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HUNTING FOR THE INTERMEDIATE MASS HIGGS BOSON IN A HADRON COLLIDER*

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ABSTRACT

We examine the feasibility of identifying in a hadron machine the standard, neutral Higgs boson, produced in association with a W, when the mass of the Higgs is between approximately 100 GeV and 2 m_W. The production cross section is calculated with quasi–realistic cuts imposed assuming that the Higgs decays into $t\bar{t}$. Possible backgrounds arising from the continuum production of $t\bar{t}$, $t\bar{b}$, or $\bar{t}b$ accompanied by a W are computed as well.

The search for the standard model Higgs boson is one of the most important efforts of present and future accelerators. A Higgs boson with mass $m_H \lesssim 100$ GeV/c^2 will be identifiable at SLC, LEP I, or LEP II through production in association with a virtual or on-shell Z^0 or in the radiative decays of toponium.[1] (The 100 GeV/c^2 mass limit is determined solely by the center of mass energy that will be available at these machines.) Heavier Higgs bosons will be produced at detectable rates first at planned hadron facilities such as the Superconducting Super Collider (SSC).[1] Unfortunately, direct production in hadron collisions of the Higgs (via gluon[2] or W pair[3] fusion) followed by its decay is identifiable only when $m_H > 2m_W$; in this case its primary decay modes are into W^+W^- and Z^0Z^0 intermediate vector boson pairs. Continuum W^+W^- and Z^0Z^0 pair production is sufficiently small that a modest pair resolution will suppress this background adequately.[4] Below $m_H = 2m_W$ but above $m_H = 2m_t$ the Higgs boson decays almost exclusively into $t\bar{t}$ pairs. In this intermediate mass range the QCD continuum production cross section is so large that any feasible $t\bar{t}$ pair mass resolution is not sufficient to make possible the identification of the Higgs. For $m_t = 40$ GeV/c^2, one finds

$$\sigma(pp \to [\ H^0 \to t\bar{t}\ ]X) \sim 10^{-3}\ \frac{d\sigma}{dM^2}\ (pp \to t\bar{t}X)\ \Delta M^2$$

when $\Delta M^2 \sim 0.1\ m_H^2$. M is the $t\bar{t}$ pair mass. Thus, it is of considerable importance to find a production mode for a Higgs boson with mass in the range 100 GeV/c^2 $\lesssim m_H \lesssim 2m_W$ for which continuum backgrounds are manageable and event rates are adequate.

In this letter we show that hadronic production of an intermediate mass Higgs in association with a trigger W^+ or W^-, followed by Higgs decay to a $t\bar{t}$ pair[5]

$$pp \rightarrow H^0\, W^\pm\, X, \quad H^0 \hookrightarrow t\bar{t} \tag{1}$$

provides a potentially viable detection mode for this otherwise problematic mass range. We demonstrate that the background reactions

$$pp \rightarrow W^\pm\, g\, X, \quad g \hookrightarrow t\bar{t} \tag{2}$$

and

$$pp \rightarrow (W^+\, \bar{t}b) \text{ or } (W^-\, t\bar{b})\, X \tag{3}$$

where the $b(\bar{b})$ in the latter reaction is misidentified as a $t(\bar{t})$, are sufficiently small that 10% to 20% resolution in $M^2_{t\bar{t}}$ and $1/100$ b/t jet discrimination will provide a clear Higgs signal. The basic cross section for reaction (1), including appropriate cuts, is of order 1 pb, equivalent to 10^4 events for a standard $L = 10^{40}/cm^2$ year. Triggering on the W via its leptonic decay modes into e, μ, or τ yields over one thousand events, assuming leptonic detection efficiencies over 50%. If any of the t's or b's decays semi–leptonically, there will be two undetected energetic ν's in the final state, the first arising from the decay of the $W^\pm$. We can have at most one undetected energetic ν and still fix accurately the invariant mass of the two–jet system using transverse momentum conservation. Thus, it is necessary to identify the t's and b's only through their purely hadronic decays. With the numbers given above we find that efficiencies of 40% for the identification of top jets in which the t, and subsequently the b, decay non–leptonically leaves a signal of about 50 events.

