Higgs-Boson–Z^0 Associated Production from Fourth-Generation Quarks at Supercollider Energies

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If a fourth generation of quarks (a, v) exists, the cross section for production of the Higgs boson in association with the Z boson may be greatly enhanced. We evaluate the subprocesses $gg \to \eta(v\bar{v}) \to ZH$, $gg \to Z^* \to ZH$, and $q\bar{q} \to Z^* \to ZH$ and find a substantial Higgs-boson signal in pp collisions at $\sqrt{s} = 40$ TeV.

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The discovery of the Higgs boson is by far the most important remaining test of the standard model. Unfortunately the Higgs-boson signal is relatively small in all processes and in many instances is obscured by backgrounds.[1,2] In this Letter we consider promising new mechanisms for Higgs-boson production at supercollider energies should there exist a fourth generation[3] of quarks (a, v) and leptons (ν_L, L). The relevant subprocesses are illustrated in Fig. 1. They involve the production of a Higgs boson in conjunction with the Z gauge boson, whose subsequent decays $Z \to l\bar{l}$ would serve as a trigger in the Higgs-boson search. The first source is a pseudoscalar quarkonium state η_v formed as a bound state of a fourth-generation charge $-\frac{1}{3}$ quark v. The η_v can be produced via gluon fusion and decays dominantly to ZH if $M_\eta \gtrsim 0.4$ TeV and $M_H \lesssim M_\eta - 250$ GeV. We assume $m_a > m_v$ and small intergeneration mixing $(\lesssim 10^{-2})$ so that the single-v-quark weak decay of η_v is suppressed. Additional continuum contributions to ZH production arise from the subprocesses $q\bar{q} \to ZH$ (Ref. 1) and $qq \to ZH$. The $gg \to ZH$ graphs may be enhanced by fourth-generation quark-loop contributions. We evaluate and compare the expected ZH event rates from these sources at the 40-TeV energy of the proposed proton-proton collider, the Superconducting Super Collider (SSC), and find potentially substantial signals. If $m_a < m_v$, the results are essentially the same with the interchange $a \leftrightarrow v$.

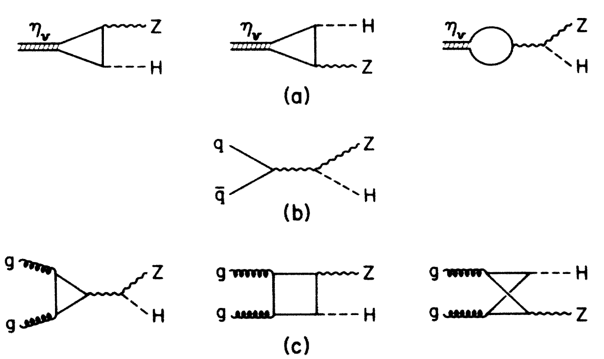

FIG. 1. Feynman diagrams contributing to the associated production of ZH pairs from (a) the η_v resonance, (b) light-quark annihilation, and (c) gluon-gluon fusion. The first two diagrams in (a) cancel. Diagrams obtainable by crossing are omitted for (c). Note that the triangle and the box diagrams in (c) are separately gauge invariant.

The cross section for η_v production is simply determined[4] from the gluon-gluon luminosity and the $\eta_v \to gg$ decay width which is given by

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

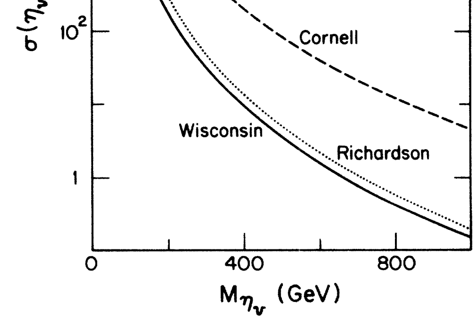

FIG. 2. The total cross section for η_v production via gg fusion at pp colliders for $\sqrt{s} = 40$ TeV for three QCD-inspired potential models.

where $R(0)$ is the radial wave function of the $\nu\bar{\nu}$ system at the origin. We evaluated $R(0)$ from three representative QCD-inspired potentials (Cornell,[5] Richardson,[6] and Wisconsin[7]) whose parameters have been previously adjusted by fits to $c\bar{c}$ and $b\bar{b}$ quarkonium data. The resulting cross sections for $pp \to \eta_\nu$ + anything at $\sqrt{s} = 40$ TeV are shown versus M_η in Fig. 2. Here we have used the Duke-Owens I structure functions,[8] but similar results are obtained with the Eichten-Hinchliffe-Lane-Quigg structure functions.[1]

The η_ν partial width to the ZH final state is

$$\Gamma(\eta_\nu \to ZH) = \frac{3\alpha_Z^2}{64} \frac{M_\eta^2}{M_Z^4} \beta^3 |R(0)|^2, \qquad (2)$$

where $\alpha_Z = \alpha/\sin^2\theta_W \cos^2\theta_W$ and

$$\beta = \{[1-(M_Z+M_H)^2/M_\eta^2] \times [1-(M_Z-M_H)^2/M_\eta^2]\}^{1/2}.$$

The resulting $\eta_\nu \to ZH$ branching fractions are given in Fig. 3 versus M_η for several values of M_H.[9]

