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Next-to-leading order QCD corrections to Higgs boson decay to quarkonium plus a photon *

Chao Zhou(周超)[1] Mao Song(宋昴)[1;1)] Gang Li(李刚)[1] Ya-Jin Zhou(周雅瑾)[2] Jian-You Guo(郭建友)[1]

[1] School of Physics and Material Science, Anhui University, Hefei 230601, China

[2] School of Physics, Shandong University, Jinan 250100, China

Abstract: In this paper, we investigate the decay of the Higgs boson to J/ψ(Υ) plus a photon based on NRQCD factorization. For the direct process, we calculate the decay width up to QCD NLO. We find that the decay width for process $H \to J/\psi(\Upsilon)+\gamma$ direct production at the LO is significantly reduced by the NLO QCD corrections. For the indirect process, we calculate the $H \to \gamma^*\gamma$ with virtual γ substantially decaying to J/ψ(Υ), including all the SM Feynman diagrams. The decay width of indirect production is much larger than the direct decay width. Since it is very clean in experiment, the $H \to J/\psi(\Upsilon)+\gamma$ decay could be observable at a 14 TeV LHC and it also offers a new way to probe the Yukawa coupling and New Physics at the LHC.

Keywords: Higgs boson, heavy quarkonium, NLO QCD

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1 Introduction

Recently, both ATLAS and CMS collaborations announced that they have observed a new boson with mass around 125 GeV, whose properties are consistent with the Standard Model(SM) Higgs in any measured channel [1–4]. After discovery of the Higgs boson, the main task is to determine its properties, such as spin, CP, and couplings. The couplings to gauge bosons and the third-generation fermions are measured directly, and are fixed through the well- measured diboson decays of the Higgs, determined at the $20\% - 30\%$ level. However, we have little information about the Higgs Yukawa couplings to the first- and second-generation quarks at current experiments, since these couplings are predicted to be small in the SM, and the inclusive decays of the Higgs to these states are swamped by large QCD backgrounds. These couplings are indirectly and weakly constrained by the inclusive Higgs production cross section [5, 6]. Such constraints only probe the simultaneous deviation of all Yukawa couplings. They do not provide information about the separate Yukawa couplings of the different quarks.

The study of heavy quarkonium is one of the interesting subjects in high energy physics, and offers a good testing ground for investigating Quantum Chromodynamics (QCD) in both the perturbative and non-perturbative regimes. The factorization formalism of non-relativistic QCD (NRQCD) [7] as a rigorous theoretical framework to describe the heavy-quarkonium production and decay has been widely investigated both at experimental and theoretical aspects. Many experimental data for heavy quarkonium production and decay are fairly well described by the NRQCD theory [8–13].

Recent works have shown that the exclusive decays of the Higgs boson to vector mesons could probe the Yukawa couplings of first- and second-generation quarks at future runs of the LHC [14]. These couplings are hard to access in hadron colliders through the direct $H \to q\bar{q}$ decays, owing to the overwhelming QCD background. While the Yukawa couplings $Hc\bar{c}$ might be probed at the LHC by making use of charm-tagging techniques, its phase must be determined through processes involving quantum interference effects, such as the decay [15]. Although the branching ratios of Higgs boson to vector mesons are small, they offer complementary information about Higgs couplings and can serve for searching for New Physics (NP) beyond the SM. Besides, subsequent decays of J/ψ(Υ) into a pair of leptons is a clean channel in experiments. Recently, Higgs rare decay to a vector quarkonium (J/ψ, Υ) received considerable attention [15–19]. The relativistic correction for the Higgs boson

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1) E-mail: songmao@mail.ustc.edu.cn

decay to an S-wave vector quarkonium plus a photon has been calculated in Ref. [35]. A search for the decays of the Higgs and Z bosons to J/ψ and Υ has been performed using integrated luminosity of 20.3 fb^{-1} with the ATLAS detector at the 8 TeV LHC. No significant excess of events was observed above expected backgrounds and 95% CL upper limits are placed on the branching fractions. In the J/ψγ and Υ(1S)γ final state the limits are 1.5×10^{-3} and 1.3×10^{-3} for the Higgs boson, respectively [20].