The matrix elements for the process $pp \to H^0\ W^{\pm}\ X$ have appeared in the literature.[4] Addition of the $t\bar{t}$ decay matrix element as required to describe process (1) (Fig. 1(a)), is straightforward. For $\Delta M^2_{t\bar{t}} \gg 2m_H\Gamma_H$ the on–shell H^0 pole approximation is adequate and interference between the signal and continuum backgrounds can be neglected. The matrix element for process (2) (Fig. 1(b)) was calculated both by hand and with the symbolic manipulation program REDUCE. That of process (3), Fig. 1(c), was arrived at using two independent REDUCE programs. The length of the matrix element expressions for process (2) and especially for process (3) require that we relegate them to a later paper. It should be noted that for process (3) we only computed the gluon gluon initiated contributions. These overwhelmingly dominate the $q\bar{q}$ initiated contributions at SSC energies, because the gg luminosity function is so much larger than that for $q\bar{q}$.[4]

Our cross sections were obtained by phase space integration of the matrix elements in two independent ways: 1) by direct integration using the adaptive numerical integration routine SHEP; and 2) by a standard Monte Carlo algorithm. To achieve rapid convergence, we found it convenient to express the 3–particle final state phase space in terms of the overall center of mass variables y_W (the W rapidity) and y_H (the $t\bar{t}$, $t\bar{b}$, or $\bar{t}b$ pair rapidity), the two decay angles of the $t\bar{t}$, $t\bar{b}$, or $\bar{t}b$ pair in the "Higgs" rest frame, and either the inverse square of the W transverse momentum (in the SHEP routine) or $\tau^{-1} = s/\hat{s}$ (in the Monte Carlo routine); here $\hat{s} = x_1 x_2 s$ is the subprocess energy. The Monte Carlo routine was further checked by comparing the full phase space integration result with the total $W\ H^0$ cross section given in Ref. 4. We employed the EHLQ distribution functions (NSET = 2) throughout;[4] $m_t = 40$ GeV/c^2.

We present a selection of results in Figs. 2 through 4. In Fig. 2 we show the cross sections for the processes (1), (2), and (3) in the W^+ case as a function of the $t\bar{t}$ (or $b\bar{t}$) mass, m_H. For all processes we have integrated over the rapidity range $-2 < y_W < 2$ and $-2 < y_H < 2$, and over $p_T^W > 40$ GeV/c. For the background reactions we present

$$\frac{d\sigma}{dM^2}\ \Delta M^2$$

at $M^2 = m_H^2$ with $\Delta M^2 = 0.1\ m_H^2$ (to repeat, M is the $t\bar{t}$ or $b\bar{t}$ jet pair mass) where $d\sigma/dM^2$ is the background cross section integrated over the above y_W, y_H, and p_T^W configuration. In Table I we list these cross sections for values of $\sqrt{s}$ from 10 to 100 TeV for $m_H = 130$ GeV/c^2. Lower machine energies, such as that projected for the Large Hadron Collider, make the event rate marginal, but do not significantly alter the signal to background ratio. We show, in Figs. 3 and 4, two distributions of experimental importance: a) the differential distribution for the top quark energy, $E_{\rm top}$; and b) the differential cross section in p_T^W. In all the above the cross sections are for the W^+ case; those in the W^- case are essentially identical. For both figures we fix $M = m_H = 130$ GeV/c^2 and $\sqrt{s} = 40$ TeV. The latter distribution illustrates that imposing a higher p_T^W cut enhances the signal to background ratio but decreases the event rate. The optimum p_T^W cut will depend on specifics of the detector and machine environment.

The results for the cross section including cuts are encouraging. The background process (2) of $W + t\bar{t}$ continuum pair produced through an intermediate gluon can definitely be made smaller than the Higgs signal given moderately good resolution in M. If it proves to be desirable to trigger on the associated W through its leptonic decay it would be necessary to identify the top jets through their purely hadronic decays without the loss of any energetic neutrinos in the flavor decay chain. Otherwise the W and $t\bar{t}$ masses could not be reconstructed. Furthermore, top–bottom jet discrimination must be made at the level of 1%, with at least moderate top detection efficiency; in this way the $W^+b\bar{t}$ (or $W^-t\bar{b}$) misidentification background would be adequately suppressed without too great a loss of event rate. While preliminary studies at Snowmass[6] 1984 indicate that achieving the required mass resolution and discrimination power will be difficult, further, more detailed studies are warranted.

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Table I

Cross sections in pb as a function of $\sqrt{s}$ for $m_H = 130$ GeV and $m_t = 40$ GeV/c^2, including the cuts specified in the text. The cross sections for associated production of a W^- are roughly equal to those for W^+.

$\sqrt{s}$	$\sigma\left(pp \to H^\circ + W^+\right)$ $\;\hookrightarrow t\bar{t}$	$\sigma\left(pp \to g + W^+\right)$ $\;\hookrightarrow t\bar{t}$	$\sigma\left(pp \to \bar{t}b + W^+\right)$
10 TeV	.22 ± .02 pb	.085 ± .02 pb	3.5 ± .5 pb
20	.38	.14	11.
40	.60	.22	31.5
60	.76	.29	48.0
100	1.1	.40	100

Figure Captions

Figure 1 Examples of Feynman diagrams calculated for a) process (1); b) process (2); and c) process (3).

