$g_{V\gamma} = -e_Q \sqrt{2N_c} \sqrt{2m_V} \phi_0. \quad (9)$$

We take ϕ_0 to be real. An imaginary contribution to g_V of higher order in α_s arises from the annihilations of light quark-antiquark pairs into the heavy quark-antiquark pair of the quarkonium. This contribution affects the short-distance coefficient of the NRQCD matrix element $\langle V | \chi^\dagger \boldsymbol{\sigma} \psi | 0 \rangle$ and is of relative order $\alpha_s^3(m_V)$. An imaginary contribution to g_V of higher order in v arises from the production of the $Q\bar{Q}gg$ Fock state of the J/ψ . This contribution affects the NRQCD matrix element $\langle V | \chi^\dagger \boldsymbol{D}^2 \boldsymbol{\sigma} \psi | 0 \rangle$ and is of relative order v^6 . Therefore, Eq. (9) determines the phase of $g_{V\gamma}$ relative to the phase of ϕ_0 , up to corrections that are negligible in comparison to other uncertainties in the calculation.

The method of computation that is based on Eq. (4) has an important advantage over a straightforward calculation in the framework of NRQCD factorization [9]. A calculation in the NRQCD factorization framework proceeds through a double expansion in powers of α_s and v . The NRQCD long-distance matrix elements that enter at each order in v are nonperturbative quantities that must be determined from lattice calculations or from phenomenology. On the other hand, the matrix element of the

electromagnetic current in Eq. (4) already contains all of the corrections of higher order in α_s and v that appear in either quarkonium decay through a single virtual photon or quarkonium production through a single virtual photon. Hence, the higher-order corrections in both α_s and v cancel when one uses Eq. (6) to express the production amplitude in terms of the decay width.

From Eq. (4), we find that the indirect-production amplitude is given by

$$\mathcal{M}_{\text{indirect}} = -e \frac{g_{V\gamma}}{m_V^2} \mathcal{M}_{H \rightarrow \gamma\gamma}, \quad (10)$$

where we have used

$$\mathcal{M}_{H \rightarrow \gamma\gamma^*} = \mathcal{M}_{H \rightarrow \gamma\gamma} + O(m_V^2/m_H^2). \quad (11)$$

From existing calculations of $\mathcal{M}_{H \rightarrow \gamma\gamma}$, it follows that

$$\begin{aligned} \mathcal{M}_{\text{indirect}} &= -e \frac{\alpha}{\pi} \frac{g_{V\gamma}}{m_V^2} (\sqrt{2}G_F)^{1/2} I [2p_\gamma \cdot \epsilon_V^* p_V \cdot \epsilon_\gamma^* \\ &\quad - (m_H^2 - m_V^2) \epsilon_\gamma^* \cdot \epsilon_V^*]. \end{aligned} \quad (12)$$

I denotes the loop-induced coupling of the Higgs to photons, which arises primarily from top-quark and W -boson loops. Its value at leading order in α_s can be found in Ref. [15]. It is known through NLO in α_s (Refs. [15–20]). The two-loop electroweak corrections to this quantity are also known [21]. We can combine the amplitudes in Eqs. (2) and (12) to obtain the following decay width:

$$\Gamma(H \rightarrow V\gamma) = \frac{1}{8\pi} \frac{m_H^2 - m_V^2}{m_H^2} |\mathcal{A}_{\text{direct}} + \mathcal{A}_{\text{indirect}}|^2, \quad (13)$$

where

$$\begin{aligned} \mathcal{A}_{\text{direct}} &= 2\sqrt{3} e_Q e \kappa_c (\sqrt{2}G_F m_V)^{1/2} \\ &\quad \times \frac{m_H^2 - m_V^2}{\sqrt{m_H}(m_H^2 - m_V^2/2 - 2m_Q^2)} \phi_0(V), \end{aligned} \quad (14a)$$

$$\mathcal{A}_{\text{indirect}} = -\frac{e g_{V\gamma}}{m_V^2} (\sqrt{2}G_F)^{1/2} \frac{\alpha}{\pi} \frac{(m_H^2 - m_V^2)}{\sqrt{2}m_H} I. \quad (14b)$$

