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A note on Higgs decays into Z boson and $J/\Psi(\Upsilon)$

Dao-Neng Gao

Interdisciplinary Center for Theoretical Study, University of Science and Technology of China, Hefei, Anhui 230026, China

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ABSTRACT

Rare decays $h \to ZV$ with V denoting the narrow $c\bar{c}$ or $b\bar{b}$ resonances, such as J/Ψ or Υ states, have been analyzed. Within the standard model, these channels may proceed through the tree-level transition $h \to ZZ^*$ with the virtual $Z^* \to V$, and also loop-induced process $h \to Z\gamma^*$, followed by $\gamma^* \to V$. Our analysis shows that, for the bottomonium final states, the decay rate of $h \to Z\Upsilon$ from the loop-induced process is small and the former transition gives the dominant contribution; while, for the charmonium final states, $\Gamma(h \to ZJ/\Psi)$ and $\Gamma(h \to Z\Psi(2S))$ induced by $h \to Z\gamma^* \to ZV$ could be comparable to the contribution given by the tree-level $h \to ZZ^* \to ZV$ transition.

After the discovery of the 125 GeV Higgs boson at the Large Hadron Collider (LHC) [1], a new era of the precise determination of the properties of this new particle has begun. So far, current measurements of the Higgs boson couplings to standard model (SM) fields are consistent with those expected within the SM, it is nevertheless conceivable that more in-depth investigations both theoretically and experimentally, may reveal the non-standard properties of the particle. Of these studies, the so-called golden channel, $h \to ZZ^* \to 4\ell$, might be an interesting decay mode towards accomplishing this goal, which is capable of both probing the nature of general hZZ couplings including the CP properties [2] and exploring exotic Higgs decays [3,4] that are not predicted by the SM.

In Ref. [4], the $h \to 4\ell$ decay spectrum has been analyzed in the kinematical region where low invariant mass of the dilepton pair, around several GeV, is not far from QCD resonances (such as heavy quarkonia J/Ψ and Υ), and non-perturbative QCD effects near from these quarkonium thresholds, induced by $h \to ZV \to Z\ell^+\ell^-$ (where $V = J/\Psi$ or Υ etc.), have to be taken into account. In the present work, we will focus on the rare decays $h \to ZV$ themselves, instead of their contributions to the $h \to 4\ell$ spectrum.

The decay rates of $h \to ZV$ have been calculated in Refs. [4,5] via the tree-level vertex $h \to ZZ^*$, with the subsequent transition $Z^* \to V$. The purpose of this note is to show that, these decays can also proceed through $h \to Z\gamma^*$, followed by $\gamma^* \to V$. Although in the SM, $h \to Z\gamma$ transition is loop-suppressed, our analysis below shall indicate that the amplitude of $h \to Z\gamma^* \to ZV$ could be enhanced, which may thus bring about significant contributions to these processes. Similar transition $h \to \gamma\gamma^*$ with $\gamma^* \to V$ has also been studied in $h \to \gamma J/\Psi(\Upsilon)$ decays by the authors of Ref. [6].

In the SM, the vertex of Higgs coupling to Z pair is

$$\mathcal{L}_{hZZ} = \frac{m_Z^2}{v} h Z_\mu Z^\mu, \tag{1}$$

and the neutral current interactions are expressed as

$$\mathcal{L}_{\rm NC} = e J_\mu^{\rm em} A^\mu + \frac{g}{\cos\theta_W} J_\mu^Z Z^\mu \tag{2}$$

with

$$J_\mu^{\rm em} = \sum_f Q_f \bar{f}\gamma_\mu f, \tag{3}$$

and

$$J_\mu^Z = \frac{1}{2}\sum_f \bar{f}\gamma_\mu(g_V^f - g_A^f\gamma_5) f. \tag{4}$$

Here $v = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV, e is the QED coupling constant, g is the $SU(2)_L$ coupling constant, θ_W is the Weinberg angle, and f denotes fermions including leptons and quarks. Also $g_V^f = T_3^f - 2Q_f \sin^2\theta_W$ and $g_A^f = T_3^f$, where Q_f is the charge, and T_3^f is the third component of the weak isospin of the fermion.

The amplitude of $h \to ZV$ via $h \to ZZ^* \to ZV$, as shown in Fig. 1, has been calculated in Ref. [4], which reads

$$\mathcal{M}_1 = -\frac{2m_Z^2 g}{v\cos\theta_W}\frac{1}{m_Z^2 - m_V^2} g_V^q f_V m_V \epsilon_V \cdot \epsilon_Z. \tag{5}$$

E-mail address: gaodn@ustc.edu.cn.

