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Higgs-scalar decays: $H \rightarrow W^{\pm} + X$

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Decays of a Higgs scalar in the mass range $m_W \lesssim m_H \lesssim 2m_W$ ($m_W = W^{\pm}$ mass $\simeq 83$ GeV) are examined. For $m_H \gtrsim 125$ GeV, the branching ratio for $H \rightarrow W^{\pm} + X$ is found to be substantial, provided the top quark is heavy, $m_t > m_H/2$. Implications of our results for hadron-hadron-collider experiments are briefly discussed.

The standard $SU(2)_L \times U(1)$ model of electroweak interactions predicts the existence of a neutral spin-zero particle H, called the Higgs scalar.[1] It is a necessary remnant of the spontaneous-symmetry-breaking mechanism which provides mass for the $W^{\pm}$, Z, quarks, and leptons. Discovery of this fundamental scalar is crucial for confirmation of the standard model.

How will the Higgs scalar be found? The answer depends on its mass, since Higgs-scalar production cross sections and decay branching ratios are highly m_H dependent. (Unfortunately, m_H is essentially a free parameter, although somewhat constrained by theory[2] to the range 7 GeV $\lesssim m_H \lesssim 1$ TeV.) A relatively light Higgs scalar $\lesssim 60$ GeV should be detectable via the decays[3] $Z \rightarrow H\mu^+\mu^-$ or $H\gamma$ (perhaps also t-quarkonium $\rightarrow H\gamma$ depending[4] on m_t) at the coming generation of e^+e^- colliders. Somewhat higher masses (up to $\simeq 100$ GeV) may be observable at CERN LEP II through the reaction[3,5] $e^+e^- \rightarrow ZH$ if high luminosity ($\simeq 10^{32}$ cm^{-2}sec^{-1}) is achieved.

On the other end of the scale, a very heavy Higgs scalar $> 2m_W \simeq 166$ GeV can best be produced at high-energy hadron-hadron colliders via gluon-gluon fusion.[6] For large enough m_H, the decays $H \rightarrow W^+W^-$ or ZZ become dominant.[7] In that case the Higgs scalar can be recognized by leptonic decays of one of the vector bosons. This scenario has been examined in Ref. 8.

What about an intermediate Higgs-scalar mass? That case has not received much attention, even though it would appear to be the most likely. In this paper we will address that possibility by examining Higgs-scalar decays for the mass range $m_W \lesssim m_H \lesssim 2m_W$ where $m_W \simeq 83$ GeV is the $W^{\pm}$ mass. Such scalars should be copiously produced at high-luminosity hadron-hadron colliders; but their detection may be difficult due to severe backgrounds. We will, however, argue that the decays $H \rightarrow WX$ or ZX followed by a leptonic decay of the $W^{\pm}$ or Z could provide a discernible signal if the branching fraction for such events is not too small. That scenario will in fact be realized if $m_H \gtrsim 125$ GeV and $m_t \gtrsim m_H/2$. The latter constraint is needed to kinematically eliminate the potentially large competing mode $H \rightarrow t\bar{t}$.

We begin by reviewing decay rates for a Higgs scalar with mass $< 2m_W$.

$H \rightarrow f\bar{f}$: The decay rate of a Higgs scalar into a quark-antiquark or lepton-antilepton pair (generically denoted by $f\bar{f}$) is given by[1,2,7]

$$\Gamma(H \rightarrow f\bar{f}) = (3)\frac{g^2}{32\pi}\frac{m_f^2}{m_W^2}m_H\left(1-\frac{4m_f^2}{m_H^2}\right)^{3/2} \quad (1)$$

with (3) a color factor for quarks and $g^2/4\pi = \alpha/\sin^2\theta_W \simeq 0.036$. Notice that H likes to decay into heavy fermions. If $m_t < m_H/2$, then $H \rightarrow t\bar{t}$ is likely to be the dominant decay mode for $m_H < 2m_W$. However, m_t is as yet unknown. In the event that $m_t > m_H/2$, $b\bar{b}$ is elevated to the dominant $f\bar{f}$ decay and it becomes interesting to consider higher-order induced decays which may then be relatively more important.

