Higgs-boson production via bremsstrahlung from heavy quarks

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We estimate the rate of Higgs-boson (H) production via bremsstrahlung in the decay of a heavy fermion (h) with mass in excess of 100 GeV. The basic reaction studied is $h \to l + W + H$ where l is a light fermion and W is the usual weak gauge boson. This is a "radiative correction" to the usual decay of a heavy quark $h \to l + W$. For sufficiently heavy quarks this process has a very substantial branching ratio with a rate comparable to that for $h \to l + W$ signaling the breakdown in the perturbation expansion in the Higgs-boson—fermion coupling.

Recently, there has been much interest in the possibility of observing heavy Higgs bosons (H) with masses in excess of $\simeq 0.2$ TeV at the Superconducting Super Collider.[1] The two main mechanisms for H production that have been most discussed in the literature are gluon fusion via a quark loop[2] and the fusion of two gauge bosons.[3] In this paper we speculate on the possible production of H by a bremsstrahlung emission from a heavy quark (with a mass $\gtrsim 0.25$ TeV or so).

As is well known, the coupling of a fermion to H is proportional to the fermion mass (m_F) and is of order the electromagnetic strength for $m_F \simeq 80$ GeV. For even heavier fermions we may expect that the production rate of H's via a bremsstrahlung-type process exceeds that for photons with appropriate energy cuts and allowing for phase-space suppression. There has been much speculation recently about the existence of a fourth generation[4] of quarks (and leptons) with such large masses that they could then lead to H production via this mechanism. Note, however, that as m_F grows very large (approaching 1 TeV or so) that ordinary perturbation theory breaks down and we should not take the results presented here (which are based on lowest-order perturbation theory) to be more than qualitative. As we will see, the production rate for H's from bremsstrahlung decays grows to be quite enormous once such large fermion masses are reached.

We will assume in our analysis the existence of a heavy quark which decays via charged currents to a W boson and a lighter fermion. We then examine the influence of additional H bremsstrahlung radiation in this process. As one would expect (as discussed below), the Superconducting Super Collider (SSC) will be a copious source of such heavy quarks.

The diagrams responsible for the process $h \to lW + H$ are shown in Fig. 1; note that the bremsstrahlung of Higgs bosons occurs from both the original heavy fermion h and the W boson. (In our calculation we will take the mass of the light fermion l to be zero.) The couplings of fermions and W bosons to Higgs scalars can be written in general as

$$L_{\text{int}} = \lambda_1(\sqrt{2}G_F)^{1/2} m_F \bar{f} f H + 2\lambda_2(\sqrt{2}G_F)^{1/2} M_W^2 W_\mu^\dagger W^\mu H \ . \tag{1}$$

Note that the standard model (SM) is given by the limit $\lambda_1 = \lambda_2 = 1$. L_{int} leads to the following matrix element for the $h \to lW + H$ process (where $r \equiv \lambda_2/\lambda_1$):

$$M = \frac{ig}{2\sqrt{2}}(\sqrt{2}G_F)^{1/2}\lambda_1 \bar{u}(p_2)\left[\gamma^\mu(1-\gamma_5)\frac{m_F}{(\not{p}_1-\not{k})-m_F} - 2rM_W{}^2\gamma_\nu(1-\gamma_5)\frac{g^{\mu\nu}-(k+q)^\mu(k+q)^\nu/M_W{}^2}{(k+q)^2-M_W{}^2}\right] \times u(p_1)\epsilon_\mu^w(k) \ . \tag{2}$$

Equation (2) leads to the following double-differential decay rate for the $h \to lWH$ process:

$$\frac{d^2\Gamma}{dx_1 dx_3} = K\delta_W{}^{-2}(T_1+T_2+T_3)m_F\lambda_1{}^2 \ , \tag{3}$$

where

$$\begin{aligned}
T_1 &= D_1{}^{-2}\{(-1+2C-\delta_H{}^2)(A+2DB\delta_W{}^{-2})+2(1-C)[A-E+2D(B-F)\delta_W{}^{-2}]\} \ , \\
T_2 &= 4r^2\delta_W{}^4 D_2{}^{-2}\{A+2BD\delta_W{}^{-2}-2(B-D)D\delta_w{}^{-4}+A\delta_W{}^{-2}[2-\delta_W{}^{-2}(1-2A)+\delta_W{}^{-4}(B-D)^2]\} \ , \\
T_3 &= -4r\delta_W{}^2(D_1D_2)^{-1}\{[1-\delta_W{}^{-2}(1-2A)+\delta_W{}^{-4}(B-D)^2](2A-E)+2[D(2B-F)+A(2-2A-C+E)]\delta_W{}^{-2} \\
&\quad -\delta_W{}^{-4}(B-D)[D(2-2A-C+E)+(2B-F)A]\} \ ,
\end{aligned} \tag{4}$$