As we know, the NLO QCD corrections to quarkonium production are usually significant [21–23]. We should generally take the NLO QCD corrections into account in studying heavy-quarkonium production processes. In this paper, we will calculate the H → J/ψ(Υ)+ γ process up to the QCD NLO within the NRQCD framework by applying the covariant projection method [24]. The paper is organized as follows. We present the details of the calculation strategies in Section 2. The numerical results are given in Section 3. Finally, a short summary and discussions are given.

2 Calculation descriptions

2.1 LO calculation for direct production

We begin by discussing the decay H → J/ψ+γ. Since the calculation of the Υ decay is identical to the J/ψ, we will not present it explicitly in this section. There are two Feynman diagrams for this process at leading order(LO), which are shown in Fig. 1. We calculate the amplitudes by making use of the standard methods of NRQCD factorization [7]. The process H → c$\bar{\text{c}}$+γ at LO is denoted as:

$$\text{H}(p_1)\to \text{c}(p_2)\bar{\text{c}}(p_3)+\gamma(p_4). \tag{1}$$

The amplitudes for the two diagrams are given by

$$\begin{aligned}\mathcal{M}_{i1}=&\bar{u}(p_2)\cdot\frac{-\text{i}em_\text{c}}{2m_\text{W}s_\text{W}}\cdot\frac{\text{i}}{\not p_1-\not p_2-m_\text{c}}\\&\cdot\text{i}\frac{2}{3}e\gamma^\mu\cdot v(p_3)\epsilon^*_\mu(p_4),\\ \mathcal{M}_{i2}=&\bar{u}(p_2)\cdot\text{i}\frac{2}{3}e\gamma^\mu\cdot\frac{\text{i}}{\not p_1-\not p_3-m_\text{c}}\\&\cdot\frac{-\text{i}em_\text{c}}{2m_\text{W}s_\text{W}}\cdot v(p_3)\epsilon^*_\mu(p_4).\end{aligned} \tag{2}$$

The relative momentum between the c and $\bar{\text{c}}$ is defined as $q=(p_2-p_3)/2$, and the total momentum of the J/ψ is defined as $p=p_2+p_3$. Then, we obtain the following relations among the momenta:

$$\begin{aligned}&p_2=\frac{1}{2}p+q,\;\; p_3=\frac{1}{2}p-q,\;\; p\cdot q=0,\\&p_2^2=p_3^2=m_\text{c}^2,\;\; p^2=E^2,\;\; q^2=m_\text{c}^2-E^2=-m_\text{c}^2v^2.\end{aligned} \tag{3}$$

In the c$\bar{\text{c}}$ rest frame, $p=(E,0)$ and $q=(0,q)$. In the non-relativistic $v=0$ limit, $p^2=4m_\text{c}^2$, $q^2=0$. In order to produce a J/ψ, the c$\bar{\text{c}}$ pair must be produced in a spin-triplet, color-singlet Fock state. We can obtain the short-distance amplitudes by applying certain projectors onto the usual QCD amplitudes for open c$\bar{\text{c}}$ production. By using the notations in Ref. [24], we get the amplitudes:

$$\mathcal{M}_{^3S_1^{(1)}}=\mathcal{E}_\alpha\text{Tr}\left[\mathcal{C}_1\Pi_1^\alpha\mathcal{M}\right]_{q=0},$$

where the spin-triplet projector is given by

$$\Pi_1^\alpha=\frac{1}{\sqrt{8m^3}}\left(\frac{\not p}{2}-\not q-m\right)\gamma^\alpha\left(\frac{\not p}{2}+\not q+m\right). \tag{4}$$

The colour singlet state will be projected out by contracting the amplitudes with the following operators :

$$\mathcal{C}_1=\frac{\delta_{ij}}{\sqrt{N_\text{c}}}. \tag{5}$$

The amplitude $\mathcal{M}$ is obtained by calculating the two Feynman diagrams in Fig. 1 in QCD perturbation theory. The trace is over both the Lorenz and color indices.