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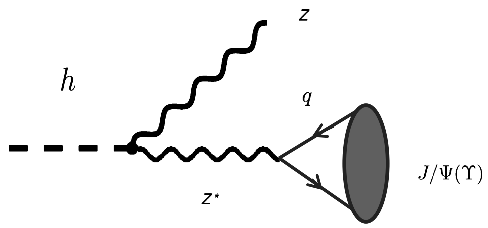

Fig. 1. The diagram for $h \to ZZ^* \to ZV$. The hZZ^* vertex is from Eq. (1), and the virtual Z boson coupling to quark pair is from Eq. (2).

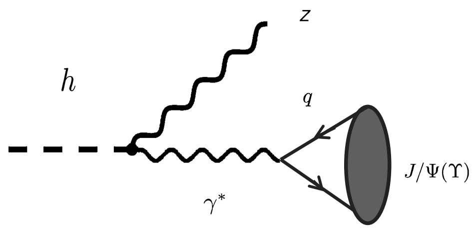

Fig. 2. The diagram for $h \to Z\gamma^* \to ZV$. The $hZ\gamma^*$ vertex is from the effective interaction in Eq. (7), and the virtual photon coupling to quark pair is from Eq. (2).

Here the superscript $q = c$ or b, and the decay constant f_V can be defined by [4,5]

$$\langle 0|\bar{q}\gamma^\mu q\big|V(p,\epsilon)\big\rangle = f_V m_V \epsilon_V^\mu, \tag{6}$$

where ϵ_V^μ is the polarization vector for $c\bar{c}$ or $b\bar{b}$ narrow resonances with $J^{PC} = 1^{--}$.

Next let us discuss the amplitude intermediated by the virtual photon. In the SM, the $h \to Z\gamma$ decay at the leading order is determined by the one-loop contribution [7]. On the other hand, more explicitly, one can write down the effective lagrangian for the $hZ\gamma$ interactions generated in the SM as follows [8,9]

$$\mathcal{L}_{\rm eff}^{hZ\gamma} = \frac{eg}{16\pi^2 v} C_{Z\gamma} Z_{\mu\nu} F^{\mu\nu} h, \tag{7}$$

where $C_{Z\gamma}$ is dimensionless effective coupling constant. In the SM at the one-loop order, $C_{Z\gamma}$ will get contributions from W-boson and top-quark loop diagrams, whose explicit expressions can be found in Refs. [10,9]. For the general effective $hZ\gamma$ interactions beyond the SM, some new structures other than Eq. (7) may of course appear [8,9].

Now the amplitude of $h \to ZV$ through $h \to Z\gamma^* \to ZV$ transition, as shown in Fig. 2, can be given by

$$\mathcal{M}_2 = \frac{\alpha_{\rm em} g f_V Q_q}{2\pi v} \frac{C_{Z\gamma}}{m_V} (k_\mu p_\nu - k\cdot p g_{\mu\nu}) \epsilon_Z^\nu \epsilon_V^\mu, \tag{8}$$

where $\alpha_{\rm em} = e^2/4\pi$. k and p are 4-momenta of Z-boson and the resonance V, respectively. It is seen that there is a $1/m_V$ factor in the above equation, which comes from the virtual photon propagator $(1/m_V^2)$ and m_V in the matrix element of Eq. (6). Also we have used $C_{Z\gamma}$ for the on-shell photon case instead of the off-shell $C_{Z\gamma^*}$, since

$$C_{Z\gamma^*} = C_{Z\gamma} + O\big(m_V^2/m_h^2\big), \tag{9}$$

which should be a good approximation for our present purpose.

The total decay amplitude of $h \to ZV$ can thus be written as

$$\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2. \tag{10}$$

After squaring the amplitude and summing the polarization of final particles, one will obtain the decay rate of the process

Table 1
Branching ratios of $h \to ZV$ decays with V denoting the narrow $c\bar{c}$ and $b\bar{b}$ resonances with $J^{PC} = 1^{--}$. The decay constants f_V's in the third column are taken from Ref. [4], and the values of $\mathcal{B}_1$ in the fourth column agree with the results given in Ref. [4].

Resonance	m_V (GeV)	f_V (MeV)	$\mathcal{B}_1(h \to ZV)$	$\mathcal{B}_2(h \to ZV)$	$\mathcal{B}(h \to ZV)$
$J/\Psi(1S)$	3.097	405	1.7×10^{-6}	1.0×10^{-6}	3.2×10^{-6}
$\Psi(2S)$	3.686	290	8.7×10^{-7}	3.7×10^{-7}	1.5×10^{-6}
$\Upsilon(1S)$	9.460	680	1.6×10^{-5}	7.5×10^{-8}	1.7×10^{-5}
$\Upsilon(2S)$	10.02	485	8.3×10^{-6}	3.4×10^{-8}	8.9×10^{-6}
$\Upsilon(3S)$	10.36	420	6.3×10^{-6}	2.4×10^{-8}	6.7×10^{-6}

