Radiative decay of heavy Higgs bosons

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The decays of heavy Higgs bosons ($m_H \gtrsim 200$ GeV) are dominated by W^+W^- and Z^0Z^0 final states. We examine the related radiative decay $H \to W^+W^-\gamma$ for hard photons, which has a fairly large relative branching ratio (20%–40%) as the Higgs-boson mass increases. This process further enlarges the width-to-mass ratio of the heavy Higgs boson, signaling a breakdown in perturbation theory as the Higgs-boson mass nears 1 TeV.

Recently, there has been much discussion of the possibility of producing heavy Higgs bosons with masses in excess of the $W^{\pm}$ and Z^0 gauge bosons.[1–3] In particular, very heavy Higgs bosons would prefer to decay into pairs of gauge bosons instead of fermions of comparable mass with a partial decay rate growing as the third power of the Higgs-boson mass. As is well known, the interaction of very heavy Higgs bosons becomes nonperturbative, and this large growth of the Higgs-boson width relative to its mass signals such a breakdown in perturbation theory.

In this paper, we examine the decay of such a very heavy Higgs boson ($m_H \geqslant 200$ GeV) into the $W^+W^-\gamma$ final state where the photon is hard ($E_\gamma \geqslant 5$ GeV); as the Higgs-boson mass grows to the TeV range, this final state has a relative branching ratio of 20%–40% and is thus a significant contributor to the total width of the Higgs boson. In fact, for m_H sufficiently large, the $W^+W^-\gamma$ partial width with these cutoffs is comparable to that for $H \to 2Z^0$ and must be included to obtain an accurate estimate of the Higgs-boson total width.

The Feynman diagrams for the process $H \to W^+W^-\gamma$ are shown in Fig. 1; the matrix element for this process is given by

$$M = M_+ - M_- \ , \tag{1}$$

where the relative sign is due to the opposite charges of the W^+ and W^- and

$$M_\pm = i\sqrt{2}egM_W\left[\frac{g_{\nu\sigma} - g_\nu^{\ \pm} q_\sigma^{\pm}/M_W^2}{q_\pm^{\ 2} - M_W^2}\right]\epsilon_\nu^+\epsilon_\mu^-\epsilon_\lambda^\gamma\Gamma^{W^\pm}_{\sigma\mu\lambda} \ , \tag{2}$$

with g being the usual weak coupling constant, M_W the W mass, and

$$\Gamma^{W^\pm}_{\sigma\mu\lambda} = g_{\sigma\mu}(2p_\pm + k)_\lambda + g_{\sigma\lambda}(p_\pm + 2k)_\mu + g_{\mu\lambda}(p_\pm - k)_\sigma, \quad q_\pm = p_\pm + k \ . \tag{3}$$

Here, $p_\pm$ ($\epsilon_\pm$) are the momenta (polarization vectors) of the outgoing $W^\pm$ and k (ϵ^γ) is the photon momentum (polarization vector). $q_\pm$ are the virtual $W^\pm$ momenta carried on the internal line. $\Gamma^{W^\pm}_{\sigma\mu\nu}$ is the reduced $WW\gamma$ vertex in the standard model with the anomalous magnetic moment set to unity.

Some lengthy algebra informs us that

$$|M|^2 = 2e^2g^2\left\{(p_+\cdot k)^2 + 2p_+\cdot p_- p_+\cdot k\, p_-\cdot k/M_W^2 + \left[2 + \left(\frac{p_+\cdot p_-}{M_W^2}\right)^2\right]\left[\frac{2p_+\cdot p_- M_W^2}{p_+\cdot k\, p_-\cdot k} - \left(\frac{M_W^2}{p_+\cdot k}\right)^2 - \left(\frac{M_W^2}{p_-\cdot k}\right)^2\right] + \frac{2p_+\cdot p_-}{M_W^2}[(p_-\cdot k)^{-1} - (p_+\cdot k)^{-1}]\left[2p_+\cdot p_- - M_W^2\left(\frac{p_+\cdot k}{p_-\cdot k} + \frac{p_-\cdot k}{p_+\cdot k}\right)\right]\right\} \ . \tag{4}$$

Defining $x_\pm = 2E_{W^\pm}/m_H$, we find the differential decay rate to be given by

$$\frac{d\Gamma(H \to W^+W^-\gamma)}{dx_+\,dx_-} = \frac{m_H\alpha^2}{2\pi\sin^2\theta_W}\{\ \} \ , \tag{5}$$

where $\{\ \}$ is given by the expression in curly brackets in (4) with the replacements

$$p_+\cdot k = \tfrac{1}{2}m_H^2(1 - x_-) \ , \quad p_-\cdot k = \tfrac{1}{2}m_H^2(1 - x_+) \ , \quad p_+\cdot p_- = \tfrac{1}{2}m_H^2(x_+ + x_- - 1) - M_W^2 \ . \tag{6}$$