After the application of this set of rules, we obtain the short-distance partial decay width $\hat{\Gamma}$ for H → c$\bar{\text{c}}$[$^3S_1^{[1]}$]+γ processes:

$$\text{d}\hat{\Gamma}(\text{H}\to\text{c}\bar{\text{c}}[^3S_1^{[1]}]+\gamma)=\frac{1}{32\pi^2}|\mathcal{M}_{^3S_1^{[1]}}|^2\frac{|p|}{m_\text{H}^2}\text{d}\Omega, \tag{6}$$

where $|p|=\dfrac{m_\text{H}^2-m_{\text{J}/\psi}^2}{2m_\text{H}}$ and m_H represent the Higgs boson mass. $\text{d}\Omega=\text{d}\phi\text{d}(\cos\theta)$ is the solid angle of particle J/ψ.

$$|\mathcal{M}_{^3S_1^{[1]}}|^2=\frac{256\pi^2\alpha^2m_\text{c}}{3m_\text{W}^2s_\text{W}^2}. \tag{7}$$

The decay width read:

$$\begin{aligned}&\Gamma(\text{H}\to\text{J}/\psi+\gamma)\\&=\hat{\Gamma}(\text{H}\to\text{c}\bar{\text{c}}(^3S_1^{[1]})+\gamma)\frac{<\mathcal{O}^{J/\psi}(^3S_1^{[1]})>}{2N_\text{c}N_\text{col}N_\text{pol}},\end{aligned} \tag{8}$$

where N_col and N_pol refer to the number of colours and polarization states of the c$\bar{\text{c}}$ pair produced. The color-singlet states $N_\text{col}=1$, and $N_\text{J}=3$ for polarization vectors $^3S_1^{[1]}$ state in 4 dimensions. $2N_\text{c}$ is due to the difference between the conventions in Ref. [24] and Ref. [7].

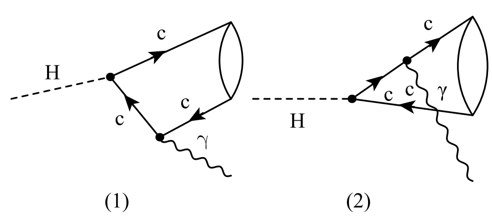

Fig. 1. The Feynman diagrams for the H → c$\bar{\text{c}}$[$^3S_1^{[1]}$]+γ direct decay process at the LO.

2.2 NLO calculation for direct production

At LO, we have two contributing Feynman diagrams, and at NLO there are 14. All Feynman diagrams are generated with program FeynArts, and evaluated by using our in-house program, which is written in the programming language Mathematica. The one-loop diagrams for the $\mathcal{O}(\alpha_s)$ corrections to $\mathrm{H}\rightarrow \mathrm{c\bar{c}}[^3S_1^{[1]}]+\gamma$ are shown in Fig. 2. The α_s corrections involving virtual gluons include the interferences between Born diagrams and one-loop virtual diagrams. The virtual diagrams are computed analytically and all tensor integrals are reduced to linear combinations of one-loop scalar functions. The virtual corrections contain Ultraviolet (UV), Infrared (IR) and Coulomb singularities. In our calculations, we adopt the dimensional regularization (DR) scheme to regularize the UV and IR divergences in D dimensions with $D\equiv 4-2\epsilon$. The UV singularities of the virtual corrections are removed by introducing a set of related counterterms. The counterterms for the charm quark wave function and the charm quark mass are defined as

$$\psi_{\mathrm{c}}^0=\left(1+\frac{1}{2}\delta Z_{\mathrm{c}}\right)\psi_{\mathrm{c}}\ , \qquad (9)$$
$$m_{\mathrm{c}}^0=m_{\mathrm{c}}+\delta m_{\mathrm{c}}.$$

The on-mass-shell scheme is adopted to fix the wave function and mass renormalization constant of the external charm quark field, then we obtain

$$\delta Z_{\mathrm{c}}=-3C_{\mathrm{F}}\frac{\alpha_s}{4\pi}\left[\Delta_{\mathrm{UV}}+\ln\frac{\mu_r^2}{m_{\mathrm{c}}^2}+\frac{4}{3}\right]\ , \qquad (10)$$
$$\frac{\delta m_{\mathrm{c}}}{m_{\mathrm{c}}}=-\frac{\alpha_s}{3\pi}\left[3\Delta_{\mathrm{UV}}+4+\ln\frac{\mu_r^2}{m_{\mathrm{c}}^2}\right]\ ,$$

where $\Delta_{\mathrm{UV}}=\frac{1}{\epsilon_{\mathrm{UV}}}-\gamma_{\mathrm{E}}+\ln(4\pi)$. After applying the renormalization procedure the UV divergences in the virtual correction are canceled. The IR singularities are analytically canceled when we add all the virtual Feynman diagrams together. We adopt the expressions in Ref. [25] to deal with the IR divergences in Feynman integral functions, and apply the expressions in Refs. [26–28] to implement the numerical evaluations for the IR safe parts of N-point integrals. In the virtual correction calculation, we find that only Fig. 2(13) and Fig. 2(14) induce Coulomb singularities, and we use a small relative velocity v between c and $\bar{c}$ to regularize them [29].

