Quarkonium production in SM Higgs decays

Cong-Feng Qiao
China Center of Advanced Science and Technology (World Laboratory),
Beijing 100080, People’s Republic of China
and I.C.T.P., P.O. Box 586, 34100 Trieste, Italy

Feng Yuan, and Kuang-Ta Chao
Department of Physics, Peking University, Beijing 100871, People’s Republic of China
and China Center of Advanced Science and Technology (World Laboratory),
Beijing 100080, People’s Republic of China

Abstract

We investigate the SM Higgs decays into heavy quarkonia $J/\psi$ and $\Upsilon$ in both color-singlet and color-octet mechanisms. It is found that in $J/\psi$ production the contribution through color-octet processes overwhelm that in color-singlet processes all the intermediate region $M_Z < M_{H^0} < 2M_W$ and the fraction ratio is comparatively large, but in $\Upsilon$ production the contribution through color-octet mechanism is negligible.

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Despite the success of the Standard Model (SM) in describing elementary particle phenomena at electroweak energy scale and below, the theory has some intrinsic shortcomings which may not be overcome in the context of the theory itself. For example, the hierarchy problem existed in the gauge symmetry breaking. The mechanism of spontaneous symmetry breaking introduced in SM to allow some of the gauge bosons and fermions to acquire mass while keeping the theory renormalizable leads to a neutral scalar particle, the Higgs boson \( H^0 \). While a worldwide experimental effort has been made, this Higgs particle has not yet been discovered.

Though the SM predicts the existence of the \( H^0 \) with unspecified mass, the couplings of it with other fundamental particles are well defined. Consequently the \( H^0 \) production cross section in various channels and the decay branching ratios of it are precisely predicted as a function of the Higgs boson mass. According to the LEP I data, based on the Bjorken process \( e^+ e^- \rightarrow H^0 Z^* \), the Higgs mass, \( M_{H^0} \), should be heavier than 77.1 GeV.

The hunt of the Higgs boson meets two problems, i.e., how to produce it and then how to detect it. Therefore, experimental researches at LEP include both \( H^0 \) production and decays, meanwhile the search range will expand with the operation of LEP at higher energy. After the operation of the Large Hadron Collider (LHC), almost all the possible energy region where Higgs may exist will be searched down. In this paper, we proceed out discussion in the intermediate energy range \( M_Z < M_{H^0} < 2 M_W \), which is the most difficult range in experiment to detect the Higgs boson.

In theory, the study for the nature of the Higgs boson have been in highlight in particle physics ever since the establishment of SM. The probabilities of finding the \( H^0 \) and other Higgs bosons appearing in theories beyond the minimal SM in various collider facilities are evaluated. Among others of Higgs boson production processes, the Yukawa process, i.e., the bremsstrahlung production of the neutral Higgs boson \( H^0 \) from a heavy fermion, of the SM Higgs boson is an important channel to discover and to investigate this particle. In experiment, the analyses of the Yukawa process have led to some constraints on the theories in respect to the Higgs sector. Among various decay processes of the Higgs boson, Fermionic decay channels of it are important channels. The observation of such decay modes may provide important information on fermion Yukawa couplings which associate with the symmetry breaking mechanism in the SM. The subprocess of the fermionic decay channels, that is quarkonium production in the Higgs boson decays that may be called the Extended Wilczek Processes (EWP), which helps to further identify the Higgs boson signals also gains much attention though there may be large theoretical uncertainties both due to the Quantum Chromodynamics (QCD) and relativistic corrections. Considering the fact that the low limit of the SM Higgs mass is up to about the mass of \( Z^0 \) boson’s and the recent developments in quarkonium production theory, in this paper we reevaluate the EWP within the scope of Standard Model.

In the past few years, two approaches in describing the heavy quarkonium produc-
tion, the fragmentation mechanism \cite{7} and the Non-Relativistic Quantum Chromodynamics (NRQCD) factorization \cite{8}, have greatly improved the theoretical studies in this area. The introduction of color-octet mechanism asks ones to reevaluate almost all the processes associated with quarkonium production, in order either to test the new production mechanism, to further understand QCD or to assess the quarkonium production rates in a specific process. Of course, the EWP is also in the case.

For charmonium and bottomonium production in the Higgs boson decay, the important color-singlet channels include \( H^0 \to V \gamma \) (electromagnetism), \( H^0 \to QQV \) (quark fragmentation), \( H^0 \to b \bar{b}V \) (photon fragmentation), and \( H^0 \to b \bar{b}Vgg \) (gluon fragmentation) processes as shown in Fig.1, and the process \( H^0 \to Vgg \) vanishes. Here, \( V \) represents a vector meson consisting of a \( QQ \) pair (\( Q \) is heavy quark \( b \) or \( c \)).