Since we will compare our results directly with those for $H \to W^+W^-$ and $2Z^0$, we note that

$$\Gamma(H \to W^+W^-) = \frac{m_H\alpha}{4\sin^2\theta_W}\left[1 - \frac{4M_W^2}{m_H^2}\right]^{1/2}\left[3\frac{M_W^2}{m_H^2} - 1 + \frac{1}{4}\frac{m_H^2}{M_W^2}\right] \ ,$$
$$\Gamma(H \to 2Z^0) = \frac{m_H\alpha}{8\sin^2\theta_W\cos^2\theta_W}\left[1 - \frac{4M_Z^2}{m_H^2}\right]^{1/2}\left[3\frac{M_Z^2}{m_H^2} - 1 + \frac{1}{4}\frac{m_H^2}{m_Z^2}\right] \ . \tag{7}$$

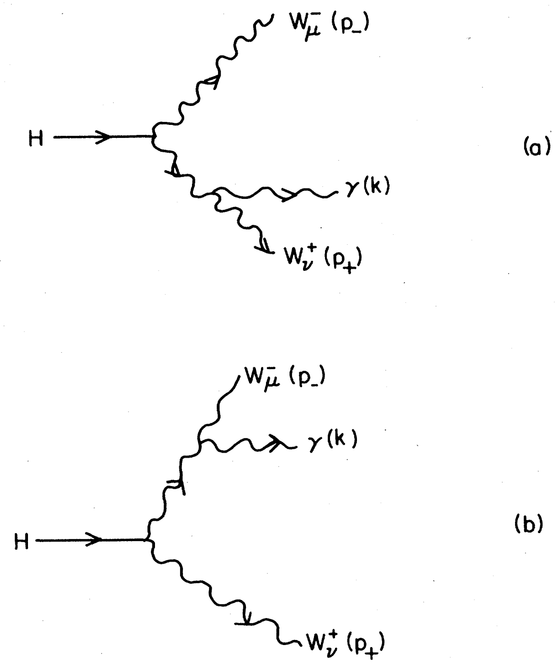

FIG. 1. Feynman diagrams for the decay $H \rightarrow W^+W^-\gamma$.

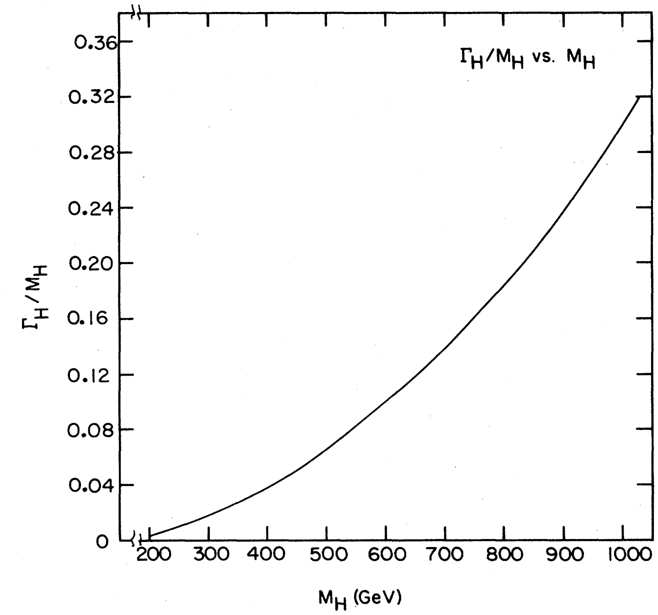

FIG. 2. $\Gamma(H \rightarrow W^+W^-)/m_H$ as a function of m_H.

We see in both cases that as $m_H{}^2/M_{W,Z}{}^2$ get large, Γ/m_H grows as $m_H{}^2$; we also see that the $2Z^0$ width is suppressed by an additional factor of ≈ 1.6 in comparison to the W^+W^- mode. Figure 2 shows a plot of $m_H{}^{-1}\Gamma(H \rightarrow W^+W^-)$ as a function of the Higgs-boson mass m_H; we see that this ratio is $\simeq 25\%$ for $m_H \simeq 0.9$ TeV, signaling the strong coupling of the Higgs boson to the longitudinal component of the W. In fact, for sufficiently large m_H this ratio exceeds unity.