$H \rightarrow gg$: The two-gluon decay of a Higgs scalar proceeds through the quark triangle diagrams in Fig. 1. The rate given by[4,9]

$$\Gamma(H \rightarrow gg) = \frac{g^2 m_H^3}{288\pi m_W^2}\left(\frac{\alpha_s(m_H/2)}{\pi}\right)^2 |I|^2 \ , \quad (2)$$

where $\alpha_s(m_H/2)$ is the running QCD coupling ($\simeq 0.1$ for $m_H \simeq 2\ m_W$) and[8]

$$I = 3\sum_{i=u,d,\ldots,t}[2\lambda_i + \lambda_i(4\lambda_i - 1)G(\lambda_i)] \ , \quad (3a)$$

$$\lambda_i = m_i^2/m_H^2 \ ,$$

$$G(\lambda_i) = -2\left[\arcsin\left(\frac{1}{2\sqrt{\lambda_i}}\right)\right]^2, \quad \lambda_i \geq \tfrac{1}{4} \ , \quad (3b)$$

$$G(\lambda_i) = \tfrac{1}{2}\ln^2\left(\frac{\eta^+}{\eta^-}\right) - \frac{\pi^2}{2} + i\pi\ln\left(\frac{\eta^+}{\eta^-}\right), \quad \lambda_i < \tfrac{1}{4} \ , \quad (3c)$$

$$\eta^{\pm} = 1 \pm (1 - 4\lambda_i)^{1/2} \ .$$

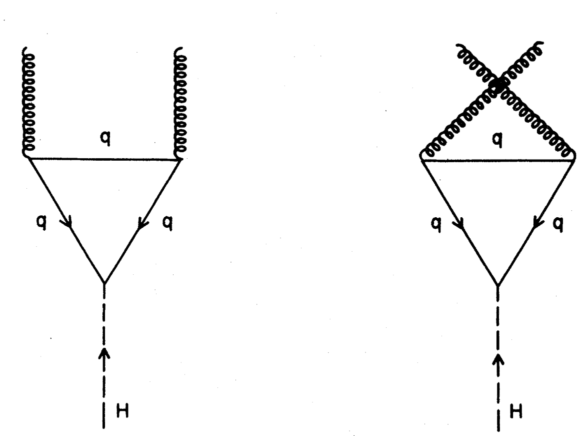

FIG. 1. Quark loop diagrams contributing to the decay $H \rightarrow 2$ gluons.

For six quark flavors we expect $|I|^2\simeq 1$–3 (depending on m_t), which leads to a small branching ratio for $H\to gg$ if $m_W\lesssim m_H\lesssim 2m_W$.

$H\to Wf\bar{f}'$: Such decays proceed through the diagram in Fig. 2 with one real and one virtual W. (We neglect Higgs-scalar–fermion couplings and all other effects proportional to m_f/m_W.) The amplitude for this process is given by[10] (neglecting finite-W-width effects[11])

$$\mathcal{M}=\frac{ig^2m_W}{\sqrt{2}}\epsilon_\mu(k)\frac{1}{m_H{}^2-2P\cdot k}\bar{u}(l)\gamma^\mu\frac{1-\gamma_5}{2}v(q)\quad . \quad (4)$$

Squaring this amplitude and summing over polarizations gives

$$\sum_{\rm pol}|\mathcal{M}|^2=\frac{g^4m_W{}^2}{(m_H{}^2-2P\cdot k)^2}\left[l\cdot q+\frac{2l\cdot k\,q\cdot k}{m_W{}^2}\right]\quad . \quad (5)$$

Integrating over the f and $\bar{f}'$ phase space in the H rest system leads to

$$\frac{d\Gamma(H\to Wf\bar{f}')}{dx}=\frac{g^4m_H}{3072\pi^3}\frac{(x^2-4\epsilon^2)^{1/2}}{(1-x)^2}\times(x^2-12\epsilon^2x+8\epsilon^2+12\epsilon^4)\quad , \quad (6)$$

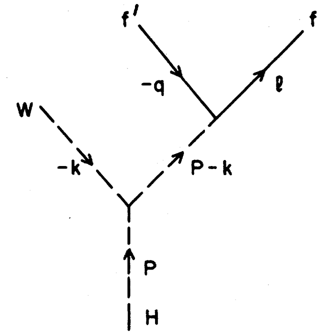

FIG. 2. Feynman diagram for $H\to Wf\bar{f}'$.

with

$$x=2E_W/m_H,\quad \epsilon=m_W/m_H,\quad 2\epsilon\leqslant x\leqslant 1+\epsilon^2\quad .$$

If instead we integrate over the W phase space and angle between f and $\bar{f}'$, the double-differential decay rate is obtained:

$$\frac{d\Gamma(H\to Wf\bar{f}')}{dy\,dz}=\frac{g^4m_H}{512\pi^3}\frac{1}{(1-y-z)^2}[(1-y)(1-z)-\epsilon^2(3-2y-2z)+2\epsilon^4]\quad ,\quad y=2E_f/m_H,\quad z=2E_{\bar{f}'}/m_H\quad . \quad (7)$$

