HEAVY HIGGS PRODUCTION AND DETECTION

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Summary

We have studied the production rate for very heavy Higgs scalars at high luminosity hadron-hadron colliders via the gluon fusion mechanism. For a Higgs mass $m_H > 2m_Z$, the decay modes $H^\circ \to W^+W^-$ or $Z^\circ Z^\circ$ dominate. Requiring that one W or Z decay into leptons may provide a detectable signal above background.

The standard $SU(2)_L \times U(1)$ model requires the existence of a neutral spin zero particle, H°, called the Higgs scalar. It is a remnant of the spontaneous symmetry breaking mechanism which provides mass for the $W^\pm$ and Z° as well as quarks and charged leptons. Detection of this fundamental scalar is crucial, if we are to confirm the standard model.

Unfortunately, the H°'s mass, m_H, is essentially a free parameter; however, theory provides some guidance. Vacuum stability requires $m_H > 7$ GeV while perturbative unitarity suggests $m_H < 1$ TeV.[1] Together, these constraints imply

$$7 \text{ GeV} < m_H < 1 \text{ TeV} \qquad (1)$$

Arguments for a more restricted range are less compelling. One possibility involves setting the Higgs mass to zero in lowest order. Radiative corrections then lead to $m_H \simeq 10$ GeV.[2] A Higgs scalar that light should be easily detected in $Z^\circ \to H^\circ e^+e^-$ or toponium $\to H^\circ\gamma$ at e^+e^- colliders.[3] Indeed, those modes may allow one to observe the H° up to $m_H \simeq 60$ GeV. However, there is no clear justification for starting with zero mass in lowest order and hence no compelling reason for accepting the light Higgs scenario. Indeed, one might guess that m_H lies closer to the scalar vacuum expectation value $v \simeq G_F^{-\frac{1}{2}} \simeq 300$ GeV, which can be considered the natural mass scale of weak interactions. If that is the case, how might such a massive scalar be observed? In this note we describe a potential mechanism for producing and detecting heavy Higgs scalar with $m_H > 2\, m_W \simeq 166$ GeV at high luminosity hadron-hadron colliders.

We begin our discussion by recalling that the coupling strength of the H° to fermions and gauge bosons is proportional to their masses. Therefore, it tends to decay into the heaviest fields possible. Phase space permitting, the $SU(2)_L \times U(1)$ model predicts the following decay rates[4]

$$\Gamma(H \to f\bar{f}) = \frac{(3)G_F}{4\pi\sqrt{2}}\, m_f^{\,2} m_H \left(1 - \frac{4m_f^2}{m_H^2}\right)^{3/2} \qquad (2)$$

$$\Gamma(H \to W^+W^-) = \frac{G_F m_H^3}{8\pi\sqrt{2}} \left(1 - \frac{4m_W^2}{m_H^2}\right)^{\frac{1}{2}} \left(1 - 4\frac{m_W^2}{m_H^2} + 12\frac{m_W^4}{m_H^4}\right) \qquad (3)$$

$$\Gamma(H \to Z^\circ Z^\circ) = \frac{G_F m_H^3}{16\pi\sqrt{2}} \left(1 - \frac{4m_Z^2}{m_H^2}\right)^{\frac{1}{2}} \left(1 - 4\frac{m_Z^2}{m_H^2} + 12\frac{m_Z^4}{m_H^4}\right) \qquad (4)$$

where the (3) in eq. (2) is a color factor for the case f = quark. To illustrate the implication of these formulas, we consider the possibilities m_H = 200, 300 and 400 GeV. Then for $m_t \simeq 30$ GeV and the standard model's value $m_W = 83$ GeV and $m_Z = 93.8$ GeV, one finds

$$\begin{array}{ll} \Gamma(H\to t\bar{t}) : \Gamma(H\to W^+W^-) : \Gamma(H\to Z^\circ Z^\circ) :: & \\ 1 : 3.2 : 1.0 & (m_H = 200 \text{ GeV}) \\ 1 : 11.3 : 5.0 & (m_H = 300 \text{ GeV}) \\ 1 : 23.7 : 11.0 & (m_H = 400 \text{ GeV}) \end{array} \qquad (5)$$

Of course the value of m_t is presently unknown; however, eq. (5) does suggest that a very heavy Higgs may decay primarily into intermediate vector bosons. That would be fortuitous, since such decays could be more easily identified (than $f\bar{f}$ ones) at hadron-hadron colliders. The signal, one intermediate vector boson decaying into leptons balanced by the other's decay products, should be quite distinct.

