Production and decay of superheavy quarkonia in multi-TeV colliders

H. Inazawa, T. Morii*, and J. Morishita†
Department of English and American Literature, Shoin Women's University,
Nada, Kobe 657, Japan
*College of Liberal Arts, Kobe University, Nada, Kobe 657, Japan
†Faculty of Foreign Languages, Himeji Dokkyo University, Kami-ohno Himeji 670, Japan

Abstract

The production and its subsequent decay of an ultraheavy bound state $Q\bar{Q}$ (0^{-+}) composed of ultraheavy (such as 4-th generation) quarks are studied in a two-Higgs-doublet model. It is found that in such heavy quarkonia the Higgs-boson exchange dominates over the gluon exchange and the production rate of such quarkonia increases largely in multi-TeV collider energies.

1. Introduction

Multi-TeV hadron colliders(SSC, LHC etc.)[1] are expected to be very effective to attack the problem of gauge symmetry breaking of electroweak theory. With these machines one can has a good chance to detect ultraheavy particles, such as fourth generation quarks/leptons, Higgs bosons, supersymmetric particles, and so on. As an interesting example, Barger et al.[2] have discussed a very promising process for Higgs-boson detection in multi-TeV hadron colliders, which is the s-channel production and its subsequent decay to HZ^0 of the superheavy quarkonia $Q\bar{Q}(0^{-+})$ through gluon fusion. They considered $Q\bar{Q}$ to be bounded by gluon interactions. For ultraheavy quarkonia, it is, however, expected that the Higgs-boson exchange force can dominate over the gluon exchange force. In the recent work[3], we pointed out that this expectation was certainly realized in some kinematical regions of the quark mass(m_Q) and the Higgs-boson mass(m_H). In this paper, we calculate the production rate of such ultraheavy quarkonia $Q\bar{Q}$ $(J^{PC} = 0^{-+})$ in a two-Higgs-doublet model and study the feasibility for its detection in multi-TeV pp colliders.

2. The model

We treat such quarkonia $Q\bar{Q}$ nonrelativistically and assume that Q belongs to the lighter member of a higher generation doublet in order to prohibit the decay of its partner in the same doublet and the intergeneration mixing angle is so small that the single decay of Q is suppressed. A two-Higgs-doublet model has two neutral scalars H_1 and H_2, one neutral pseudoscalar and two charged Higgs bosons. Here we are concerned with the neutral Higgs bosons which are described as[4]

$$\begin{aligned} H_1 &= \sqrt{2}[(\mathrm{Re}\phi_D^0 - v_D)\cos\xi + (\mathrm{Re}\phi_U^0 - v_U)\sin\xi], \\ H_2 &= \sqrt{2}[(-\mathrm{Re}\phi_D^0 + v_D)\sin\xi + (\mathrm{Re}\phi_U^0 - v_U)\cos\xi], \end{aligned} \tag{1}$$

where ξ is an unknown mixing angle. v_D and v_U are the vacuum expectation values of unmixed Higgs fields (ϕ_D, ϕ_U) coupled to D(charge $-1/3$) and U(charge $2/3$), respectively and satisfy the relation, $(v_D^2 + v_U^2)^{1/2} = v \simeq 246\text{GeV}$. At present we do not know the exact values of ξ, v_D and v_U, though there have been some discussions about the ratio $\zeta = v_U/v_D$[4]. Here, for simplicity, we assume $\xi = 0$ together with very large M_{H_2}, neglecting the contribution of the H_2 exchange. We treat ζ as a free parameter. A coupling strength of a neutral Higgs, say H_1, to an ultraheavy quark, say D, is enhanced by a factor $(v/v_D) = (1+\zeta^2)^{1/2}$ over the case of the minimal model. Hereafter, we consider the $D\bar{D}$ bound states and describe H_1 and D as H and Q, respectively. Now, let us get into the discussion of the wave function at the origin of $Q\bar{Q}(0^{-+})$. To obtain the magnitude of the wave function at the origin and the binding energy of quarkonia $Q\bar{Q}$, we have solved numerically the Schrödinger equation with the potential,