The decay width of the process of Fig.1(a) can be calculated straightforward making use of the standard formalism \cite{11}.

\[
\Gamma = \frac{\alpha e_Q^2}{27 v^2} \xi_V (1 - \xi_V^2) < 0 | \mathcal{O}_1^V (^3S_1) | 0 >, \tag{1}
\]

where \( e_Q \) is the charge fraction of heavy quark, \( e_c = \frac{2}{3} \) and \( e_b = -\frac{1}{3} \); \( v \) is the characteristic quantity which sets the scale of spontaneous symmetry breaking in \( SU(2)_L \times U(1) \) theory and \( v \approx 246 \text{ GeV} \); \( \xi_V \) is defined as \( \xi_V = \frac{M_V}{M_{H^0}} \). \( M_V \) and \( M_{H^0} \) are the masses of the bound systems and the SM Higgs boson; \( < 0 | \mathcal{O}_1^V (^3S_1) | 0 > \) is the matrix element of color-singlet four fermion operator of quarkonium, which is associated with the nonperturbative part of the quarkonium production and its value may be determined by quarkonium electronic decay widths or from the potential model. Because the Higgs \( H^0 \) couples preferentially to the heavy fermion, when \( M_{H^0} < 2 M_w \), \( M_w \) is the mass of \( W \) boson, the dominant decay channel in Higgs decays is \( H^0 \to b \bar{b} \) even considering the virtual \( Z^* \) and \( W^* \) process \cite{11}. So, here after, we will constrain the \( H^0 \) coupling only to the quarks (\( b, c \)) in our discussion.

\[
\Gamma_{H^0 \to b \bar{b}} = \frac{3 m_b^2}{8 \pi v^2} M_{H^0} (1 - 4 \eta^2)^{3/2}, \tag{2}
\]

where \( \eta \equiv m_b/M_{H^0} \). From Eq.(1) and Eq.(2), the fraction ratio

\[
R_{J/\psi} \equiv \frac{\Gamma_{H^0 \to J/\psi \gamma}}{\Gamma_{H^0 \to b \bar{b}}} = \frac{32 \pi \alpha}{729 M_{H^0} m_b^2} \frac{\xi_{J/\psi} (1 - \xi_{J/\psi}^2)}{(1 - 4 \eta^2)^{3/2}} < 0 | \mathcal{O}_1^{J/\psi} (^3S_1) | 0 >, \tag{3}
\]

\[
R_{\Upsilon} \equiv \frac{\Gamma_{H^0 \to \Upsilon \gamma}}{\Gamma_{H^0 \to b \bar{b}}} = \frac{8 \pi \alpha}{729 M_{H^0} m_b^2} \frac{\xi_{\Upsilon} (1 - \xi_{\Upsilon}^2)}{(1 - 4 \eta^2)^{3/2}} < 0 | \mathcal{O}_1^{\Upsilon} (^3S_1) | 0 > \approx \frac{16 \pi \alpha}{729 M_{H^0}^2 m_b} (1 - \xi_{\Upsilon})^{-1/2} < 0 | \mathcal{O}_1^{\Upsilon} (^3S_1) | 0 >, \tag{4}
\]

can then be easily obtained. The decay \( H^0 \to V \gamma \) with the subsequent decay \( V \to e^+ e^- \) from experimental point of view presents the clearest signal in searching the Higgs boson.
Unfortunately, the ratios of these decay rates to the decay rate $H^0 \to b\bar{b}$ is too small (see below and Ref.[11]).

Because the minimal value of the mass of $H^0$ is over 77.1 GeV, the decay widths, therefore the fraction ratios of the process shown in fig.1(b) can be evaluated using the universal quark fragmentation functions [12].

$$R_{J/\psi} \equiv \frac{\Gamma(H^0 \to c\bar{c}J/\psi)}{\Gamma(H^0 \to b\bar{b})} = 2 \times P_{c \to J/\psi} \times \frac{m_c^2}{m_b^2},$$

(5)

where $P_{c \to J/\psi}$ is the universal fragmentation probability, and

$$P_{c \to J/\psi} = \frac{16}{243} \alpha_s(2m_c)^2 \frac{\langle 0|O_1^{J/\psi}(3S_1)|0\rangle}{m_c^3} (\frac{1189}{30} - 57\ln2).$$

(6)