It is interesting to compare $\eta \to H + Z^0$ with the decay $\psi \to H + \gamma$ (recall that $\eta \not\to H + \gamma$) first studied by Wilczek.[10] The latter process is enhanced by a factor of $O((M_\psi/M_Z)^2)$ from the Yukawa coupling to the heavy fermion, whereas the process $\eta \to H + Z^0$ has an enhancement $O((M_\eta/M_Z)^4)$ from the Yukawa coupling together with the fact that the Z^0 can be longitudinal. We note that the decays $\eta \to Z^0 Z^0$ or $\eta \to W^+ W^-$ with longitudinal Z^0 or $W^\pm$ are not allowed by considerations of angular momentum and CP conservation.

The cross section for ZH production at the SSC via the η_ν resonance is shown in Fig. 4(a). We ignore any potential K-factor enhancements from higher-order QCD diagrams. For a cross section of 1 pb and an integrated luminosity of 10^{40} cm^{-2} (anticipated annually at the SSC), 10^4 ZH events may be expected. Radial excitations could increase this rate. Allowing for a factor of $\frac{1}{15}$ for the $Z \to l^+ l^-$ branching fraction leaves a wide range of Z and H masses accessible to detection.

We next turn our attention to the continuum subprocesses. The $q\bar{q} \to ZH$ contribution has previously been considered in Ref. 1; this cross section, which is independent of the fourth-generation quarks, is shown

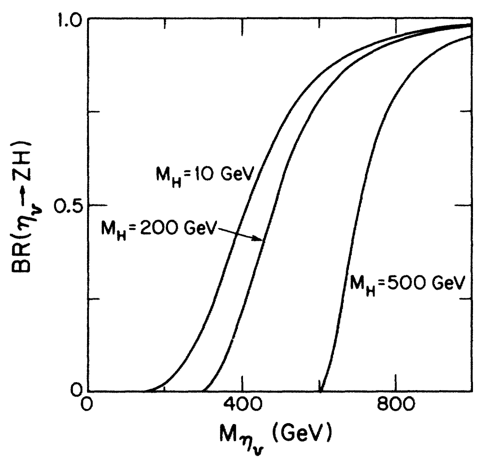

FIG. 3. The branching fraction for $\eta_\nu \to ZH$ as a function of M_η for several values of the Higgs-boson mass.

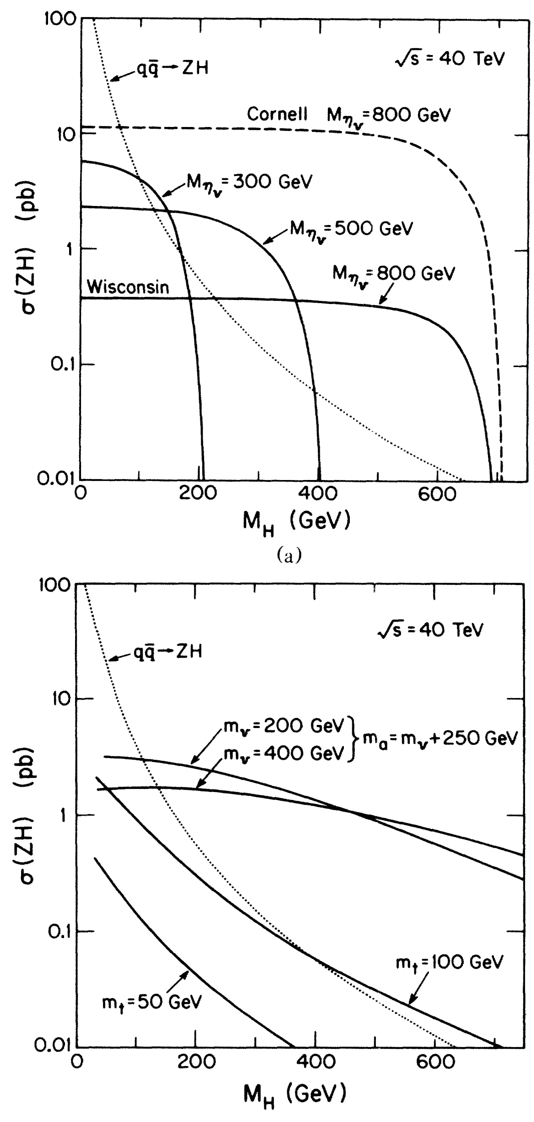

FIG. 4. (a) The production cross section for ZH production through the η_ν resonance for the Wisconsin potential for different η_ν masses. Also shown is the cross section from the Cornell potential for $M_\eta = 800$ GeV. The corresponding cross section can be easily evaluated for other η_ν masses since the ratio of η_ν production for the two potentials can be read off from Fig. 2. (b) The contribution of the triangle graph to ZH production via gluon fusion. Also shown is the contribution from $q\bar{q}$ annihilation.

