# SUPERHEAVY QUARKONIUM AND THE INTERMEDIATE MASS HIGGS

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## Abstract

We show that if these exists a fourth generation of quarks $a$ and $v$ ($m_a > m_v$) with small mixings ($\lesssim 10^{-2}$) so that the single quark decay of the $v$ quark is suppressed, then the pseudoscalar bound state $\eta_v$ of the $v\bar{v}$ system decays dominantly via $\eta_v \to Z^0 + H$ for a range of $v$-quark and Higgs boson masses. This gives a new way to simultaneously search for the Higgs boson and the fourth generation quark at the SSC. Signal-to-background ratio exceeding one appear to be possible even for the intermediate Higgs mass region.

The search for the Higgs boson is expected to be one of the most important areas of investigation at the SSC. Unfortunately, the Higgs signal is small and backgrounds present major problems to its detection,[1,2] especially for the case of the intermediate mass Higgs with $2m_t < m_H < 2M_W$. However, if there exists a fourth generation of quarks $(a, v)$ with masses $m_a > m_v$, then the production of the pseudoscalar bound state $\eta(v\bar{v})$ with dominant branching fraction $\eta \to H + Z^0$ gives a promising new signal for Higgs detection.[3] The relevant Feynman diagrams are shown in Fig. 1a.

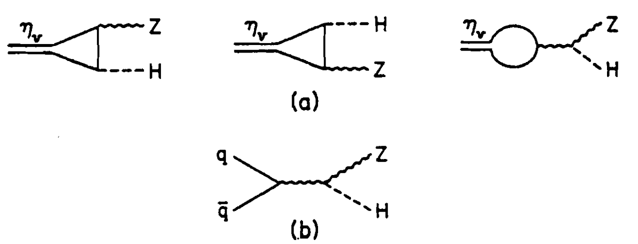


Fig. 1. Feynman diagrams contributing to (a) the decay $\eta_v \to Z^0 + H$ and (b) the $Z^0 - H$ continuum via light quark fusion.

The cross section for $\eta_v$ production depends on the gluon luminosity and the partial width $\Gamma(\eta_v \to gg)$ and is given by,[4]

$$\Gamma(p\bar{p} \to gg + X \to \eta_v + X) = K\frac{\pi^2}{8M_\eta^3}\Gamma(\eta_v \to gg)\ \tau \int_\tau^1 \frac{dx}{x}\ D_g(x, M_\eta^2)\, D_g\Big(\frac{\tau}{x}, M_\eta^2\Big) \qquad (1a)$$

with

$$\Gamma(\eta_v \to gg) = \frac{8\alpha_s^2(M_\eta^2)}{3}\frac{1}{M_\eta^2}|R(0)|^2 \qquad (1b)$$

In Eq. (1), $D_g$ is the gluon distribution in the proton, $\tau = M_\eta^2/s$ and R(0) is the value of the radial wave function of the $v\bar{v}$ system evaluated at the origin. $K$ is a possible QCD enhancement factor which we set equal to one in our analysis. We have evaluated the radial wave function using three representative QCD-inspired potentials (Cornell,[5] Richardson[6] and Wisconsin[7]) whose parameters have been adjusted by fits to charmonium and bottomonium data. The resulting cross sections for $pp \to \eta_v + X$ at $\sqrt{s} = 40$ TeV are shown in Fig. 2. We use the Duke-Owens[8] structure functions (set I) but similar results are obtained using EHLQ[1] structure functions.