We have included the m_V^2 dependence of $\mathcal{A}_{\text{indirect}}$ that arises from the tensor in Eq. (12) and the exact m_V^2 dependences of the phase space and of $\mathcal{A}_{\text{direct}}$. We note that I is negative for relevant values of the Higgs mass, except for a small phase of about 0.005. Using Eq. (9), where it can be seen that $g_{V\gamma}$ contains a factor e_Q , we find that the interference between production mechanisms is destructive for both the J/ψ and the $Y(1S)$ final states. Making use of Eq. (10), we can write the indirect contribution to \mathcal{A} in terms of the $H \rightarrow \gamma\gamma$ amplitude,

$$\begin{aligned} \mathcal{A}_{\text{indirect}} &= \frac{e g_{V\gamma}}{m_V^2} [16\pi\Gamma(H \rightarrow \gamma\gamma)]^{1/2} \\ &\quad \times \frac{m_H^2 - m_V^2}{m_H^2} \left[1 - \left(\frac{m_V}{183.43 \text{ GeV}} \right)^2 \right], \end{aligned} \quad (15)$$

where we have multiplied $\Gamma(H \rightarrow \gamma\gamma)$ by a factor of 2 to remove its identical-particle symmetrization factor, and we have dropped the small phase of I , which affects the interference term in the cross section by an amount that is completely negligible in comparison with the theoretical uncertainties in the interference term. In Eq. (15), we have included the corrections of order m_V^2/m_H^2 to $\Gamma(H \rightarrow \gamma\gamma^*)$ that appear at leading order in α_s . These can be inferred from the results for the $HZ\gamma$ coupling that are given in Ref. [22]. In our numerical analysis, we obtain $\mathcal{A}_{H \rightarrow \gamma\gamma}$ from the results for the $H \rightarrow \gamma\gamma$ branching ratio and the H total width in Refs. [23,24]. This has the effect of incorporating higher-order radiative corrections into our prediction.

C. Numerical results

The contribution of the indirect-production amplitude to the $H \rightarrow V\gamma$ rate can be calculated in the SM with a precision of a few percent.³ Hence, these uncertainties should not be an obstacle in discerning the contribution that arises from the direct production mechanism. Our predictions for the indirect contributions for $m_H = 125$ GeV are

$$\Gamma_{\text{indirect}}(H \rightarrow J/\psi\gamma) = (1.32 \pm 0.04) \times 10^{-8} \text{ GeV}, \quad (16a)$$

$$\Gamma_{\text{indirect}}(H \rightarrow Y(1S)\gamma) = (1.02 \pm 0.02) \times 10^{-9} \text{ GeV}, \quad (16b)$$

where we have used $\alpha(m_{J/\psi}) = 1/132.64$ and $\alpha(m_{Y(1S)}) = 1/131.87$ in computing the photon-quarkonium couplings.

The principal uncertainties in the direct-production amplitudes arise from ϕ_0 [Eq. (3)], from uncalculated corrections of order α_s^2 , which are not included in the calculation of Ref. [13], and from uncalculated corrections of order v^2 .

³Uncertainties in the indirect widths arise as follows. The leading correction to the single-virtual-photon quarkonium-production amplitude arises from triple-gluon quarkonium production, where one gluon has energy of order m_V and the other two gluons have energies of order $m_V v$ in the quarkonium rest frame. This correction is suppressed as $\alpha_s^{3/2}(m_t)\alpha_s^{1/2}(m_V)v^2(m_V^2/m_t^2)/(\pi\alpha)$ relative to the amplitude that we compute. The suppression factor is about 7×10^{-5} for the J/ψ and 3×10^{-4} for the $Y(1S)$. The theoretical uncertainty from uncalculated higher-order corrections to $\Gamma(H \rightarrow \gamma\gamma)$ is estimated to be 1% (Ref. [24]). The uncertainties in m_t and m_W result in uncertainties in $\Gamma(H \rightarrow \gamma\gamma)$ of about 2.2×10^{-4} and 2.4×10^{-4} , respectively. The uncertainties in g_V^2 that arise from the uncertainties in the quarkonium leptonic widths are about 2.5% for the J/ψ and about 1.3% for the $Y(1S)$. Adding these uncertainties in quadrature, we conclude that the uncertainty in $\Gamma_{\text{indirect}}(H \rightarrow J/\psi\gamma)$ is about 2.7% and the uncertainty in $\Gamma_{\text{indirect}}(H \rightarrow Y(1S)\gamma)$ is about 1.6%. We have not included the uncertainty in $\Gamma_{\text{indirect}}(H \rightarrow V\gamma)$ that arises from the uncertainty in m_H . For a 1 GeV uncertainty in m_H , this is an uncertainty of about 3.5%. However, if m_H is ultimately measured with a precision of about 0.1%, then this source of uncertainty will become negligible.