and with

$$A=\tfrac{1}{2}x_2,\quad B=\tfrac{1}{2}x_3,\quad C=\tfrac{1}{2}x_1,$$
$$D=\tfrac{1}{2}(1-x_1)+\tfrac{1}{2}(\delta_H{}^2-\delta_W{}^2)\,,$$
$$E=\tfrac{1}{2}(1-x_3)+\tfrac{1}{2}(\delta_W{}^2-\delta_H{}^2)\,, \tag{5}$$
$$F=\tfrac{1}{2}(1-x_2)-\tfrac{1}{2}(\delta_W{}^2+\delta_H{}^2)\,,$$
$$D_1=\delta_H{}^2-2C,\quad D_2=\delta_H{}^2+2F\,.$$

Here we have used the definitions

$$K=\frac{G_F{}^2M_W{}^4}{64\pi^3}\,,$$
$$\delta_H=m_H/m_F,\delta_W=m_W/m_F\,, \tag{6}$$
$$x_1=2E_H/m_F,\quad x_2=2E_l/m_F,\quad x_3=2E_W/m_F\,,$$

with the energy-momentum constraint $x_1+x_2+x_3=2$. The rest of the notation is self-explanatory.

To obtain the decay rate we must integrate Eq. (3) over the allowed ranges of x_1 and x_3:

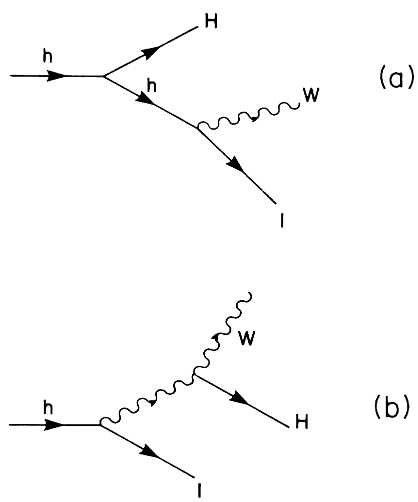

FIG. 1. Feynman diagrams responsible for the $h\to lWH$ decay mode.

$$\Gamma(h\to lWH)=\int_{2\delta_H}^{1-(\delta_W{}^2-\delta_H{}^2)}dx_1\int_{1+(\delta_W+\delta_H)^2-x_1}^{1-(\delta_H{}^2-\delta_W{}^2)}dx_3\left[\frac{d^2\Gamma}{dx_1dx_3}\right]. \tag{7}$$

This rate must be compared with that for the usual decay mode $h\to lW$:

$$\Gamma(h\to lW)=\frac{G_FM_W{}^2}{8\pi\sqrt{2}}m_F\delta_W{}^{-2}(1-3\delta_W{}^4+\delta_W{}^6)\,. \tag{8}$$

In Figs. 2 and 3 we plot the ratio (with $\lambda_1=\lambda_2=1$)

$$R\equiv\Gamma(h\to lWH)/\Gamma(h\to lW) \tag{9}$$

as a function of m_F for different values of $m_H\geq 100$ GeV. Note the rapid increase in R with increasing m_F.

Using the production-cross-section estimates of Eichten, Hinchliffe, Lane, and Quigg[1] (EHLQ) for heavy-quark pair production we can estimate the number of H's expected to be produced per year (N). We find that

$$N=\sigma_hL\frac{2R}{1+R}\,, \tag{10}$$

where σ_h is the $pp\to h\bar{h}+X$ production cross section and L is the SSC integrated luminosity (we assume $10^{33}\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ for 10^7 sec so that $L=10^{40}\ \mathrm{cm}^{-2}$). With σ_h in picobarns, N is given numerically by

$$N=2\times10^4R(1+R)^{-1}/\mathrm{yr}\,.$$

As an example, consider the value of N for $m_F=0.4$ TeV and $m_H=0.25$ TeV; using the estimates of EHLQ and Fig. 2 we find $N\simeq165$ events/yr which is reasonably substantial. For $m_F=0.8$ TeV and $m_H=0.25$ TeV we obtain