To obtain the width for the $H \rightarrow W^+W^-\gamma$ mode we integrate (5) subject to a photon-energy cutoff which we expect to be in the 5–20-GeV range for a detector at a machine such as the proposed Superconducting Super Collider[4] (SSC). In Fig. 3 we plot the ratio

$$R \equiv \Gamma(H \rightarrow W^+W^-\gamma)/\Gamma(H \rightarrow W^+W^-)$$

for various lower limits on the photon energy. For reasonably light Higgs bosons (200–300 GeV) the value of R is only several percent as would be expected of a radiative correction, but as m_H increases to 1 TeV we see that R tends to be 20%–40% range, which is indeed comparable to the ratio of $\Gamma(H \rightarrow 2Z^0)/\Gamma(H - W^+W^-)$ as advertised. The ratio R will climb even further as the value of m_H is further increased above 1 TeV.

A Higgs boson in the mass range of interest could be produced at the SSC with a significant cross section so that the $W^+W^-\gamma$ decay mode could be easily studied.[3] Although the decay of a very heavy Higgs boson into W^+W^- or $2Z^0$ may be difficult to observe,[5] the large branching ratio into a final state including a hard photon may help in its observation. The greatest difficulty in observing these decays may be significant background from the subprocess $q\bar{q} \rightarrow W^+W^-\gamma$. Figures 151 and 152 of Ref. 5 show that for $30 \leq m_t \leq 70$ GeV, the cross section ($m_H = 800$ GeV) times branching ratio for $pp \rightarrow H \rightarrow W^+W^-$ is $\simeq 2$ pb, so that from radiative Higgs-boson decay we would expect $\simeq \frac{1}{2}$ pb. With a luminosity of 10^{33} cm^{-2}sec^{-1} and 1 year (10^7 sec) of running time we would expect $\simeq 5000$ events. As a background estimate for the process $q\bar{q} \rightarrow W^+W^-\gamma$, we examine Fig. 122 of Ref. 5 and integrate $d\sigma/dm$ from 0.5 to 0.8 TeV. This gives us $\sigma(pp \rightarrow W^+W^-)$ with pair

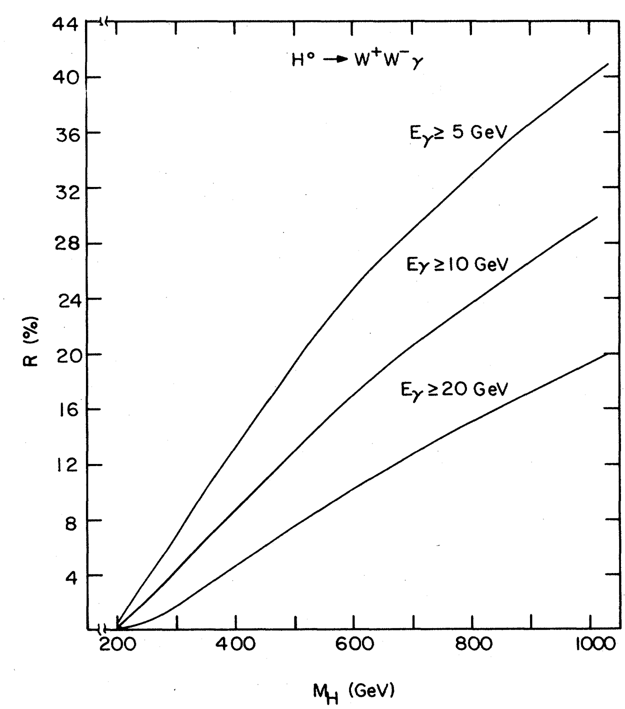

FIG. 3. $R \equiv \Gamma(H \rightarrow W^+W^-\gamma)/\Gamma(H \rightarrow W^+W^+)$ as a function of m_H for various cutoffs of the photon energy spectrum.

masses in this range, the range expected from radiative decay, which yields $\sigma \simeq 5$ pb. The further suppression accompanying $\sigma(pp \rightarrow W^+W^-\gamma)$ by α/π for W-pair masses in this range strongly indicates the approximate equality of the signal to background for this process. Even if the W's are only observed in their purely leptonic modes ($e\bar{\nu}$ and $\mu\bar{\nu}$), we would expect $\simeq 250$ events of this kind per year.

It should be noted, as always, that when one includes the virtual HWW vertex correction to the bremsstrahlung diagram considered here the total rate for $H \rightarrow W^+W^- + W^+W^-\gamma$ is finite and quite insensitive to the cutoff E_γ applied above. One goal was merely to examine the rate of hard ($E_\gamma \geq 5$ GeV) photon production in this decay.

Our last point is that for very heavy Higgs bosons with width $\gtrsim 100$ GeV the signal is spread out over a considerable area, which may make the $W^+W^-\gamma$ signal somewhat difficult to detect.

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