$$V(r) = -\frac{G_F m_Q m_{\bar{Q}}}{2\sqrt{2}\pi}(1+\zeta^2)\frac{\exp(-m_H r)}{r} - \frac{4}{3}\frac{\alpha_s(m_Q^2)}{r}, \tag{2}$$

where G_F is the Fermi coupling constant and $\alpha_s = 12\pi/(21\ln(m_Q^2/\Lambda^2))$ with $\Lambda = 0.12\text{GeV}$. Results are presented in Fig. 1. For ultra heavy quarkonia $Q\bar{Q}$, there is an appropriate region of parameters, ζ, m_H, and m_Q, where the magnitude of the wave function at the origin increases largely due to the Higgs-boson exchange over the gluon exchange and at the same time the binding energy E_B is significantly smaller than m_Q and thus the nonrelativistic approximation works; for example, $|\psi(0)|^2/|\psi_g(0)|^2 = 9.6$ and $|E_B/m_Q| = 0.014$, for $\zeta = 2$, $m_H = 50\text{GeV}$, and $m_Q = 200\text{GeV}$.

3. Production cross section of $Q\bar{Q}(0^{-+})$

To calculate the production cross section of such quarkonia $Q\bar{Q}$ through two-gluon fusion, we have to know the total decay width $\Gamma(Q\bar{Q})$ and the two-gluon decay width $\Gamma(Q\bar{Q} \to gg)$. Since we neglect the contributions coming from other Higgs bosons except for the lighter one of neutral Higgs bosons, H_1(which is denoted as H in this paper), the dominant decay process of $Q\bar{Q}$ is $Q\bar{Q} \to HZ^0$, which is enhanced by a factor $(1+\zeta^2)$ compared to the case of the minimal model with single Higgs doublet. We calculate the total decay width by using the wave function at the origin and by taking into account the processes, $Q\bar{Q} \to HZ^0, gg, t\bar{t}, q\bar{q}, \gamma\gamma, \gamma Z^0, Z^0Z^0, W^+W^-$(We set the top quark mass to be 40GeV). The results are presented in Fig. 2 for the case of $\zeta = 2$. The dashed lines show the magnitudes of $\Gamma_g(Q\bar{Q})$ versus $M_{Q\bar{Q}}$ where $\Gamma_g(Q\bar{Q})$ is due to the gluon exchange alone. Since an ultraheavy quarkonium $Q\bar{Q}(0^{-+})$ decays predominantly into the Higgs boson and Z^0 because of the large Yukawa coupling of the Higgs boson to Q together with the fact that Z^0 can be longitudinal, we calculate the production cross section σ of an S-state quarkonium through the process $pp \to gg \to Q\bar{Q} \to HZ^0$, which is calculated as[3]

$$\begin{aligned}\sigma(pp \to gg \to Q\bar{Q} \to HZ^0) = &\int_{(M_H+M_{Z^0})^2} dM^2 \, \frac{\pi^2\tau}{8M_{Q\bar{Q}}^3} \\ \times\Gamma(Q\bar{Q} \to gg)\cdot B(Q\bar{Q} \to HZ^0)\cdot R(\tau, Q^2)\cdot &\frac{1}{\pi}\cdot\frac{M_{Q\bar{Q}}\Gamma(Q\bar{Q})}{(M^2 - M_{Q\bar{Q}}^2)^2 + (M_{Q\bar{Q}}\Gamma(Q\bar{Q}))^2},\end{aligned} \tag{3}$$

where $Q^2 = M_{Q\bar{Q}}^2/4$ and $\tau = M_{Q\bar{Q}}^2/s$ with the incident energy square s. By using the gluon distribution functions $g(x, Q^2)$ of Duke-Owens parametrization (set I)[5], $R(\tau, Q^2)$ is written as

$$R(\tau, Q^2) = \int_{\tau}^{1} \frac{dx}{x} \cdot g(x^2, Q^2) g(\tau/x, Q^2). \tag{4}$$