2.3 Indirect decay calculation

The direct Higgs decay process to the heavy quarkonium plus photon is mainly produced through the Higgs and charm quarks Yukawa coupling. The indirect decay process is mainly produced through the Higgs decaying into two photons, then one virtual photon substantially decaying to a $\mathrm{c\bar{c}}$ quark pair. Since Higgs decays into the di-photon process are forbidden at tree level in SM, the leading order contribution comes from the one-loop

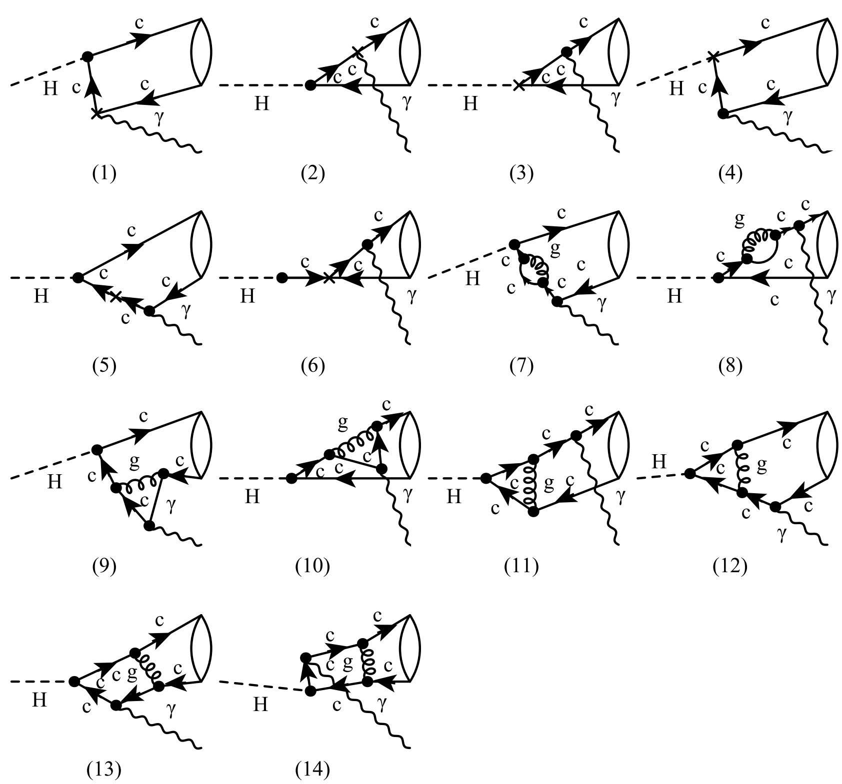

Fig. 2. The Feynman diagrams for the $\mathrm{H}\rightarrow \mathrm{c\bar{c}}[^3S_1^{[1]}]+\gamma$ direct decay process at QCD NLO.

Feynman diagrams, including top quark and W boson triangle diagrams, which are shown in Fig. 3. Due to the fact that the coupling strength of Higgs and top(W) is proportional to the particle mass, the contribution of indirect decay is not small. The process Higgs decays into di-photon at leading order in $\alpha_{\rm s}$ have been calculated in Ref. [30]. The two-loop electroweak and QCD corrections to this process have also been studied in Ref. [31]. In Ref. [14], the authors gave the approximate results for the Higgs decay to J/ψ(Υ) and photon through Higgs decaying into two photons. In our paper, we analytically calculate this process based on NRQCD factorization. In Feynman gauge, there are 28 Feynman diagrams, which include the contributions from not only the top and W-boson loops, but also the ghost and Goldstone loops. First we generate the amplitudes of Higgs decay to di-photon, which is given by

$$\mathcal{M}^{\mu\nu}_{\rm H\to\gamma\gamma}=\frac{{\rm i}\alpha^{\frac{3}{2}}}{24m_{\rm W}s_{\rm W}\sqrt{\pi}}\times(\mathcal{A}g^{\mu\nu}+\mathcal{B}p^{\nu}p_4^{\mu}). \tag{11}$$