How does one produce a heavy Higgs scalar? In pp or $p\bar{p}$ colliders the dominant production mechanism should be gluon-gluon fusion (see fig. 1). The

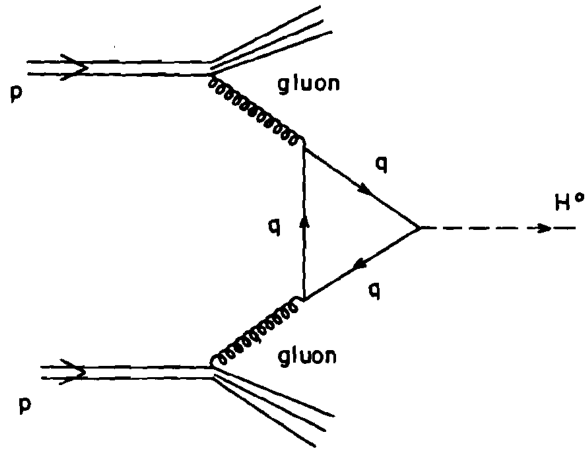

Fig. 1. H° Production via gluon-gluon fusion.

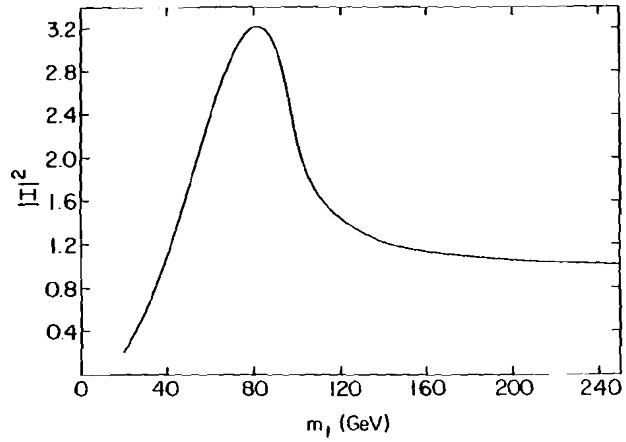

Fig. 2. The value of $|I|^2$ vs. m_t for m_H = 200 GeV.

cross-section for this process has been calculated by Georgi, Glashow, Machacek and Nanopoulos.[5] They found

$$\sigma_H = \sigma_o \, |I|^2 \int_{\ell n\sqrt{\tau}}^{-\ell n\sqrt{\tau}} dy \; \tau F_G(\sqrt{\tau}e^{y}) \, F_G(\sqrt{\tau}e^{-y}) \tag{6a}$$

$$\sigma_o = \frac{G_F}{\sqrt{2}} \frac{\pi}{288} \left(\frac{\alpha_s(m_H/2)}{\pi}\right)^2 \simeq 5 \times 10^{-38} \text{ cm}^2 \tag{6b}$$

where $\tau = m_H{}^2/s$, F_G is the gluon distribution function and

$$I = 3 \sum_i \left(2\lambda_i + \lambda_i(4\lambda_i - 1) \int_0^1 dx \, \frac{1}{x} \ell n \left(1 - \frac{x(1-x)}{\lambda_i}\right)\right) \tag{7}$$

$\lambda_i = m_i{}^2/m_H{}^2$, i = u,d,s,c,b,t

The $|I|^2$ factor in eq. (6) results from the quark loops in fig. 1. We can express the integral in eq. (7) in terms of tabulated functions[6]

$$\int_0^1 dx \, \frac{1}{x} \ell n \left(1 - \frac{x(1-x)}{\lambda}\right) = -2\left(\arcsin\left(\frac{1}{2\sqrt{\lambda}}\right)\right)^2, \; \lambda > \tfrac{1}{4} \tag{8}$$

$$= \tfrac{1}{2}\ell n^2 \left(\frac{\eta^+}{\eta^-}\right) - \frac{\pi^2}{2} + i\pi\ell n \left(\frac{\eta^+}{\eta^-}\right), \; \lambda < \tfrac{1}{4}$$

where $\eta^{\pm} = \frac{1}{2} \pm (\frac{1}{4} - \lambda)^{\frac{1}{2}}$.