$M_{Q\bar{Q}}$ dependence of the cross section $\sigma(pp \to gg \to Q\bar{Q} \to HZ^0)$ at $\sqrt{s} = 40$ TeV are shown in Fig. 3 together with the results calculated from the gluon exchange alone σ_g(in dashed line) for $m_H = 100$ GeV. As shown in this figure, the production rate becomes very large in comparison with the one due to the gluon exchange alone for large $M_{Q\bar{Q}}$; for example, $\sigma(pp \to gg \to Q\bar{Q} \to HZ^0)/\sigma_g(pp \to gg \to Q\bar{Q} \to HZ^0) \simeq$ 55pb/6.5pb$\simeq$ 8.5 at $\sqrt{s} =$ 40TeV for $\zeta = 2$,$M_{Q\bar{Q}} \simeq$ 400GeV, and $m_H =$ 50GeV.

4. Discussion on feasibility

The dominant decay mode $Q\bar{Q} \to HZ^0$ leads to a variety of characteristic event topologies corresponding to various final states, depending on m_H. We limit the discussion in the region $m_H < 2M_W$. Then, the Higgs boson decays predominantly to $t\bar{t}$ or $b\bar{b}$, depending on the top quark mass. Thus, the characteristic event topology of final states comes to be l^+l^- + 2jets($t\bar{t}$ or $b\bar{b}$), where l^+l^- and 2jets are produced into back to back, or missing($\nu\bar{\nu}$)+2jets($t\bar{t}$ or $b\bar{b}$), where only 2jets produced in one side will be detected. As shown in Fig. 3, it is expected that we have the very large production event numbers for $pp \to gg \to Q\bar{Q} \to HZ^0$ which amount to 5.5×10^5 at $\sqrt{s} =$ 40TeV for $M_{Q\bar{Q}} \simeq$ 400GeV, $m_H =$ 50GeV if the integrated luminosity $L = 10^{40}$cm^2. The background to the signal comes from the QCD hard processes $q\bar{q} \to HZ^0$, $q\bar{q} \to gZ^0 \to t\bar{t}Z^0$(or $b\bar{b}Z^0$) and the quark loop contributions $gg \to HZ^0$. The production rate of such background processes except for the heavy quark loop process $gg \to HZ^0$ is of orders of magnitudes smaller than the cross section σ of the present signal process[6]. Some people have calculated the cross section of the heavy quark loop process $gg \to HZ^0$ which is of order of pb for $m_Q =$ 200GeV, $m_H =$ 100GeV at $\sqrt{s} =$ 40TeV[2,7]. The production rate of the signal process is much larger than their results. Moreover, it is remarkable that the signal process $gg \to Q\bar{Q} \to HZ^0$ has a resonance structure in the invariant mass distribution of M_{HZ^0}. This is not the case for the QCD hard processes. However, we should be more careful for the signal $HZ^0 \to l^+l^-b\bar{b}(t\bar{t})$ because we should take into account of the background from Z^0 radiations (followed by $\nu\bar{\nu}$) by b or $\bar{b}$(t or $\bar{t}$) in $b(t)$ pair productions. Furthermore, top quark pair productions without Z^0 radiations subsequently decaying semileptonically may fake $Q\bar{Q} \to l^+l^-b\bar{b}$ events if missing momenta due to neutrinos are small. However, the final state event topology of our process $gg \to Q\bar{Q} \to HZ^0 \to l^+l^-b\bar{b}(t\bar{t})$ and that of these background processes is very different in the present mass region. In our case the jets originated from H and the lepton pair from Z^0 get into back to back, while in the case of these backgrounds this is not the case because a jet will necessarily accompany a lepton. Therefore, we expect that the signal can be separated clearly from the QCD background by studying the event topology and the invariant mass distribution of M_Z^0.