The expressions of coefficients $\mathcal{A}$ and $\mathcal{B}$ are listed in the appendix. Then we multiply it to the amplitude of virtual photon decay to c$\bar{\rm c}$ quarks pair. After the application of the projection operator, we get the short-distance amplitude,

$$\begin{aligned}\mathcal{M}_{\rm indirect}=&\mathcal{M}^{\mu\nu}_{\rm H\to\gamma^*\gamma}\frac{2}{3}e\frac{-g^{\mu\sigma}}{p_1^2}\\ &{\rm Tr}\Big[\frac{1}{\sqrt{8m_{\rm c}^3}}\left(\frac{\not p}{2}-\not q-m_{\rm c}\right)\\ &\gamma^{\mu}\left(\frac{\not p}{2}+\not q+m_{\rm c}\right)\frac{\delta_{ij}}{\sqrt{N_{\rm c}}}\Big]_{q=0}\epsilon^*_{\sigma}\epsilon^*_{\nu}.\end{aligned} \tag{12}$$

Following the Passarino-Veltman (PV) method, we can express the tensor integrals as a linear combination of tensor structures and coefficients, where the tensor structures depend on the external momenta and the metric tensors, while the coefficients depend on one-loop scalar

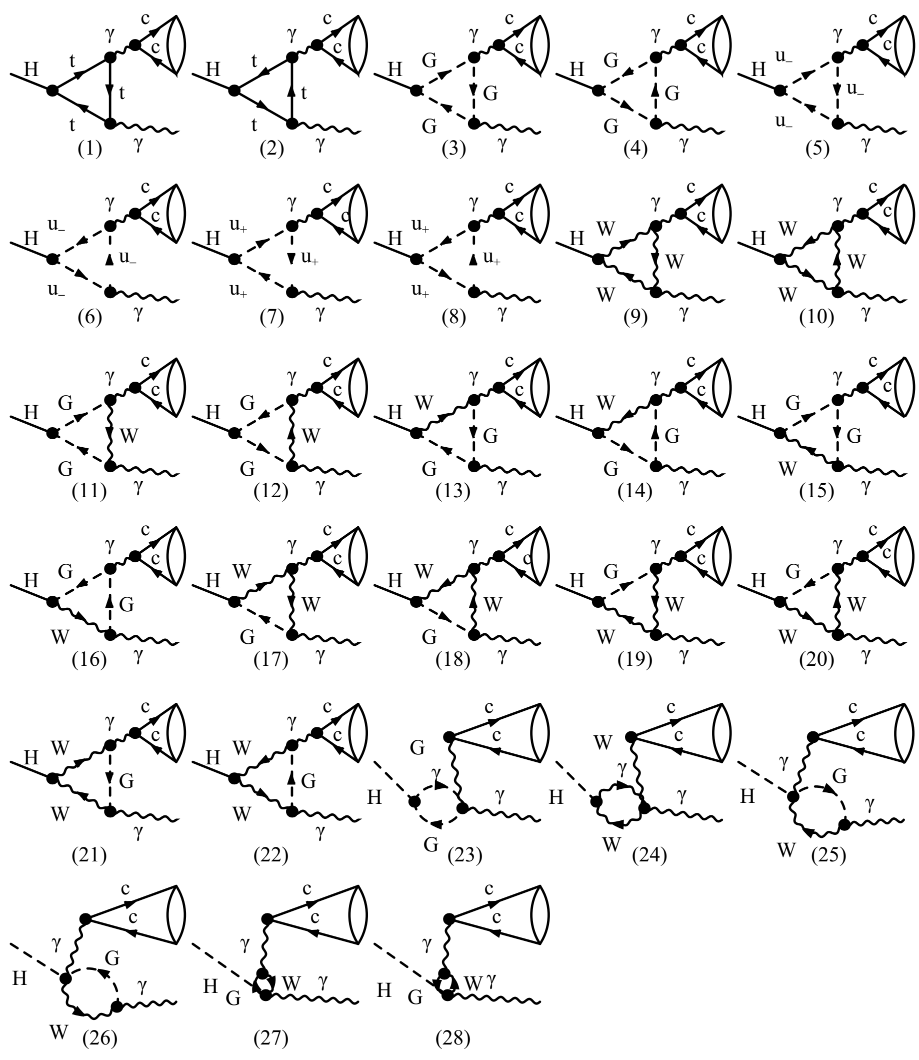

Fig. 3. The Feynman diagrams for the $\rm H\to c\bar{c}[^3S_1^{[1]}]+\gamma$ indirect decay process.