[Note that $x+y+z=2$ allows any double-differential rate combination to be obtained from Eq. (7).] Integrating either Eq. (6) or (7) gives

$$\Gamma(H\to Wf\bar{f}')=\frac{g^4m_H}{3072\pi^3}F(\epsilon)\quad , \quad (8a)$$

$$F(\epsilon)=\frac{3(1-8\epsilon^2+20\epsilon^4)}{(4\epsilon^2-1)^{1/2}}\arccos\left[\frac{3\epsilon^2-1}{2\epsilon^3}\right]-(1-\epsilon^2)\left[\frac{47}{2}\epsilon^2-\frac{13}{2}+\frac{1}{\epsilon^2}\right]-3(1-6\epsilon^2+4\epsilon^4)\ln\epsilon\quad . \quad (8b)$$

To obtain the inclusive rate $\Gamma(H\to W^\pm X)$, we multipy Eq. (8a) by 18 (the factor 18 corresponds to the number of distinct final states with a W^+ or W^- and light-fermion pair; the top quark is not included):

$$\Gamma(H\to W^\pm X)=\frac{3g^4m_H}{512\pi^3}F(\epsilon)\quad . \quad (9)$$

In the case of the Z boson, a similar analysis (neglecting $H\to Zt\bar{t}$) yields

$$\Gamma(H\to ZX)=\frac{g^4m_H}{2048\pi^3\cos^4\theta_W}\times(7-\tfrac{40}{3}\sin^2\theta_W+\tfrac{160}{9}\sin^4\theta_W)F(\epsilon')\quad , \quad (10)$$

$$\epsilon'=m_Z/m_H,\quad m_Z\simeq 93.8\text{ GeV},\quad \sin^2\theta_W\simeq 0.215\quad .$$

Partial rates for $H\to Zf\bar{f}$ are obtained by multiplying Eq. (10) by the $Z\to f\bar{f}$ branching ratio.

We are now in a position to compare Higgs-scalar decay branching ratios. If $m_t<m_H/2$, the decay $H\to t\bar{t}$ will dominate. In that case from Eqs. (1) and (9) one finds

$$\frac{\Gamma(H\to W^\pm X)}{\Gamma(H\to t\bar{t})}=\frac{\alpha}{4\pi\sin^2\theta_W}\frac{m_W{}^2}{m_t{}^2}F(\epsilon)\left[1-\frac{4m_t{}^2}{m_H{}^2}\right]^{-3/2}\quad . \quad (11)$$

This branching ratio is plotted in Fig. 3 for $m_t=36$ GeV. Notice that it ranges from 1–10% for $m_H\simeq 135$–160 GeV. Hence, in that scenario $H\to W^\pm X$ is important for a narrow range of m_H values. If on the other hand $m_t>m_H/2$, the primary decays become $H\to b\bar{b}$, $c\bar{c}$, $\tau\bar{\tau}$, gg, $W^\pm X$, and ZX. Branching ratios for these modes are illustrated in Fig. 4. The $H\to W^\pm X$ mode becomes significant ($>10\%$) for $m_H\gtrsim 125$ GeV and exceeds 50% for $m_H>150$ GeV.

Is this scenario $m_H>125$ GeV and $m_t>m_H/2$ a realistic expectation? A recent analysis by Bég, Panagiotakopoulos, and Sirlin[12] based on theoretical consistency suggests that

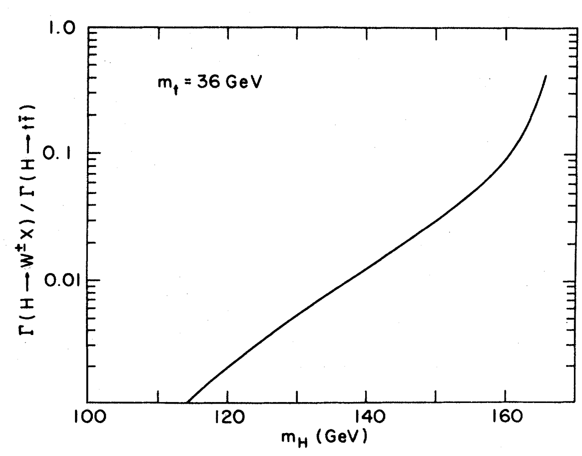

FIG. 3. Branching fraction $\Gamma(H\to W^\pm X)/\Gamma(H\to t\bar{t})$ for $m_t=36$ GeV.