As Eq.(5),(6), the fraction ratio of $\Gamma_{H^0 \to b\bar{b}\Upsilon}$ over $\Gamma_{H^0 \to b\bar{b}}$ can be readily obtained,

$$R_\Upsilon \equiv \frac{\Gamma(H^0 \to b\bar{b}\Upsilon)}{\Gamma(H^0 \to b\bar{b})} = 2 \times P_{b \to \Upsilon}.$$  

(7)

Here $P_{b \to \Upsilon}$, the fragmentation probability of $b \to \Upsilon$, is in the same form as Eq.(6),

$$P_{b \to \Upsilon} = \frac{16}{243} \alpha_s(2m_b)^2 \frac{\langle 0|O_1^\Upsilon(3S_1)|0\rangle}{m_b^3} (\frac{1189}{30} - 57\ln2).$$

(8)

The process as shown in Fig.1(c) can be calculated using the standard method in computing the quarkonium production and decays and the result is simplified into the following form after neglecting the mass of the $b(\bar{b})$ quark (antiquark), except for in the Higgs-quark coupling vertex.

$$\frac{d\Gamma(H^0 \to Vb\bar{b})}{dz_1dz_2} = \frac{\alpha^2 m_b^2 c Q_M^2}{M^2 H^0 v^2 \pi} \frac{\langle 0|O_1^V(3S_1)|0\rangle}{z_1^2 z_2^2} [(z_1z_2 - \xi_V^2)(z_1^2 + z_2^2) + 2z_1z_2(z_1 - 1)(z_2 - 1)],$$

(9)

where $z_1 = 1 - \frac{2k\cdot p_2}{M^2 H^0}$, $z_2 = 1 - \frac{2k\cdot p_1}{M^2 H^0}$ and their integration regions are $r \leq z_1 \leq 1$, $r/z_1 \leq z_2 \leq 1 + r - z_1$. $k$, $p$, $p_1$, $p_2$ are the momenta of the Higgs boson, bound state, and the final quarks appearing in Fig.1(c). Because Eq.(9) is a differential equation, it can be used to evaluated the energy distribution of quarkonia, which is different from that of the two-body decay mode. After integrating over $z_1$ and $z_2$, the total decay width can be obtained and hence the fraction ratios.

The decay width of the process $H^0 \to b\bar{b}Vgg$ as shown in Fig.1(d) can be expressed as

$$\Gamma(H^0 \to b\bar{b}g^*, g^*(\mu) \to ggV) = \int_{M^2}^{M^2 H^0} d\mu^2 \Gamma(H^0 \to b\bar{b}g^*(\mu)) P_{g^* \to ggV}.$$  

(10)

Here, $P_{g^* \to ggV}$ is the decay distribution of the virtual gluon with virtuality $\mu$, and it is defined as

$$\Gamma(g^* \to ggV) = \pi \mu^3 P_{g^* \to ggV}.$$  

(11)
The expression of \( \Gamma(g^* \to ggV) \) can be found in Ref.\[13\], the \( P_{g^* \to ggV} \), therefore, may be induced.

\[
\mu^2 P(g^* \to Vgg) = C_V r \int_{2\sqrt{r}}^{1+r} dx_V \int_{x_1}^{x_+} dx_1 f(x_V, x_1; r),
\]

where \( r \equiv M^2_V/\mu^2 \), and

\[
C_{J/\psi} = \frac{10\alpha_s^3}{243\pi^2} \frac{<0|O_1^{J/\psi}(3S_1)|0>}{M^{3}_{J/\psi}}, \quad C_\Upsilon = \frac{10\alpha_s^3}{243\pi^2} \frac{<0|O_1^{\Upsilon}(3S_1)|0>}{M^{3}_{\Upsilon}}.
\]

The function \( f \) in Eq.(12) is of the form

\[
f(x_V, x_1; r) = \frac{(2 + x_2)x_2}{(2 - x_{J/\psi})^2(1 - x_1 - r)^2} + \frac{(2 + x_1)x_1}{(2 - x_{J/\psi})^2(1 - x_2 - r)^2} + \frac{1}{1 - x_2 - r^2(1 - x_1 - r)^2} + \frac{1}{1 - x_2 - r^2(1 - x_1 - r)^2} + \frac{2(1 - x_{J/\psi})(1 - r)}{1 - x_2 - r^2(1 - x_1 - r)^2} + \frac{1}{r},
\]

where \( x_i \equiv 2E_i/\mu \) with \( i = V, g_1, g_2 \) are the energy fractions carried by the quarkonia and two gluons in the \( g^* \) rest frame, and then \( x_2 = 2 - x_1 - x_{J/\psi} \). The limits of the \( x_1 \) integration in Eq.(12) are

\[
x_{\pm} = \frac{1}{2}(2 - x_V \pm \sqrt{x^2_1 - 4r}).
\]

\( \Gamma(H^0 \to b\bar{b}g^*)(\mu) \) is the same as Eq.(9) with just \( M_V \) being changed to \( \mu \). Therefore, the fraction ratio \( H^0 \to b\bar{b}Vgg \) to \( H^0 \to b\bar{b} \) then can be calculated using Eqs.(2) and (10).