integrals, kinematics invariants and the dimension of the integral. The one-loop integrals are calculated analytically by using dimensional regularization in $D=4-2\epsilon$ dimensions. Finally, we squared all the amplitudes in 4 dimensions.

3 Numerical results and discussion

In this section, we discuss our numerical results for both the central values and theoretical errors for the $\mathrm{H}\to\mathrm{J}/\psi+\gamma$ and $\mathrm{H}\to\Upsilon(1S)+\gamma$ decays. The relevant parameters are taken as [32]

$$\alpha^{-1}=137.036, m_{\mathrm{Z}}=91.1876\ \mathrm{GeV}, m_{\mathrm{W}}=80.385\ \mathrm{GeV},$$
$$m_{\mathrm{c}}=m_{\mathrm{J}/\psi}/2=1.5\ \mathrm{GeV}, m_{\mathrm{b}}=m_{\Upsilon(1S)}/2=4.75\ \mathrm{GeV},$$
$$m_{\mathrm{t}}=173.2\ \mathrm{GeV}. \quad (13)$$

We take two-loop running α_s in the calculation, and the corresponding fitted value $\alpha_s(M_Z)=0.118$ is used for the calculations. The renormalization and NRQCD scales are chosen as $\mu_r=m_{\mathrm{H}}$ and $\mu_\Lambda=m_{\mathrm{c}}(m_{\mathrm{b}})$, respectively. The Long Distance Matrix Elements (LDME) for J/ψ and Υ used in this paper are set as: [33] $<\mathcal{O}^{J/\psi}[^3S_1^{(1)}]>=1.3\ \mathrm{GeV}^3$, $<\mathcal{O}^{\Upsilon}[^3S_1^{(1)}]>=9.28\ \mathrm{GeV}^3$.

Finally, we get the decay widths for $\mathrm{H}\to\mathrm{J}/\psi(\Upsilon)+\gamma$ for the direct and indirect processes:

$$\Gamma_{\mathrm{LO}}^{\mathrm{direct}}(\mathrm{H}\to\mathrm{J}/\psi+\gamma)=5.334\times10^{-10}\ \mathrm{GeV}$$
$$\Delta\Gamma_{\mathrm{NLO}}^{\mathrm{direct}}(\mathrm{H}\to\mathrm{J}/\psi+\gamma)=-4.099\times10^{-10}\ \mathrm{GeV}$$
$$\Gamma^{\mathrm{direct}}(\mathrm{H}\to\mathrm{J}/\psi+\gamma)=1.235\times10^{-10}\ \mathrm{GeV}$$
$$\Gamma^{\mathrm{indirect}}(\mathrm{H}\to\mathrm{J}/\psi+\gamma)=1.013\times10^{-7}\ \mathrm{GeV}$$
$$\Gamma_{\mathrm{LO}}^{\mathrm{direct}}(\mathrm{H}\to\Upsilon+\gamma)=2.998\times10^{-9}\ \mathrm{GeV}$$
$$\Delta\Gamma_{\mathrm{NLO}}^{\mathrm{direct}}(\mathrm{H}\to\Upsilon+\gamma)=-1.845\times10^{-9}\ \mathrm{GeV} \quad (14)$$
$$\Gamma^{\mathrm{direct}}(\mathrm{H}\to\Upsilon+\gamma)=1.153\times10^{-9}\ \mathrm{GeV}$$
$$\Gamma^{\mathrm{indirect}}(\mathrm{H}\to\Upsilon+\gamma)=5.659\times10^{-9}\ \mathrm{GeV}. \quad (15)$$