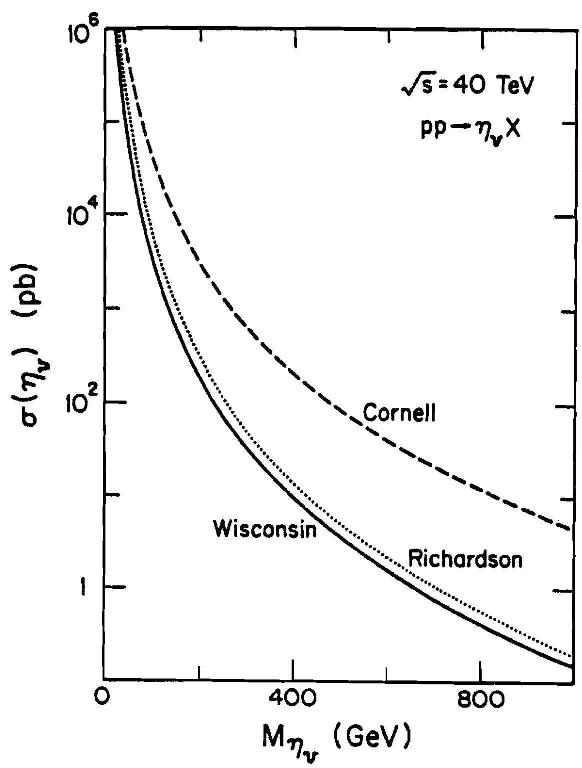


Fig. 2. The total cross section for $\eta_v$ production by gluon fusion at $pp$ colliders for $\sqrt{s} = 40$ GeV for three different quarkonium potentials.

If we can ignore single quark decays (we assume $m_a > m_v$ and also that the intergeneration mixing is $\lesssim O(10^{-2})$), bound state decays via annihilation dominate. The $\eta_v$ can decay into gauge boson pairs ($gg$, $\gamma\gamma$, $Z^0\gamma$, $Z^0Z^0$ and $W^+W^-$),

$ZH$ pairs and heavy fermion pairs. The branching fraction for $\eta_v \rightarrow ZH$ is shown in Fig. 3. In our computation we have ignored potentially large contributions from the decay of $\eta_v$ into new sequential heavy leptons or a heavy top quark. For $m_t = 50$ GeV, the branching fraction in Fig. 3 is reduced by $\lesssim 10\%$. We see that $\eta_v$ dominantly decays via the $Z$ + Higgs mode if $M_\eta \gtrsim 0.4$ TeV and $M_H \lesssim M_\eta - 250$ GeV. This is due to the enhancement factor $O\left((M_\eta^2/M_Z^2)^2\right)$ coming from the Yukawa coupling and from the fact that the mediating $Z^0$ in Fig. 1a is longitudinal. We note here that the decays $\eta \rightarrow Z^0Z^0$ or $\eta \rightarrow W^+W^-$ with $W^\pm$ and $Z^0$ longitudinal are not allowed by angular momentum and CP conservation.

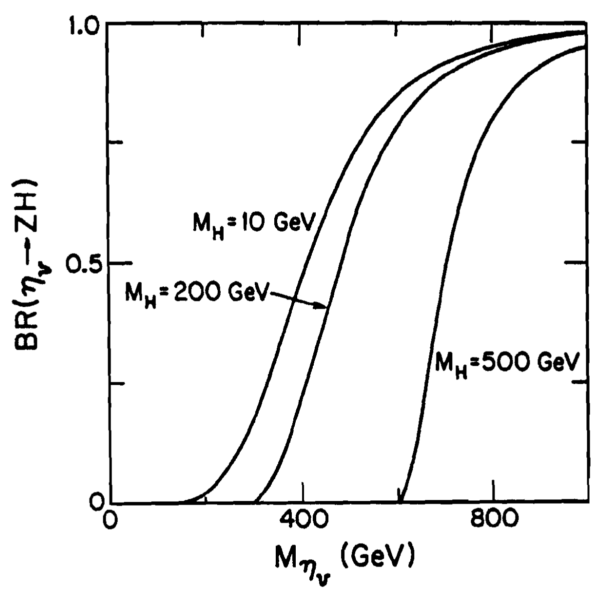


Fig. 3. The branching fraction for the decay $\eta_v \rightarrow Z^0 + H$ as a function of the mass of $\eta_v$ for different Higgs boson masses.

The cross section for $ZH$ production at the SSC via the $\eta_v$ resonance is shown in Fig. 4. Also shown is the $ZH$ cross section from light quark fusion (see Fig. 1b). For a cross section of 1 pb and an integrated luminosity of $10^{40}\text{cm}^{-2}$ anticipated annually at the SSC, $\sim 10^4$ $ZH$ events may be expected. The leptonic decay of the $Z^0$ would serve as a trigger for these events. Even after allowing for a 6% branching fraction for $Z^0 \rightarrow \ell^+\ell^-$, a wide range of $\eta_v$ and Higgs masses are accessible to detection. The cross sections shown in Fig. 4 are obtained using the radial wave function obtained from the Wisconsin potential, which as can be seen from Fig. 2, is a conservative estimate. The corresponding rates for other potentials can be obtained by scaling the cross sections as in Fig. 2. We have considered only the lowest $\eta_v$ state and that radial excitations would enhance the production rate by a potential-dependent factor which varies between 2.3 and 1.6 for $m_v$ between 50 GeV and 500 GeV for the Wisconsin potential. For the Richardson potential and the Cornell potential, this factor is typically 1.7 and 1.2, respectively.