$$\Gamma(h \to ZV) = \Gamma_1 + \Gamma_2 + \Gamma_{12} \tag{11}$$

with

$$\Gamma_1 = \frac{m_h^3 (g_V^q f_V)^2}{16\pi v^4} \frac{\lambda^{1/2}(1, r_Z, r_V)}{(1 - r_V/r_Z)^2} \big[(1 - r_Z - r_V)^2 + 8 r_Z r_V\big] \tag{12}$$

from $\mathcal{M}_1$,

$$\Gamma_2 = \frac{\alpha_{\rm em}^3 f_V^2 Q_q^2 m_h^3}{32\pi^2 v^2 \sin^2\theta_W} \frac{C_{Z\gamma}^2}{m_V^2} \lambda^{1/2}(1, r_Z, r_V) \times \big[(1 - r_Z - r_V)^2 + 2 r_Z r_V\big] \tag{13}$$

from $\mathcal{M}_2$, and

$$\Gamma_{12} = \frac{3\alpha_{\rm em}^2 f_V^2 g_V^q Q_q m_h C_{Z\gamma}}{8\pi \cos\theta_W \sin^2\theta_W v^2} \frac{\lambda^{1/2}(1, r_Z, r_V)}{1 - r_V/r_Z} (1 - r_Z - r_V) \tag{14}$$

from the interference between $\mathcal{M}_1$ and $\mathcal{M}_2$. Here $r_Z = m_Z^2/m_h^2$, $r_V = m_V^2/m_h^2$, and $\lambda(a,b,c) = a^2 + b^2 + c^2 - 2(ab + ac + bc)$.

Using the decay width of Higgs boson $\Gamma_h \approx 4.07$ MeV, and defining

$$\mathcal{B}_i(h \to ZV) = \Gamma_i/\Gamma_h \tag{15}$$

for $i = 1, 2$, and

$$\mathcal{B}(h \to ZV) = \frac{\Gamma(h \to ZV)}{\Gamma_h}, \tag{16}$$

one can get branching ratios of $h \to ZV$ decays, which have been listed in Table 1. $\mathcal{B}_1(h \to ZV)$ in the fourth column is given by the tree level transition $h \to ZZ^* \to ZV$ of Fig. 1, which has been calculated by the authors of Ref. [4]. The main results of this note are given in the fifth and sixth column. It is shown that, for the narrow $c\bar{c}$ resonances $J/\Psi(1S)$ and $\Psi(2S)$, contributions from Fig. 2 via $h \to Z\gamma^* \to ZV$ $(\mathcal{B}_2)$ are significant; while for the bottomonium resonances, it is a different story, and Fig. 1 gives the dominant contribution. It is seen that, in Eq. (12), the vector coupling of the Z boson to charm quarks $g_V^c = 1/2 - 4/3 \sin^2\theta_W$, which is accidentally small. This leads to the suppression of Γ_1 and the relative enhancement of Γ_2. Comparing with the $c\bar{c}$ case, however, the relative large coupling g_V^b and the large masses of $b\bar{b}$ states (note that there is a factor $1/m_V^2$ appearing in Eq. (13) for Γ_2) will result in a factor about 1/40 suppression in Γ_2 if we do not take into account the difference of f_V's.

Experimentally, the decay channel $h \to Z\gamma$ has been studied by ATLAS [11] and CMS [12] at LHC. Within the SM, this process is loop-induced, which thus is sensitive to physics beyond the SM [13]. The above analysis shows that rare decays $h \to ZJ/\Psi$ and $h \to Z\Psi(2S)$ could get significant contributions from $h \to Z\gamma^*$ followed by $\gamma^* \to J/\Psi$ or $\Psi(2S)$ transitions. Thus the future precise experimental studies of these rare decays may provide some complimentary information for the $h \to Z\gamma$ decay, both in and beyond the SM.

To summarize, in the SM, the rare decay modes $h \to ZV$ with $V = J/\Psi$ or Υ states may happen through two ways, one is $h \to ZZ^* \to ZV$, the other is $h \to Z\gamma^* \to ZV$. These decay rates via the first way have been evaluated in Ref. [4]. In order to complete the analysis, we calculate both of them in the present paper. Our study indicates that, for the narrow $b\bar{b}$ resonances, the decay rates via the second way are small and the first way gives the dominant contribution; while, due to the accidental smallness of the vector coupling of the Z boson to charm quarks and the small masses of charmonium resonances, the decay rates of $h \to ZJ/\Psi$ and $h \to Z\Psi(2S)$ through the second way could be comparable to the contributions induced by $h \to ZZ^* \to ZV$.

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