We estimate the order- α_s^2 corrections to be 2% and the order- v^2 corrections to be 30% for the J/ψ and 10% for the $Y(1S)$. We make use of these uncertainty estimates to obtain the following predictions for the SM widths of H into quarkonium plus photon for $m_H = 125$ GeV:

$$\Gamma_{\text{SM}}(H \rightarrow J/\psi\gamma) = (1.00_{-0.10}^{+0.10}) \times 10^{-8} \text{ GeV}, \quad (17a)$$

$$\Gamma_{\text{SM}}(H \rightarrow Y(1S)\gamma) = (5.74_{-4.64}^{+8.27}) \times 10^{-11} \text{ GeV}. \quad (17b)$$

In computing the direct amplitudes, we have used $\alpha = \alpha(m_H/2) = 1/128$. In order to maintain compatibility with the result of Ref. [13], which is given in terms of the heavy-quark pole mass, we have set $m_c = m_c(\text{pole}) = (1.67 \pm 0.07) \text{ GeV}$ and $m_b = m_b(\text{pole}) = (4.78 \pm 0.06) \text{ GeV}$ in the direct amplitudes. We note that the $H \rightarrow J/\psi\gamma$ rate is under reasonably good theoretical control.

In order to get a feeling for the sizes of the SM rates that are associated with these production modes, we convert them to branching ratios, using the result for the total Higgs width that is given in Ref. [24]. We obtain the following results for J/ψ and Y decays:

$$\text{BR}_{\text{SM}}(H \rightarrow J/\psi\gamma) = (2.46_{-0.25}^{+0.26}) \times 10^{-6}, \quad (18a)$$

$$\text{BR}_{\text{SM}}(H \rightarrow Y(1S)\gamma) = (1.41_{-1.14}^{+2.03}) \times 10^{-8}. \quad (18b)$$

We note that, for the J/ψ final state, a consideration of the direct amplitude alone would lead instead to a branching ratio of 5.48×10^{-8} , while for the $Y(1S)$ it would lead to 3.84×10^{-7} . The inclusion of the indirect amplitude is crucial in order to obtain an accurate prediction for the $V\gamma$ production rate. In order to compute the rate for the experimentally clean l^+l^- final state, we must multiply these results by branching ratios for $V \rightarrow l^+l^-$, which are 5.93% for the J/ψ and 2.48% for the $Y(1S)$, with $l = e$ or μ . We will estimate the event yields more carefully in Sec. III, but for now we simply multiply the branching ratios above by the inclusive cross sections that are tabulated in Ref. [25] in order to determine the number of events that will be produced at the LHC. It is clear that the Y rate in the SM is far too small to be seen, and so we focus on the J/ψ . Summing over both electron and muon final states and combining the event yields of ATLAS and CMS, we find 0.3 $J/\psi \rightarrow l^+l^-$ events for an integrated luminosity of 20 fb^{-1} at an 8 TeV LHC. This event yield is too small to be observed. However, an integrated luminosity of 3000 fb^{-1} at a 14 TeV LHC would produce 100 $J/\psi \rightarrow l^+l^-$ events. The J/ψ mode should be observable at the high-luminosity LHC run, as we discuss in more detail in the next section.

As we have mentioned, the quantities that appear in the indirect-production amplitude are very well known, and the key quantity that appears in this amplitude, $\Gamma(H\gamma\gamma)$, will be measured with increasing precision at the LHC. Therefore, it is possible, in principle, to distinguish the effect of the amplitude that arises from direct $H\bar{Q}Q$ coupling from the effect of the indirect-production amplitude.