Summing over the five known quark flavors in eq. (7) using m_u = 3 MeV, m_d = 8 MeV, m_s = 180 MeV, m_c = 1.25 GeV, m_b = 4.5 GeV and varying the top quark's mass m_t, we find for m_H = 200 GeV the $|I|^2$ values illustrated in fig. 2. Note that $|I|^2$ is sensitive to the value of m_t. It peaks at about 3.2 for $m_t \simeq$ 80 GeV and is 0.23 for m_t = 20 GeV. In general $|I|^2$ depends primarily on $m_t{}^2/m_H{}^2$ for 3 fermion generations. For the purposes of this discussion we will employ $|I|^2$ = 1 for all m_H considered, but the reader should keep in mind the uncertainty in this parameter. In particular, the existence of a fourth generation of heavy quarks or new exotic (higher color representations) quarks could easily increase $|I|^2$ by an order of magnitude. Also, for $m_H \simeq$ 1 TeV, $|I|^2$ may be significantly less than 1 if there are no new quark species and $m_t \ll m_H$.

To estimate the production cross-section in eq. (6a), we need to employ gluon distribution functions in the rapidity integration. Of course, there is considerable uncertainty in F_G and it enters twice in σ_H. So, we expect an uncertainty of at least a factor of four in such an analysis. For definiteness, we have used the gluon distribution functions of Baier et al.[7] with Λ_{QCD} = 0.1 GeV. Then, for $|I|^2$ = 1 and an integrated luminosity of Lt = 10^{40} cm^{-2}, we give in table I the number of H°'s produced as a function of $\sqrt{s}$ for m_H = 200, 300 and 400 GeV.

Table I. H° Production

$\sqrt{s}$ (GeV)	Number of H° m_H = 200 GeV	(Lt=10^{40} cm^{-2}) 300 GeV	400 GeV
800	78	8	1
1,000	190	30	5
2,000	1.5×10^3	476	183
5,000	1.1×10^4	4.9×10^3	2.7×10^3
10,000	3.8×10^4	1.9×10^4	1.2×10^4
20,000	1.2×10^5	6.5×10^4	4.4×10^4

From the point of view of production rate, high energy and high luminosity provide the best situation. (However, see discussion of backgrounds below.) At the lowest energy considered, $\sqrt{s}$ = 800 GeV, high luminosity could render the H° detectable if $m_H \simeq$ 200 GeV and σ_H is actually about an order of magnitude larger than our estimate. We recall that our estimates carry about a factor of 4 uncertainty coming from the gluon distribution functions in eq. (6) and even more uncertainty in $|I|^2$; so an order of magnitude shift in σ_H is not out of the question. In any case, given the production of H°s with $m_H \gtrsim$ 200 GeV, eq. (5) tells us that most decay into W^+W^- or

$Z^\circ Z^\circ$ pairs. Triggering on a leptonic decay of a W or Z may provide a detectable signal; so we now consider backgrounds to such signatures.

To eliminate the QCD multijet background we must require that at least one of the W's or the Z's decays leptonically. Thus we have four possibilities:

(a)
$$\begin{array}{cccc} H^\circ \to & Z^\circ & + & Z^\circ \\ & \downarrow & & \downarrow \\ & \binom{e^+e^-}{\mu^+\mu^-} & & \binom{e^+e^-}{\mu^+\mu^-} \end{array}$$

$$\frac{\Gamma a}{\Gamma_{tot}} \simeq (.19-.31) \times (2 \times .03)^2 \simeq \frac{1}{1500} \tag{9a}$$

(b)
$$\begin{array}{cccc} H^\circ \to & Z^\circ & + & Z^\circ \\ & \downarrow & & \downarrow \\ & \binom{e^+e^-}{\mu^+\mu^-} & & \text{jets} \end{array}$$

$$\frac{\Gamma b}{\Gamma_{tot}} \simeq (.19-.31)\times 2\times(2\times .03)\times .735 \simeq \frac{1}{60} \tag{9b}$$