If $m_H < 2m_t$, the important decay processes of the Higgs boson are $H \to b\bar{b}$ and $\tau\bar{\tau}$.

(Here we neglect $H \rightarrow c\bar{c}$ because of the assumption, $\xi = 0$.) In this case, we calculate the differential cross section $d\sigma/dy$ at $y = 0$ for various final states at $\sqrt{s} = 16$TeV and 40TeV for the case of $\zeta = 2$ and $m_Q = 200$ GeV with $m_H = 10$GeV, 50GeV, and 100GeV. The results are presented in Table 1, where some of the final states have the cross section of the order of pb in multi-TeV regions. Therefore there would be a good chance for detecting the signals.

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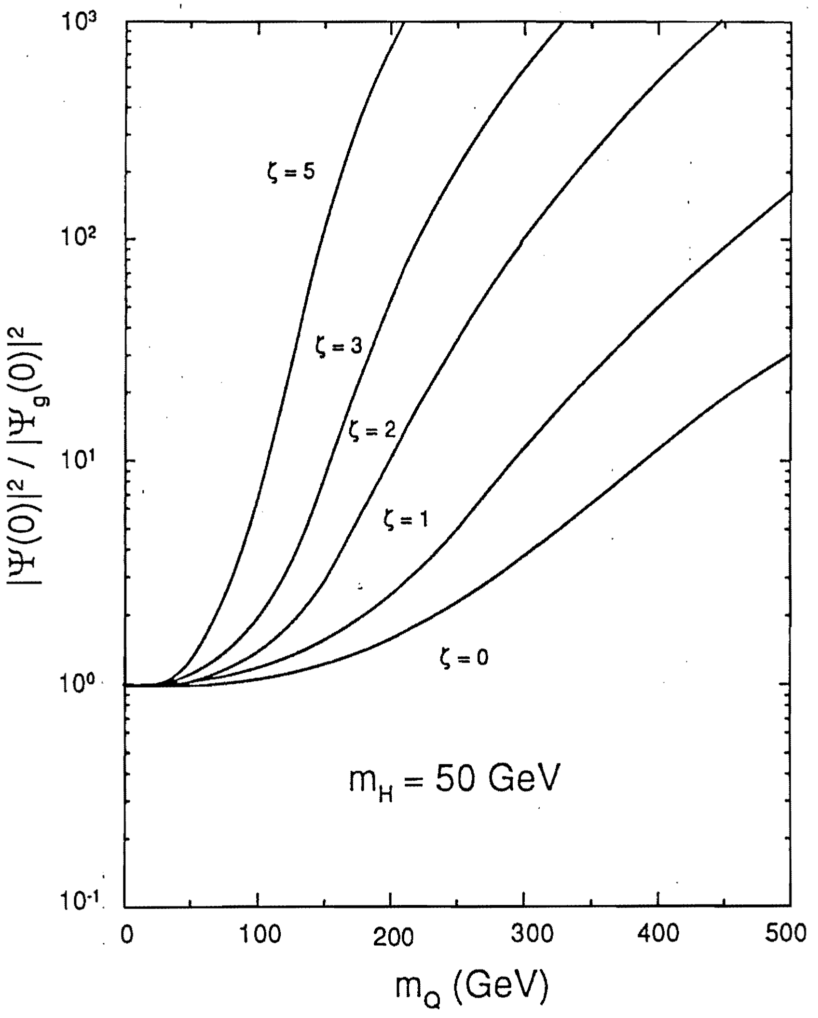
Figure captions

Fig. 1 Quark mass dependence of the wave function at the origin divided by the one due to the gluon exchange alone for $m_H = 50$GeV and various ζ.