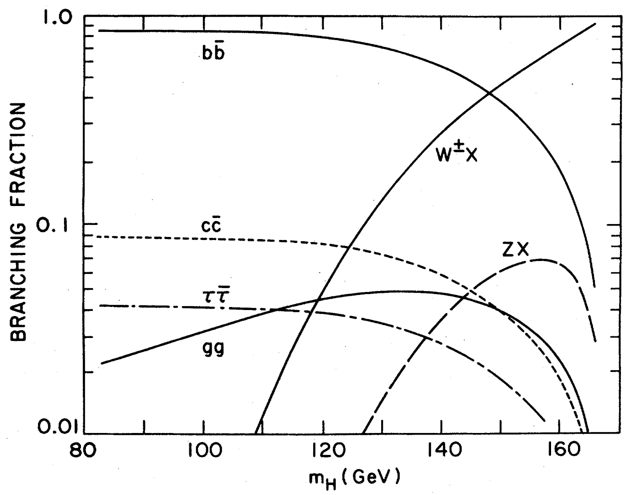

FIG. 4. Higgs-scalar decay branching ratios for $m_t > m_H/2$. For definiteness we used $m_t = 90$ GeV in Eq. (3).

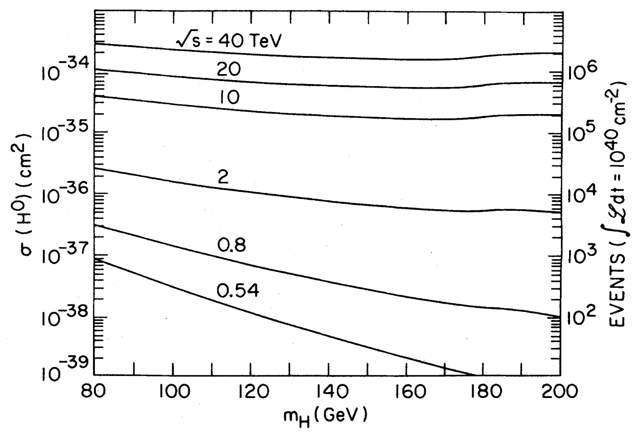

FIG. 5. Higgs-scalar production cross section via gluon-gluon fusion for a variety of $\sqrt{s}$ collider values. The scale on the right-hand side corresponds to the total number of Higgs scalars produced for an integrated luminosity of 10^{40} cm^{-2}.

$m_H > 125$ GeV may actually require that m_t (or some heavier fermion) is greater than $m_H/2$. So the decay $H \rightarrow W^{\pm}X$ may indeed turn out to be prevalent. (Note, if $m_t \lesssim 60$ GeV, the top quark should be discovered at the CERN $p\bar{p}$ collider after the next run.)

Assuming that a significant fraction of all Higgs scalars produced at hadron-hadron colliders decay via $H \rightarrow W^{\pm}X$, how might they be detected? The clearest signature would seem to be a high-energy electron or muon produced by the subsequent decay $W \rightarrow e\nu$ or $\mu\nu$ in events with $X = 2$ hadronic jets.[13] Those final-state configurations should account for about 14% of all $H \rightarrow W^{\pm}X$ decays. In such events the missing neutrino energy can be determined from momentum-balance considerations and the Higgs-scalar mass reconstructed.

Viability of the above scenario requires the production of a significant number of Higgs scalars. In Fig. 5 we give estimated cross sections for gluon + gluon $\rightarrow H$ for a variety of $\sqrt{s}$ values at hadron-hadron colliders.[8] Of course, due to uncertainties in the gluon distribution functions and value of $|I|^2$, our cross-section estimates should be considered very approximate. In any case, Fig. 5 suggests that the combination of high energy and high luminosity potentially provides a large number of Higgs scalars for the range $m_W < m_H < 2m_W$.

In conclusion, the decay $H \rightarrow W^{\pm}X$ is a potentially important mode for detecting the Higgs scalar at the next generation of high-luminosity colliders, particularly if $m_t > m_H/2$. That channel may also be the harbinger of entirely new nonstandard physics (for example, pseudoscalars with mass $\simeq 150$ GeV). Indeed, the physics of $W^{\pm}X$ events may prove to be experimentally much richer than anticipated.

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[10]The decay $H \rightarrow Wf\bar{f}'$ was first considered by Rizzo (Ref. 7). Our conclusion regarding the utility of this mode is more optimistic. In addition our computed rate is a factor of $\frac{4}{3}$ larger.

[11]For ϵ very near $\frac{1}{2}$ the finite width of the W should be included by replacing $(1-x)^2$ with $(1-x)^2 + \epsilon^2 \Gamma_W^2/m_H^2$ ($\Gamma_W = W$ decay width) in Eq. (6). Our graphs include this effect.

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[13]The usefulness of this signature was pointed out to us by F. Paige.