The heavy quarkonium production color-octet mechanism provides the process \( H^0 \to QQ^{(3S_1, 8)}g \to Vg \) with soft hadrons, as shown in Fig.2(a), existing as the leading order process in \( \alpha_s \). Although this process makes a less significant contribution to the \( J/\psi \) production in \( Z^0 \) decays \[14\], comparing with other higher order processes, it may play a relatively more important role in the case of \( H^0 \) decays. On the other hand, after summing over the soft hadrons that accompany the quarkonium \( V \) and over the collinear hadrons that make up the gluon jet, the decay rate can be factored into the product of a two-body decay rate and a nonperturbative matrix element, and the two-body decay mode has a unique distributions in the kinematic variables of final states relative to that of three-body’s. Another color-octet process which might play an important role in charmonium production in \( H^0 \) decays is shown in Fig.2(b).

Although the nonperturbative color-octet matrix elements in these color-octet processes are suppressed by \( v^4 \) with respect to that of color-singlet processes according to NRQCD velocity scaling rules, the strong coupling constant \( \alpha_s \) greatly enhanced them relative to the
corresponding electromagnetic processes. The calculation of the decay widths of these color-octet channels is similar to the corresponding color-singlet processes, with only the change of coupling constant, the color factor, and the nonperturbative matrix elements. Therefore, $H^0$ decay widths of the processes as shown in Fig.2 can be inferred from Eq.(1) and Eq.(9).

$$\Gamma(H^0 \to V_g X) = \frac{\alpha_s}{3N_c} \xi_V (1 - \xi_V^2) < 0|O_V^{(3S_1)}|0 >.$$  (16)

Here, the X stands for the soft hadrons produced in the neutralization process of the color-octet $(Q\bar{Q})_8$ evolving into the heavy quarkonium. The differential decay width of the Fig.2(b) process reads as

$$\frac{d\Gamma(H^0 \to V_b \bar{b} X)}{dz_1 dz_2} = \frac{\alpha_s^2 m_b^2 M_{H^0}}{12 M_{J/\psi}^3 v^2 \pi} \frac{<0|O_V^{(3S_1)}|0 >}{z_1^2 z_2^2} \left[(z_1 z_2 - \xi_V^2)(z_1^2 + z_2^2) + 2z_1 z_2(z_1 - 1)(z_2 - 1)\right],$$  (17)

where the integration variables $z_1$ and $z_2$ change in the same regions as that in Eq.(9). In the above $<0|O_V^{(3S_1)}|0 >$ is the matrix element of four fermion color-octet operator. Its value may be determined by the fitting of theoretical predictions to the experimental data or from the lattice QCD calculations. Note that in the process of Fig.2(a) the color-octet $Q\bar{Q}(1S_0^{(8)})$ and $Q\bar{Q}(3P_J^{(8)})$ have zero contributions to the $H^0$ decay widths. From Eqs.(2), (16), and (17) the fraction ratios of quarkonium production over b-quark pair production then can be obtained.

In the numerical calculation, we take $\alpha_s(2m_c) = 0.26, \alpha_s(2m_b) = 0.19,$

$$M_{J/\psi} = 2m_c, \quad M_{\Upsilon} = 2m_b, \quad m_b = 4.9 \text{ GeV}, \quad m_c = 1.5 \text{ GeV},$$

and $\langle 0|O^{J/\psi (3S_1)}|0 > = 1.2 \text{ GeV}^3, \quad \langle 0|O^{T (3S_1)}|0 > = 9.3 \text{ GeV}^3,$

$$\langle 0|O^{J/\psi (3S_1)}|0 > = 6.6 \times 10^{-3} \text{ GeV}^3, \quad \langle 0|O^{T (3S_1)}|0 > = 5.9 \times 10^{-3} \text{ GeV}^3.$$  (18)

With the mass of SM Higgs boson changing from 65 GeV to 155 GeV, the relative weights and the magnitudes of the total fraction ratios of $R_{J/\psi}$ and $R_{\Upsilon}$ are shown in Fig.3 and Fig.4. There are multiple components to each of the color-octet and -singlet contributions in these figures. For the convenience in comparing the relative importance of those diagrams in Fig.1 and Fig.2, we plot each component of the octet and singlet in Fig.3 and Fig.4. Each figure of them in fact contains nine curves corresponding to six subprocesses of Fig.1 and Fig.2, the sum of both octet and singlet subprocess, and the total. However, because the diversities of each component are so large that some curves overlap, which means the dominant contribution is almost the same as total.