Fig. 2 The total decay width $\Gamma(Q\bar{Q})$versus $M_{Q\bar{Q}}$ for $\zeta = 2$. The dashed lines denote $\Gamma g(Q\bar{Q})$ for $m_H = 50$GeV.

Fig. 3 The production cross section of $pp \rightarrow gg \rightarrow Q\bar{Q} \rightarrow HZ^0$ as a function of $M_{Q\bar{Q}}$ for $\zeta = 2$ at $\sqrt{s} = 40$TeV. The dashed lines show the cross section due to the gluon exchange alone for $m_H = 50$GeV.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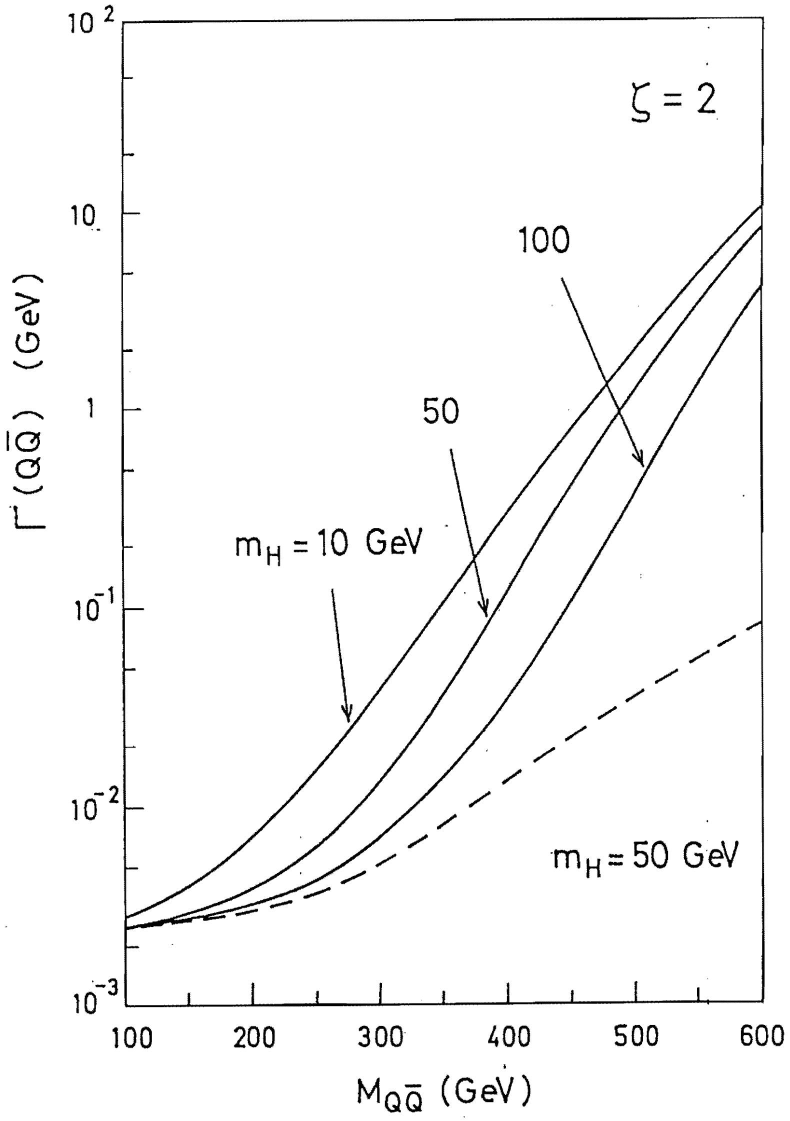
10^1
10^0
10^{-1}
0
100
200
300
400
500
$\zeta = 5$
$\zeta = 3$
$\zeta = 2$
$\zeta = 1$
$\zeta = 0$
$m_H = 50$ GeV
$|\Psi(0)|^2 / |\Psi_g(0)|^2$
m_Q (GeV)