Using the width of Higgs boson decays within the Standard Model $\Gamma(\mathrm{H})=4.195^{+0.164}_{-0.159}\times10^{-3}$ GeV[34], we obtain the following results for the branching fractions in the SM:

$$\mathcal{B}^{\mathrm{direct}}(\mathrm{H}\to\mathrm{J}/\psi+\gamma)=2.94\times10^{-8}$$
$$\mathcal{B}^{\mathrm{indirect}}(\mathrm{H}\to\mathrm{J}/\psi+\gamma)=2.41\times10^{-5}$$
$$\mathcal{B}^{\mathrm{direct}}(\mathrm{H}\to\Upsilon+\gamma)=2.75\times10^{-7}$$
$$\mathcal{B}^{\mathrm{indirect}}(\mathrm{H}\to\Upsilon+\gamma)=1.35\times10^{-6}. \quad (16)$$

As the results show, for the decay process $\mathrm{H}\to\mathrm{J}/\psi+\gamma$, the direct contribution is much smaller than the indirect contribution, so it is difficult to observe the direct contribution in the total cross section and not suitable for studying the coupling of Higgs and charm quarks. For the process $\mathrm{H}\to\Upsilon+\gamma$, the direct and indirect contributions are comparable and the total cross section is sensitive to the direct decay process, so this process can be used to study the coupling of Higgs and bottom quarks. In addition, the process $\mathrm{H}\to\mathrm{J}/\psi(\Upsilon)+\gamma$ decay can also be used to test the coupling of Higgs to top quarks and W bosons.

The main uncertainties for the results of $\mathrm{H}\to\mathrm{J}/\psi(\Upsilon)+\gamma$ arise from the uncertainties in LDMEs, renormalization scale, and the relativistic corrections. The relativistic corrections and the uncertainties have been discussed in Ref. [35]. In Table 1, we illustrate the renormalization scale dependence of the direct and indirect decay widths for the process $\mathrm{H}\to\mathrm{J}/\psi(\Upsilon)+\gamma$. We assume $\mu=\mu_r$ and define $\mu_0=m_{\mathrm{H}}$. When the scale μ running from $\mu_0/4$ to $4\mu_0$, The related theoretical uncertainty for $\mathrm{H}\to\mathrm{J}/\psi+\gamma$ amounts to $^{+55.0}_{-83.2}\%$ for direct process and to $^{+4.2}_{-4.1}\%$ for indirect process, and the related theoretical uncertainty for $\mathrm{H}\to\Upsilon+\gamma$ amounts to $^{+40.2}_{-26.5}\%$ for the direct process and to $^{+4.2}_{-4.2}\%$ for the indirect process. The LO direct process is independent of the renormalization scale μ_R, because it is a pure electroweak channel.

Table 1. The renormalization scale dependence of the direct and indirect decay widths for the process $\mathrm{H}\to\mathrm{J}/\psi(\Upsilon)+\gamma$.

$\mathrm{H}\to\mathrm{J}/\psi+\gamma$ ($\times10^{-10}$ GeV)				
μ/GeV	$\Gamma_{\mathrm{LO}}^{\mathrm{direct}}$	$\Delta\Gamma_{\mathrm{NLO}}^{\mathrm{direct}}$	Γ^{direct}	$\Gamma^{\mathrm{indirect}}$
$\mu_0/4$	5.334	−5.127	0.207	1056
$\mu_0/2$	5.334	−4.554	0.780	1035
μ_0	5.334	−4.099	1.235	1013
$2\mu_0$	5.334	−3.728	1.606	992.1
$4\mu_0$	5.334	−3.420	1.914	971.3
$\mathrm{H}\to\Upsilon+\gamma$ ($\times10^{-10}$ GeV)				
μ/GeV	$\Gamma_{\mathrm{LO}}^{\mathrm{direct}}$	$\Delta\Gamma_{\mathrm{NLO}}^{\mathrm{direct}}$	Γ^{direct}	$\Gamma^{\mathrm{indirect}}$
$\mu_0/4$	29.98	−23.08	6.9	58.98
$\mu_0/2$	29.98	−20.50	9.48	57.78
μ_0	29.98	−18.45	11.53	56.59
$2\mu_0$	29.98	−16.79	13.19	55.41
$4\mu_0$	29.98	−15.40	14.58	54.24