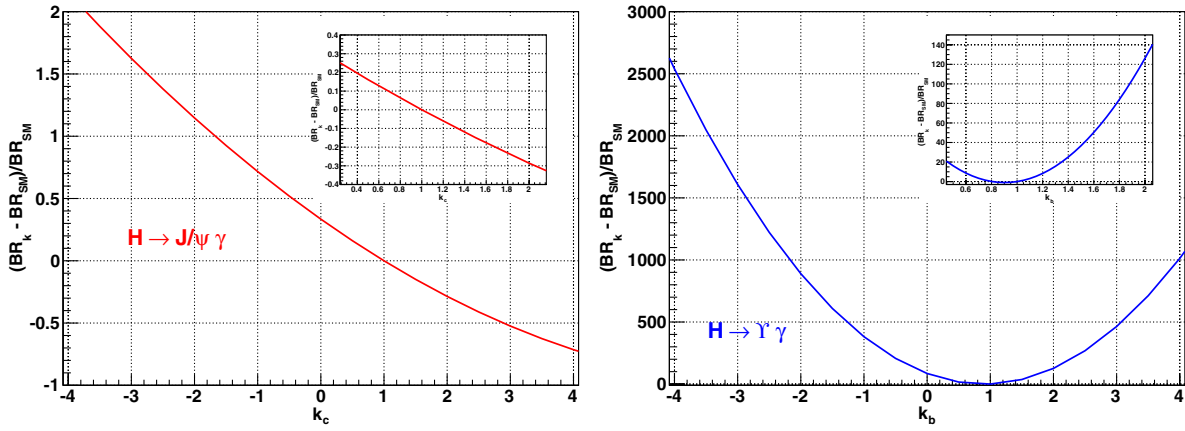


FIG. 1 (color online). The relative deviations in the branching ratios for $H \rightarrow J/\psi\gamma$ (left panel) and $H \rightarrow Y(1S)\gamma$ (right panel) as functions of the scaling parameters κ_Q , which are defined in Eq. (1).

We note that turning off the direct-production amplitude for the J/ψ would lead to a branching ratio of 3.25×10^{-6} and 132 events. This is a statistically significant deviation of about 30% from the SM event yield. Hence, measurement of the $H\bar{c}c$ coupling is a reasonable goal for future experimental searches.

Deviations of κ_Q from unity parametrize deviations of the $H\bar{Q}Q$ coupling from its SM value. We show in Fig. 1 the relative deviations in the $H \rightarrow J/\psi\gamma$ and $H \rightarrow Y(1S)\gamma$ branching ratios as functions of κ_Q . The shifts in the experimentally promising J/ψ mode can reach 100% for values of κ_c that are a few times the SM value. In the case of $Y(1S)$ production, the deviations are extraordinarily large: within the SM there is a strong cancellation between the direct and indirect production mechanisms that is lifted if the $H\bar{b}b$ coupling is changed. Changes in this coupling of a few times the SM value can, therefore, likely be probed in this channel at the LHC. Because the interference of the $Y(1S)$ SM production amplitudes is almost completely destructive, most values of $\kappa_b \neq 1$ result in an increase in the predicted branching ratio relative to its SM value.

Now let us investigate whether the $J/\psi\gamma$ decay mode is visible over the continuum $H \rightarrow \mu^+\mu^-\gamma$ decay mode. We estimate the continuum background by integrating the continuum production rate [26] over the range $m_{\mu^+\mu^-} \in [m_{J/\psi} - 0.05 \text{ GeV}, m_{J/\psi} + 0.05 \text{ GeV}]$. The integration range is consistent with the experimental resolution, which is discussed in the next section. We find that

$$\text{BR}_{\text{cont}}(H \rightarrow \mu^+\mu^-\gamma) = 2.3 \times 10^{-7}, \quad (19)$$

which is comparable in size to $\text{BR}_{\text{SM}}(H \rightarrow J/\psi\gamma) \times \text{BR}(J/\psi \rightarrow \mu^+\mu^-)$. Our conclusion is that the $J/\psi\gamma$ mode should be visible over the continuum background.

III. EXPERIMENTAL PERSPECTIVES

The ATLAS and CMS collaborations can search for the $V\gamma$ decay channels by using the single-lepton, dilepton or

lepton-plus-photon triggers. The Higgs-to- $V\gamma$ decay is characterized by a high- p_T photon recoiling against a lepton-antilepton pair from the V decay. The vector quarkonium state will be highly boosted, causing the two leptons to be close to each other in angle, with their momenta transverse to the boost axis anticorrelated. On the basis of these event characteristics and the current performance of the ATLAS and CMS detectors and event reconstruction, the following conclusions can be drawn.