From the results shown in Fig.3 and Fig.4, it is interesting to see that the heavy quarkonium production in MS Higgs decays has two distinct features. First, generally, within the
color-singlet model the $\Upsilon$ production rate is smaller than that of $J/\psi$'s at collider facilities, but in the SM Higgs decays where they have a comparable fraction ratios because of the fact that the Higgs tends to couple with heavy fermions. From Fig.3 and Fig.4 we can see that the process Fig.1(b) always takes the leading contribution among all color-singlet ones no matter in $J/\psi$ production or $\Upsilon$ production.

Second, the color-octet mechanism makes a dominant contribution in the $J/\psi$ production, however it makes a negligible contribution in the $\Upsilon$ production. This is because that for the intermediate mass Higgs the color-octet decay mode in Fig.2(b) always overwhelms that in Fig.2(a), but in Fig.2(b) gluon propagator in $\Upsilon$ production suppresses the decay width relative to the $J/\psi$ production. This unique character provides the EWP of $J/\psi$ production more reachable in experiment than $\Upsilon$ production if the color-octet mechanism does really work. In other words, if we would have measured a larger production rate in $\Upsilon$ production than in $J/\psi$ in the Higgs decays, we may conclude that the color-singlet mechanism is the dominant one in quarkonium production, otherwise, the other production mechanism, e.g., the color-octet one, must have taken part in.

For the LHC luminosity of $\int \mathcal{L} = 10^5 \text{ pb}^{-1}$ there will yield $\mathcal{O}(0.2-1 \times 10^7)$ SM Higgs events in the mass range $155 \text{ GeV} > M_{H^0} > 65 \text{ GeV}$ with c.m. energy $\sqrt{s} = 14 \text{ TeV}$ [16]. From this the quarkonium events produced at the proton collider LHC can be readily estimated. For instance, at a mass of $M_{H^0} = 100 \text{ GeV}$, from Fig.3 and Fig.4 we can read that the $R_{J/\psi}$ and $R_{\Upsilon}$ to be about $10^{-4}$ and $2 \times 10^{-5}$, from Ref.[16] we get to know that the $H \rightarrow b\bar{b}$ branching ratio is about 80%. So, at this point the cross section times the branching ratio for $pp \rightarrow H (\rightarrow J/\psi, \Upsilon) + X$ will yield about 200 $J/\psi$ and 80 $\Upsilon$ events.

In conclusion, after taking the color-octet mechanism into consideration the quarkonium, especially the charmonium, decay mode of SM Higgs may be detectable in the next generation collider, the LHC. That means the concerned quarkonium production process discussed in this paper may stand as an implement to the two-photon decay mode in identifying the SM Higgs in the intermediate mass region.

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Figure Captions

Fig.1. Color-singlet processes of $H^0$ decays into quarkonia, (a) electromagnetism process (b) quark fragmentation process (c) the photon fragmentation process (d) gluon fragmentation process.

Fig.2. Color-octet processes of $H^0$ decays into quarkonia, (a) the lowest order QCD process (b) gluon fragmentation process.

Fig.3. The total fraction ratios, relative weights of the different $J/\psi$ production mechanisms, and different subprocesses in $H^0$ decays. The dotted curve and the dashed curve illustrate the total fraction ratios of the color-singlet and color-octet mechanisms, respectively, the solid curve is a sum of them, and the subprocesses contributions are labeled a-d and A-B corresponding to the ones in Fig.1 and Fig.2.

Fig.4. The total fraction ratios, relative weights of the different $\Upsilon$ production mechanisms, and different subprocesses in $H^0$ decays. The curves in this figure are labeled the same as those in Fig.3.
Fig. 1
Fig. 2
Fig. 3

$R_{jW}$ vs. Higgs Mass (GeV)
Fig. 4

The graph shows the relationship between the Higgs Mass (GeV) and the quantity $R_T$ on a log-log scale. The graph includes four lines labeled as A, B, a, d, and c, each representing different theoretical predictions or data sets. The x-axis represents the Higgs Mass in GeV, while the y-axis represents $R_T$ on a logarithmic scale ranging from $10^{-9}$ to $10^{-4}$. The graph helps in understanding the behavior of $R_T$ as a function of the Higgs mass, which is crucial for theoretical and experimental studies in particle physics.