4 Summary

In this paper, we investigated the decay of the Higgs boson to J/ψ(Υ) plus a photon based on NRQCD factorization. For the direct process, we have calculated the decays width up to QCD NLO and found that the LO decay widths are significantly reduced by the NLO QCD corrections. For the indirect process, we calculated the process $\mathrm{H}\to\gamma^*\gamma$ with virtual γ substantially decaying to J/ψ(Υ), including all the SM diagrams. The decay width of indirect production is much larger than the direct decay width. Therefore, it is difficult to probe the Yukawa coupling of Higgs and charm quarks using the process $\mathrm{H}\to\mathrm{J}/\psi(\Upsilon)+\gamma$. However, it still offers a new way to probe the Yukawa coupling of Higgs and top quarks or bottom quarks and New Physics at the LHC.

Appendix A

In this Appendix, we list the expression of coefficients $\mathcal{A}$ and $\mathcal{B}$ for process Higgs indirect decay to di-photon. The one-loop integrals are defined as in Ref. [36]. Our results are shown as follows,

$$
\begin{aligned}
\mathcal{A} = & -32m_{\rm T}^2+81m_{\rm W}^2+12m_{\rm W}^2\times\texttt{B0}[0,m_{\rm W}^2,m_{\rm W}^2] \\
& +12m_{\rm W}^2\texttt{B0}[4m_{\rm C}^2,m_{\rm W}^2,m_{\rm W}^2]-64m_{\rm T}^2\times\texttt{B0}[m_{\rm H}^2,m_{\rm T}^2,m_{\rm T}^2] \\
& +12m_{\rm H}^2\texttt{B0}[m_{\rm H}^2,m_{\rm W}^2,m_{\rm W}^2]+72m_{\rm W}^2\times\texttt{B0}[m_{\rm H}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& +128m_{\rm C}^2m_{\rm T}^2\times\texttt{C0i}[\text{cc0},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm T}^2,m_{\rm T}^2,m_{\rm T}^2] \\
& -32m_{\rm H}^2m_{\rm T}^2\times\texttt{C0i}[\text{cc0},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm T}^2,m_{\rm T}^2,m_{\rm T}^2] \\
& -216m_{\rm C}^2m_{\rm W}^2\times\texttt{C0i}[\text{cc0},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& +54m_{\rm H}^2m_{\rm W}^2\times\texttt{C0i}[\text{cc0},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& +24m_{\rm W}^4\times\texttt{C0i}[\text{cc0},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& +256m_{\rm T}^2\times\texttt{C0i}[\text{cc00},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm T}^2,m_{\rm T}^2,m_{\rm T}^2] \\
& -48m_{\rm H}^2\times\texttt{C0i}[\text{cc00},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& -378m_{\rm W}^2\times\texttt{C0i}[\text{cc00},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& -120m_{\rm C}^2m_{\rm W}^2\times\texttt{C0i}[\text{cc1},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& +18m_{\rm H}^2m_{\rm W}^2\times\texttt{C0i}[\text{cc1},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& -264m_{\rm C}^2m_{\rm W}^2\times\texttt{C0i}[\text{cc11},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& -264m_{\rm C}^2m_{\rm W}^2\times\texttt{C0i}[\text{cc12},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& +66m_{\rm H}^2m_{\rm W}^2\times\texttt{C0i}[\text{cc12},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& -24m_{\rm C}^2m_{\rm W}^2\times\texttt{C0i}[\text{cc2},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& +6m_{\rm H}^2m_{\rm W}^2\times\texttt{C0i}[\text{cc2},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2],
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{B} = 2\times(& 32m_{\rm T}^2\times\texttt{C0i}[\text{cc0},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm T}^2,m_{\rm T}^2,m_{\rm T}^2] \\
& -12m_{\rm W}^2\times\texttt{C0i}[\text{cc0},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& -128m_{\rm T}^2\times\texttt{C0i}[\text{cc12},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm T}^2,m_{\rm T}^2,m_{\rm T}^2] \\
& +24m_{\rm H}^2\times\texttt{C0i}[\text{cc12},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& +57m_{\rm W}^2\times\texttt{C0i}[\text{cc12},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2] \\
& +18m_{\rm W}^2\times\texttt{C0i}[\text{cc2},4m_{\rm C}^2,m_{\rm H}^2,0,m_{\rm W}^2,m_{\rm W}^2,m_{\rm W}^2]).
\end{aligned}
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