- (1) The resolution of the invariant mass of the lepton and antilepton is almost independent of their kinematics. The average lepton momentum is expected to be around 30 GeV. Therefore, the resolution of the muon transverse momenta ($\mu^+\mu^-$ invariant mass) can be as good as 1.3% (1.8%) [27].
- (2) The resolution of the photon energy is around 1% [28].
- (3) The resulting resolution of the three-body (Higgs) invariant mass is around 2.1%. However, if the leptons and the photon are both at high pseudorapidity, then the resolution will be only about 4%.
- (4) The production vertex is well defined by the leptons and, owing to the high energy of the photon, the contamination from pile-up events (those with multiple interactions per bunch crossing) is expected to be small.

As is shown in Fig. 2, studies that are based on the MCFM [29] event generator predict that the detector geometrical acceptance for Higgs-to- $\mu\mu\gamma$ events is better than 70%. After a basic event selection has been performed, 45–60% of the signal events will remain. Since there is no missing energy in the signal events and the expected mass resolution is a few GeV, a clear resonance over the background in the $\mu\mu\gamma$ invariant mass distribution is expected. To first approximation, the sensitivity of the measurement is given by $\sqrt{(S+B)/S}$, where S and B are the signal and background events, respectively. The numerator corresponds to the statistical uncertainty of the observed sample. Figure 3

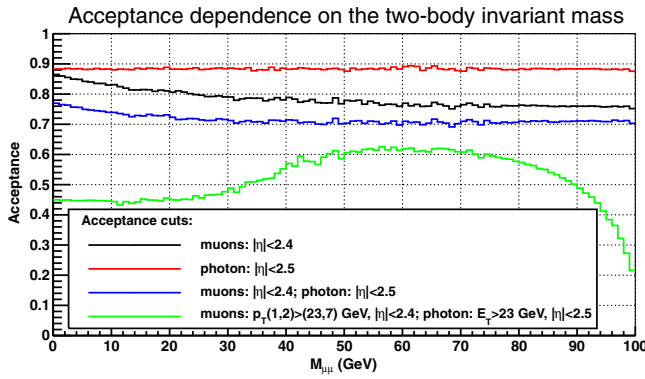


FIG. 2 (color online). Top curve: Geometrical acceptance for the Higgs to $\mu\mu\gamma$ decay channel for $m_H = 125$ GeV. Lower curves: Acceptance after the application of additional kinematic requirements.

shows the expected sensitivity as a function of the signal events at different values of $k = B/S$ (background-to-signal ratio). On the basis of the $H \rightarrow Z\gamma$ search at ATLAS and CMS [30], we expect the performance and sensitivity of the ATLAS and CMS detectors for $H \rightarrow J/\psi\gamma$ in the electron channel to be similar to that for $H \rightarrow J/\psi\gamma$ in the muon channel.

Given the sensitivity that is required to observe the process $H \rightarrow \gamma\gamma$ at the LHC, we estimate that a sensitivity of about 30–40% is required in order to observe the process $H \rightarrow V\gamma$ at the LHC. The current $H \rightarrow \gamma\gamma$ searches, which were performed using the 8 TeV data, observed

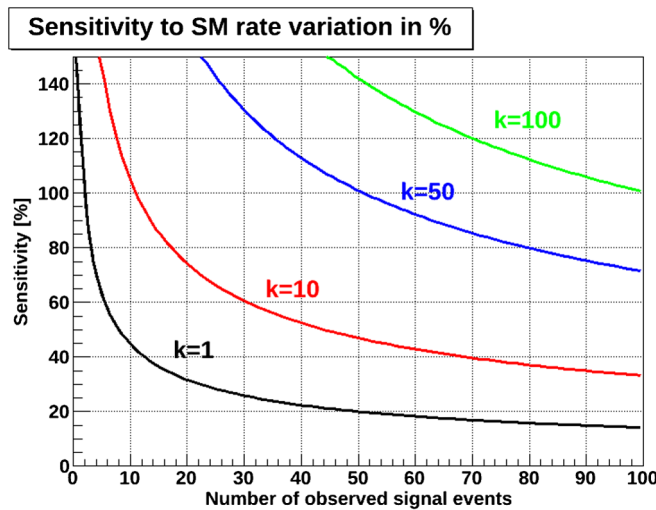


FIG. 3 (color online). Search sensitivity for the process $H \rightarrow J/\psi\gamma \rightarrow l^+l^-\gamma$ as a function of the number of expected signal events. k is the ratio of background over signal; as discussed in the text, $k < 10$ is expected in the experimental analysis. If one combines the events in the muon and electron channels and combines the ATLAS and CMS data, then about 50 reconstructed $H \rightarrow J/\psi\gamma \rightarrow l^+l^-\gamma$ signal events are expected for an integrated luminosity of 3000 fb^{-1} at a center-of-mass energy of 14 TeV.