in Fig. 4(b). The subprocess $gg \to ZH$ can proceed via a heavy-quark triangle or box diagram [see Fig. 1(c)]. The triangle graph can be straightforwardly evaluated, but the box graph is more difficult to calculate. However, since the triangle diagram contributes to only one partial wave ($J=0$) while the box diagram can contribute to all partial waves, the two graphs are expected to be essentially incoherent. Consequently, the triangle graph gives a lower bound on the $gg \to ZH$ contribution. We find that the ZH cross section from this contribution is given by[11]

$$\hat{\sigma}(gg \to ZH) = \frac{\alpha_s^2 \alpha_W^2 \beta^3}{1024\pi M_W^4 \hat{s}} \left| m_Q^2 I\left(\frac{4m_Q^2}{\hat{s}}\right) - m_{Q'}^2 I\left(\frac{4m_{Q'}^2}{\hat{s}}\right)\right|^2, \quad (3)$$

where $\alpha_W = \alpha/\sin^2\theta_W$,

$$\beta = \{[1-(M_Z+M_H)^2/\hat{s}][1-(M_Z-M_H)^2/\hat{s}]\}^{1/2},$$

and (Q,Q') are the heavy-quark members of a weak isodoublet. The function I is given by

$$I(x) = \frac{1}{2}\left[\ln\left(\frac{1+(1-x)^{1/2}}{1-(1-x)^{1/2}}\right) - i\pi\right]^2$$

for $0<x<1$ and $I(x) = -2\arctan^2[1/(x-1)^{1/2}]$ for $x \geq 1$. This subprocess cross section grows like $\hat{s}$ within the range $4m_Q^2 \lesssim \hat{s} \lesssim 4m_{Q'}^2$ and thus becomes more important for a larger Q'-Q mass difference. Note that the cross section vanishes if there is no mass splitting within the doublet.[12]

The ZH production cross section for gluon fusion through the triangle graph at the SSC is shown in Fig. 4(b) for two sets of quark masses. The strong coupling α_s is evaluated at $\hat{s}$. Also shown is the contribution from the third generation, with a t-quark mass of 50 or 100 GeV but without fourth-generation quarks. We conclude that if there are nondegenerate fourth-generation quarks, or if the top quark is very heavy, the gluon contribution to ZH production can substantially exceed that from the usual light-quark sources. We remark also that unlike the ZH pairs from the continuum subprocesses, the ZH pairs from the η_ν peak sharply in invariant mass. The width of the peak is governed by the experimental resolution.

We now briefly discuss the signatures expected for various Higgs-boson masses. If the Higgs boson is 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 $2M_W > M_H > 2m_t$, $t\bar{t}$ decays would dominate and so one would expect $t\bar{t}Z^0$ events with the $t\bar{t}$ invariant mass peaking at M_H. The dominant background to this is from Z^0+QCD $t\bar{t}$ events from gluon fusion which has not been calculated. Our rough estimate based on the existing $gg \to W + t\bar{b}$ cross section[13] shows that for the process $\eta_\nu \to ZH$ the signal is at worst comparable to the background after cuts on $t\bar{t}$ and $Zt\bar{t}$ invariant masses. We thus expect that a Higgs boson in this mass region would be observable via this channel at the supercollider. Finally, we consider the possibility $M_H \lesssim 2m_t$. The dominant decay would then be into $b\bar{b}$ pairs (which would probably be obscured by QCD background[13]). In this case, however, one could look for $H \to \tau^+\tau^-$. Although the branching fraction is only ~3%–4%, this decay mode leads to essentially background-free $\tau^+\tau^- + Z^0$ events with a cross section of 0.04–0.4 pb, corresponding to 20–200 easily identifiable and background-free $\tau^+\tau^- l\bar{l}$ events per year.

In summary, we have shown that if there exists a fourth generation of quarks the production of ZH pairs is greatly enhanced at supercollider energies. For representative choices of the masses for fourth-generation quarks the ZH signal can be separated from the background allowing for Higgs-boson identification for M_H up to 0.5 TeV. The processes considered here may well be the most promising way to look for Higgs bosons at hadron colliders.

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$$\Gamma(\eta_v \rightarrow L\bar{L}) = \frac{3\alpha_Z^2}{32}\frac{M_L^2}{M_Z^4}\left(1-\frac{4M_L^2}{M_Z^2}\right)^{1/2}|R(0)|^2,$$

and $\bar{t}t$, with $\Gamma(\eta_v \rightarrow t\bar{t})$ a factor 3 larger for $M_L \rightarrow m_t$ above. We ignore a potentially large contribution from $\eta_v \rightarrow t\bar{t}$ if m_t is large. For $m_t = 50$ GeV, the $\eta_v \rightarrow ZH$ branching ratio is reduced by about 10% except near the edge of phase space. For simplicity in our present discussion we have also ignored the $L\bar{L}$ decay mode, which becomes important only when ZH is kinematically suppressed.

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