(c)
$$\begin{array}{cccc} H^\circ \to & W^\pm & + & W^\mp \\ & \downarrow & & \downarrow \\ & \binom{e^\pm\nu}{\mu^\pm\nu} & & \text{jets} \end{array}$$

$$\frac{\Gamma c}{\Gamma_{tot}} \simeq .6\times 2\times(2\times .08)\times .752 \simeq \frac{1}{7} \tag{9c}$$

(d)
$$\begin{array}{cccc} H^\circ \to & W^+ & + & W^- \\ & \downarrow & & \downarrow \\ & \binom{e^+\nu}{\mu^+\nu} & & \binom{\mu^-\nu}{e^-\nu} \end{array}$$

$$\frac{\Gamma d}{\Gamma_{tot}} \simeq .6\ (2\times .08)^2 \simeq \frac{1}{65} \tag{9d}$$

There is, of course, a continuum background from the processes $q\bar{q}\to W^+W^-$ and $q\bar{q}\to Z^\circ Z^\circ$. These graphs have been calculated by Brown, et al.,[8] and the cross sections and rates for them are given in Table II.

Mode (9a) is, in principle, the cleanest but the branching ratio is very small. For $\sqrt{s}$ = 10 TeV and m_H = 200 GeV we have from Tables I and II a signal of $3.8\times 10^4\times(1/1500)$ = 25 events on a background of $4.3\times 10^3\times(2\times .03)^2$ = 15 events. For m_H = 300 GeV there is a signal of 13 events on a background of 8. These numbers do not include any triggering or detection inefficiency, which would reduce the signal and background by the same amount. Thus the purely leptonic $Z^\circ Z^\circ$ mode looks quite difficult unless substantially higher integrated luminosity can be achieved.

Table II. Differential cross section $d\sigma/dM$ for $pp(\bar{p}p)\to W^+W^-(Z^\circ Z^\circ+X)$ at various values of $\sqrt{s}$ and the WW mass. The numbers of events are given in parentheses assuming $LT = 10^{40}$ cm^{-2} and integrating over ±5% in mass. (All units are GeV or cm^2/GeV.)

Mass	Mode	dσ/dM	dσ/dM	dσ/dM
		pp, $\sqrt{s}$=800	$\bar{p}p$, $\sqrt{s}$=2000	pp, $\sqrt{s}=10^4$
200	W^+W^-	2.2×10^{-39} (4.5×10^2)	7.3×10^{-38} (1.5×10^4)	2.1×10^{-37} (4.3×10^4)
200	$Z^\circ Z^\circ$	2.2×10^{-40} (45)	7.3×10^{-39} (1.5×10^3)	2.1×10^{-38} (4.3×10^3)
300	W^+W^-	6.3×10^{-41} (19)	1.8×10^{-38} (5.5×10^3)	7.7×10^{-38} (2.3×10^4)
300	$Z^\circ Z^\circ$	6.3×10^{-42} (2)	1.8×10^{-39} (5.5×10^2)	7.7×10^{-39} (2.3×10^3)

The branching ratio for mode (9c) is very much larger. The momentum of the missing neutrino can be determined by an OC fit using transferse momentum balance and the constraint of the W mass. This procedure has not been examined in detail, but it should provide reasonably good resolution on the H° mass. From Tables I and II and the appropriate branching ratios, we find the following numbers of events (signal/background):

	$\sqrt{s}$=800 GeV	$\sqrt{s}$=2000 GeV	$\sqrt{s}=10^4$ GeV
m_H=200 GeV	11/240	210/3610	5400/10300
m_H=300 GeV	1/5	68/1320	2700/5530

While the signal/background ratio is always less than 1/1, the signal for $\sqrt{s}$ = 10 TeV is statistically very significant.