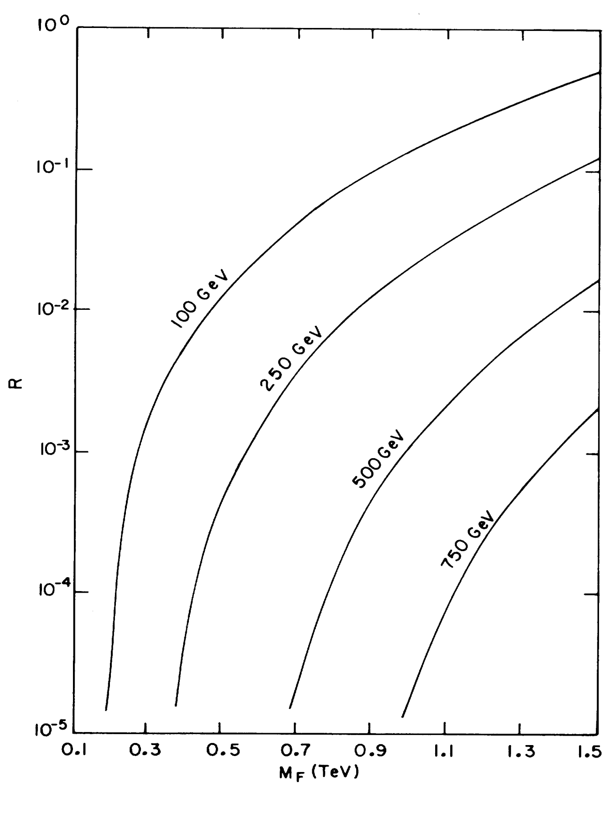

FIG. 2. The ratio R defined in the text for $0.1\leq m_F\leq 1.5$ TeV with various values of m_H shown on the curves.

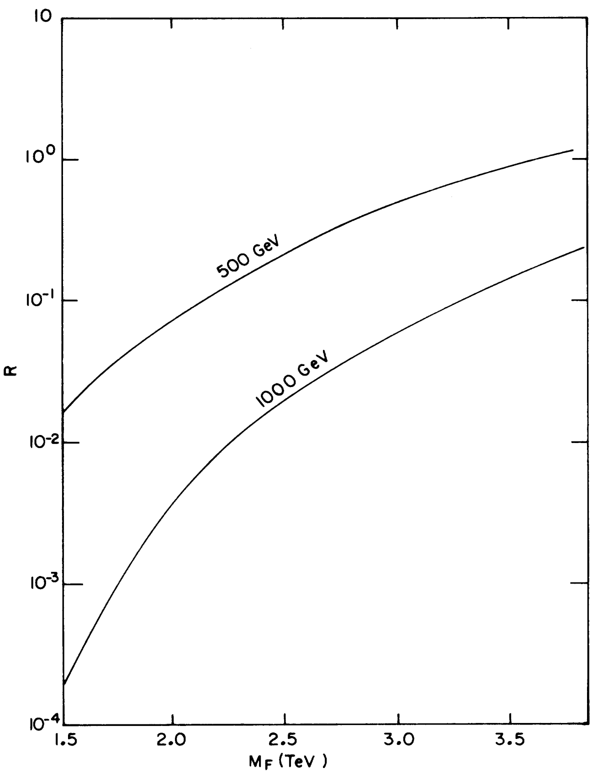

FIG. 3. Same as Fig. 2 but for $1.5 \leq m_F \leq 3.8$ TeV.

$\simeq$1200 events/yr which is quite large. For even heavier quarks (keeping m_H fixed) the value of N increases since R increases faster than σ_h falls for quark masses of interest. Note that these values are comparable to or larger than the expected number of H's produced by gauge-boson fusion models.[3] The signal for such events should be reasonably clean since we expect $H \rightarrow W^+W^-, 2Z^0$'s (which may subsequently decay leptonically) and a third gauge boson already exists from the normal decay of the second member of the $h\bar{h}$ pair. Thus a two-jet plus multiple leptons plus missing energy final state should provide a signal for both new heavy-quark production as well as Higgs-boson production via bremsstrahlung from the heavy quark.

We have examined the production rate of Higgs bosons by bremsstrahlung off of a possible heavy fourth-generation quark at SSC energies. We have found that the event rates are reasonably large for the Higgs-boson and heavy-fermion masses of interest. The rapid increase in the branching ratio R is another signal for the breakdown in perturbation theory when Higgs-boson couplings to fermions become large. Thus for such large couplings our results can only be qualitative but they suggest that this mechanism may be quite viable as a source of Higgs bosons.

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[1]See, for example, E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984).

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