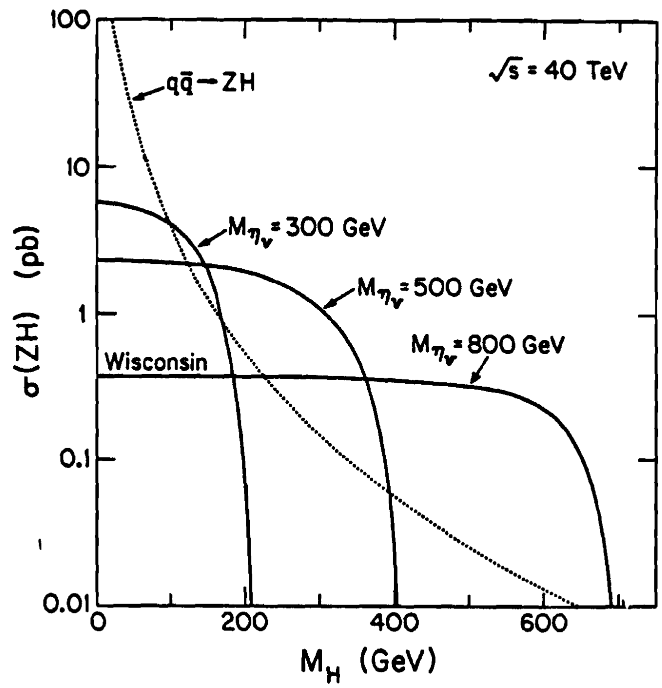


Fig. 4. The cross section for $Z^0H$ production via the $\eta_v$ resonance for the Wisconsin potential as a function of the Higgs boson mass. The cross section for $Z^0H$ production via light quark fusion is shown as a dotted line.

We now turn to a brief discussion of the signatures expected for various Higgs masses. If the Higgs were heavy enough, it would decay into $W^\pm$ and $Z^0$ pairs in the ratio 2:1 leading to characteristic three gauge boson events with little associated hadronic activity. For $2M_W > M_H > 2M_t$, the Higgs would dominantly decay via $H \rightarrow t\bar{t}$, and so, one would expect $t\bar{t}Z^0$ events with the $t\bar{t}Z^0$ mass peaking at $M_\eta$. We note that the reaction $gg \rightarrow Z^0t\bar{t}$, which leads to the same final state is a potentially severe background to the Higgs signal due to the large gluon luminosity at the SSC. It is clear that the experimental resolution attainable will play a crucial role in separating the signal from this background. The $Z^0t\bar{t}$ background has been studied by Gunion and Kunzst[9] and it appears that a signal to background ratio exceeding unity can be obtained assuming reasonable mass resolutions on $M_{t\bar{t}}$ and $M_{Z^0t\bar{t}}$. The decay of the $\eta_v$ thus provides a promising new way of searching for the intermediate mass Higgs.

If $M_H < 2M_t$, the dominant decay of the Higgs, $H \rightarrow b\bar{b}$ would probably be obscured by QCD backgrounds. In this case, one could look for $H \rightarrow \tau^+\tau$. Although the branching fraction for this is only 3–4%, this decay leads to essentially background free $\tau^+\tau^- + Z^0$ events with a cross section of 0.04–0.4 pb corresponding to 20–200 gold-plated $\tau^+\tau^-\ell^+\ell^-$ events per year.

In addition to the $Z^0 + H$ mode discussed here, the decay of quarkonium leads to other interesting signals. In particular, the production of gauge boson pairs via $\eta_v$ and $\psi_v$ resonances is large so that the production of bound states may provide us with a clean signal for new heavy colored fermions be they fourth generation quarks or other colored exotica, at the SSC. These matters are currently under investigation.[10]

In summary, we have shown that if there exists a fourth generation of quarks, the production of $Z^0H$ pairs may be greatly enhanced at supercollider energies. For representative choices of masses for the fourth generation quarks, the $Z^0H$ signal[3] from the decay of the pseudoscalar bound state $\eta_v$ appears to be separable from the background[9] allowing for Higgs boson identification for $M_H$ up to 0.5 TeV, including the intermediate mass Higgs.

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