about 400 signal events per experiment in a mass window around 125 GeV, with a background-to-signal ratio that is estimated to be about 50. In an $H \rightarrow J/\psi\gamma$ search, the background-to-signal ratio is expected to be 10 or lower after one has imposed the requirement that the dilepton pair and the photon be back-to-back and the requirement that the dilepton invariant mass be consistent with the J/ψ mass. Suppose that an overall acceptance and event-reconstruction efficiency of 50% is achieved and that one combines the events in the electron and the muon decay channels and combines the ATLAS and CMS data. Then, 50 signal events can be expected for an integrated luminosity of 3000 fb^{-1} at a center-of-mass energy of 14 TeV. As is shown in Fig. 3, this data sample could be large enough for one to observe the $H \rightarrow J/\psi\gamma$ decay channel at the LHC. If a background-to-signal ratio of unity can be achieved, then the measurement may be sensitive to the direct-production amplitude, and, therefore, to the $H\bar{c}c$ coupling in the SM.

IV. CONCLUSIONS

In this paper we have reconsidered the decays $H \rightarrow V\gamma$, with $V = J/\psi, \Upsilon(1S)$. We have identified a previously unstudied mechanism for this decay: $H \rightarrow \gamma^*\gamma$, followed by the transition $\gamma^* \rightarrow V$. This indirect production mechanism is the dominant contribution to quarkonium production in Higgs decays, and leads to a production rate for the $J/\psi\gamma$ final state that is an order of magnitude larger than had previously been estimated.

The indirect production mechanism interferes at the amplitude level with the direct production mechanism, which proceeds via the $H\bar{Q}Q$ coupling. This interference enhances the effect of the direct-production amplitude on the $H \rightarrow V\gamma$ decay rate, opening the possibility that the $H\bar{Q}Q$ coupling can be measured at the LHC. In the SM, the interference term shifts the $H \rightarrow J/\psi\gamma$ rate by 30%. If the $H\bar{c}c$ coupling deviates from its SM value by a factor of two or more, then this shift can reach 100% or more. In the case of the $H \rightarrow \Upsilon(1S)\gamma$ decay rate, for which there is an almost complete cancellation between the direct and indirect amplitudes in the SM, a deviation of the $H\bar{b}b$ coupling from its SM value by a factor of two or more can shift the decay rate by a factor of 1000 or more. We have argued that the indirect-production amplitude is known with few-percent accuracy within the SM. Therefore, the uncertainty in the indirect-production amplitude would not preclude the measurement of an $H\bar{c}c$ coupling that is of order the SM value or an $H\bar{b}b$ coupling that is a few times the SM value.

We have presented numerical results for both the $J/\psi\gamma$ and $\Upsilon(1S)\gamma$ final states, and we have performed a realistic analysis of the $J/\psi \rightarrow l^+l^-$ signal at the LHC. At a high-luminosity LHC that has accumulated several inverse attobarns of integrated luminosity, the l^+l^- decay mode should be observable. Consequently, it may be possible to

detect the effect of the direct-production amplitude, and thereby to obtain a direct measurement of the $H\bar{c}c$ coupling at the LHC.

We conclude that the $J/\psi\gamma$ decay mode of the Higgs may enable the direct measurement of the $H\bar{c}c$ coupling at the LHC—something that was previously believed to be impossible. Such a measurement would provide a further test of the hypothesis that the observed Higgs-like particle has the couplings of an elementary SM Higgs. We believe that the possibility of observing the $H\bar{c}c$ coupling through the $J/\psi\gamma$ decay mode provides a motivation for the high-luminosity run of the LHC, and we encourage the ATLAS and CMS collaborations to pursue this measurement.

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