For mode (9b) there is no missing neutrino and the $Z^\circ Z^\circ$ continuum is only 10% of the W^+W^- one. However, we must consider the additional background from higher order QCD graphs involving one Z° and two extra jets which happen to give the Z° mass. A full calculation of these graphs has not been done and would be non-trivial. To estimate their importance we used ISAJET[9] to generate $pp(\bar{p}p)\to Z^\circ$ + jet + X events and have selected those in which the jet mass equals m_Z ± 10 GeV. This calculation treats the kinematics correctly, but it uses a leading-log approximation to the matrix element far from the region in which it is justified. The results are given in Table III. This is the dominant background for $Z^\circ Z^\circ$. Multiplying by the appropriate branching ratios we obtain the following number of events (signal/background)

	$\sqrt{s}$=800 GeV	$\sqrt{s}$=2000 GeV	$\sqrt{s}=10^4$ GeV
m_H=200 GeV	1/2	25/70	633/700
m_H=300 GeV	-	8/600	317/2000

This signal is statistically marginal even at $\sqrt{s}$ = 10 TeV, but not having to do an OC fit for a neutrino may offer some significant advantage.

Table III: Differential cross section $d\sigma/dM$ for $pp(\bar{p}p) \to Z^\circ$ + jet + X vs. the Z° + jet mass M; the jet mass in $m_Z \pm 10$ GeV. The cross section varies rapidly near threshold and may not be reliable there. The number of events are given in parentheses assuming $Lt = 10^{40}$ cm^{-2} and integrating over ±5% in M. (All units are GeV or cm^2/GeV.)

Mass	$d\sigma/dM$	$d\sigma/dM$	$d\sigma/dM$
	pp, $\sqrt{s}$=800	pp, $\sqrt{s}$=2000	pp, $\sqrt{s}=10^4$
200	1.7×10^{-40} (33)	5.8×10^{-39} (1200)	5.8×10^{-38} (1.2×10^4)
300	3.3×10^{-40} (100)	3.3×10^{-38} (1.0×10^4)	3.3×10^{-37} (1.0×10^5)

For mode (9d) there are two missing neutrinos so the H° mass cannot be reconstructed.

What if $m_H \simeq 1$ TeV, the upper limit in eq. (1)? Even in that case, high luminosity hadron-hadron colliders may be significant producers of H°s provided $\sqrt{s}$ is high and $|I|^2 \simeq 1$. (Unfortunately, for $m_H = 1$ TeV and $m_t = 20$ GeV we find $|I|^2 = 0.002$. To get $|I|^2 \simeq 1$ requires $m_t \simeq 200$ GeV or heavy new quark flavors.) For $|I|^2 \simeq 1$ and $Lt = 10^{40}$ cm^{-2}, we find the following results

$\sqrt{s}$ (GeV)	Number of H°s (m_H=1 TeV)
2,000	1
5,000	210
10,000	1.9×10^3
20,000	9.8×10^3

Clearly, high luminosity is a must for high energy colliders if one wants to find a heavy Higgs scalar.

The above considerations were for a Higgs scalar in the standard model. However, the basic idea, to trigger on decays involving intermediate vector bosons also applies to other heavy scalars or pseudoscalars present in more exotic theories. For example, technicolor models contain a variety of pseudoscalars with masses on the order of a few hundred GeV.[10] One of these, the η_T with mass $\simeq$ 240 GeV is a neutral color octet which has a gluon fusion production cross-section about 500 times larger than a H° of the same mass.[10] It can decay into Z° + gluon.[10] Unfortunately, the branching ratio into that model is uncertain. Ref. 10 estimated it to be about 0.002 which implies about 40 $\eta_T \to Z^\circ$ + gluon decays for $Lt = 10^{40}$ cm^{-2} at $\sqrt{s}$ = 800 GeV. Requiring $Z^\circ \to e^+e^-$ or $\mu^+\mu^-$ leaves about 2 or 3 clean events. Of course, the Z° + gluon branching ratio may be significantly larger in which case the signal will be much more easily detected.

In conclusion, we have found that high luminosity hadron-hadron colliders may have significant heavy Higgs production rates via the gluon fusion mechanism. For $m_H \gtrsim 180$ GeV, the W^+W^- and $Z^\circ Z^\circ$ decays of the H° dominate. In that case triggering on an intermediate vector boson leptonic decay may allow detection of the H° above competing background. At high $\sqrt{s}$ the signal is statistically significant even for the values of $|I|^2$ and the gluon distribution function chosen. At lower energies, the cross-section must be at least an order of magnitude larger (which may be the case) if we are to detect the H°. The basic idea of looking for heavy new particles via their decays into intermediate vector boson pairs appears to be an interesting possibility at high luminosity hadron-hadron colliders.

References

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