Fig. 1


10^2
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1
10^{-1}
10^{-2}
10^{-3}
100
200
300
400
500
600
$\zeta = 2$
100
50
$m_H = 10$ GeV
$m_H = 50$ GeV
$\Gamma(Q\bar{Q})$ (GeV)
$M_{Q\bar{Q}}$ (GeV)

Fig. 2

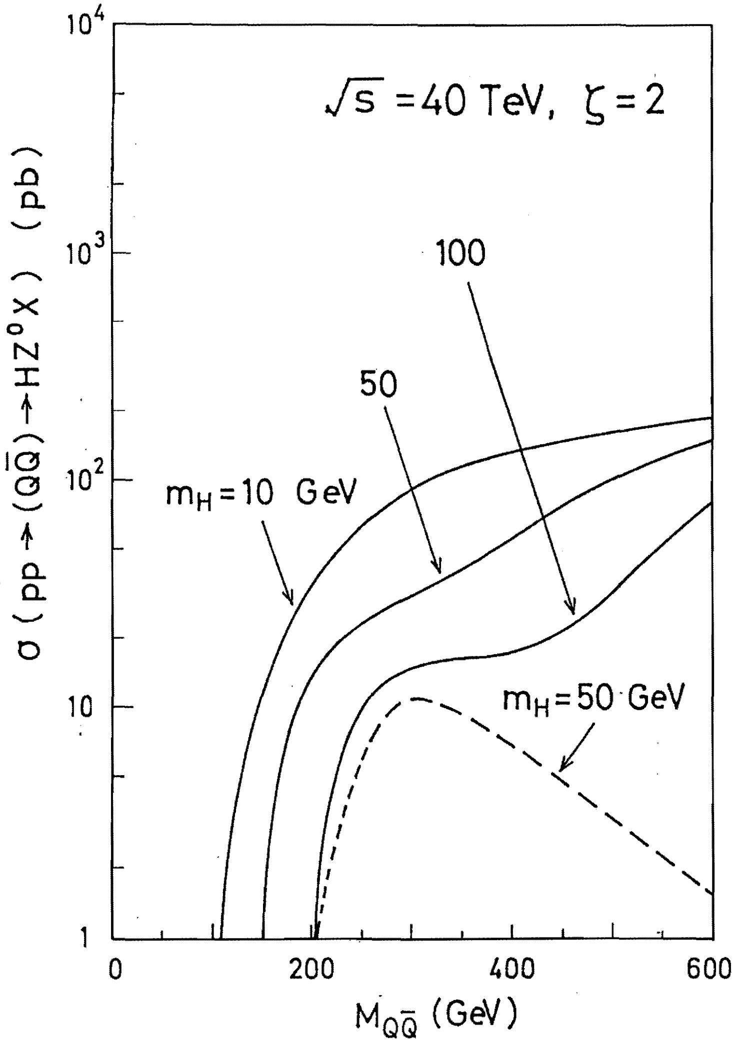

Fig. 3

Table 1

	$(d\sigma/dy)\|_{y=0}$ (pb)					
Final states*)	$\sqrt{s}$ = 16 TeV			$\sqrt{s}$ = 40 TeV		
	m_H = 10 (GeV)	m_H = 50 (GeV)	m_H = 100 (GeV)	m_H = 10 (GeV)	m_H = 50 (GeV)	m_H = 100 (GeV)
$b\bar{b} + l^+l^-$	0.182	0.115	0.037	0.685	0.383	0.139
$b\bar{b}$ + missing	1.087	0.690	0.222	4.082	2.289	0.829
$\tau\bar{\tau} + l^+l^-$	0.094	0.006	0.002	0.353	0.021	0.007
$\tau\bar{\tau}$ + missing	0.560	0.038	0.012	2.103	0.126	0.044

*) In these final states, l^+l^- denotes e^+e^-, $\mu^+\mu^-$ or $\tau^+\tau^-$ and missing represents the sum of neutrino-antineutrino pairs for three generations.