Figure 2 The total cross sections for the W^+ case of processes (1), (2), and (3) divided by 100 at $\sqrt{s} = 40$ TeV as a function of Higgs (*i.e.*, $t\bar{t}$ or $t\bar{b}$) mass, represented by the solid, dashed, and dotted curves respectively. $\Delta M^2 = .1\ m_H^2$.

Figure 3 The differential distribution in $E_{\rm top}$ for the W^+ case of processes (1), (2), and (3) divided by 100 at $\sqrt{s} = 40$ TeV with $m_H = 130$ GeV/c^2, represented by the solid, dashed, and dotted curves respectively. $\Delta M^2 = .1\ m_H^2$.

Figure 4 The differential distribution in p_T^W for the W^+ case of processes (1), (2), and (3) divided by 100 at $\sqrt{s} = 40$ TeV with $m_H = 130$ GeV/c^2, represented by the solid, dashed, and dotted curves respectively. $\Delta M^2 = .1\ m_H^2$.

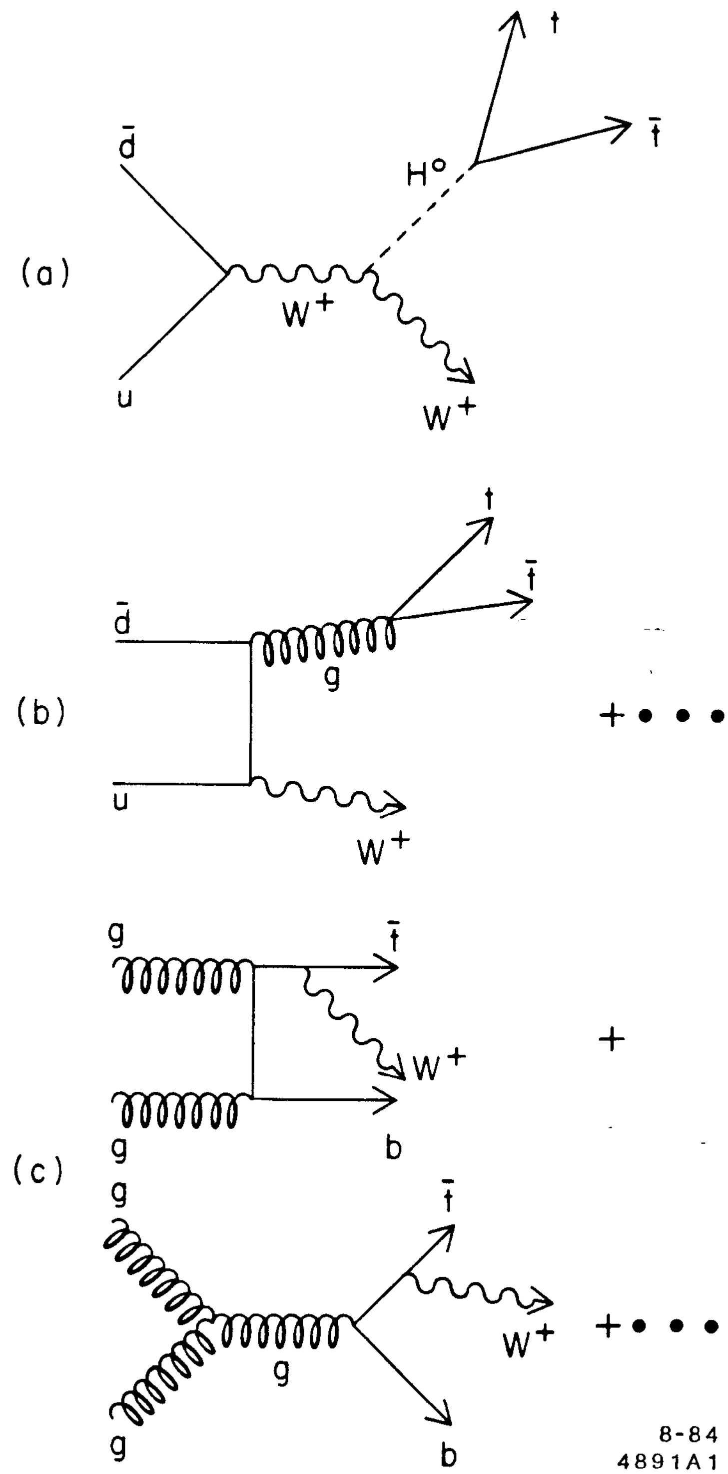


Fig. 1

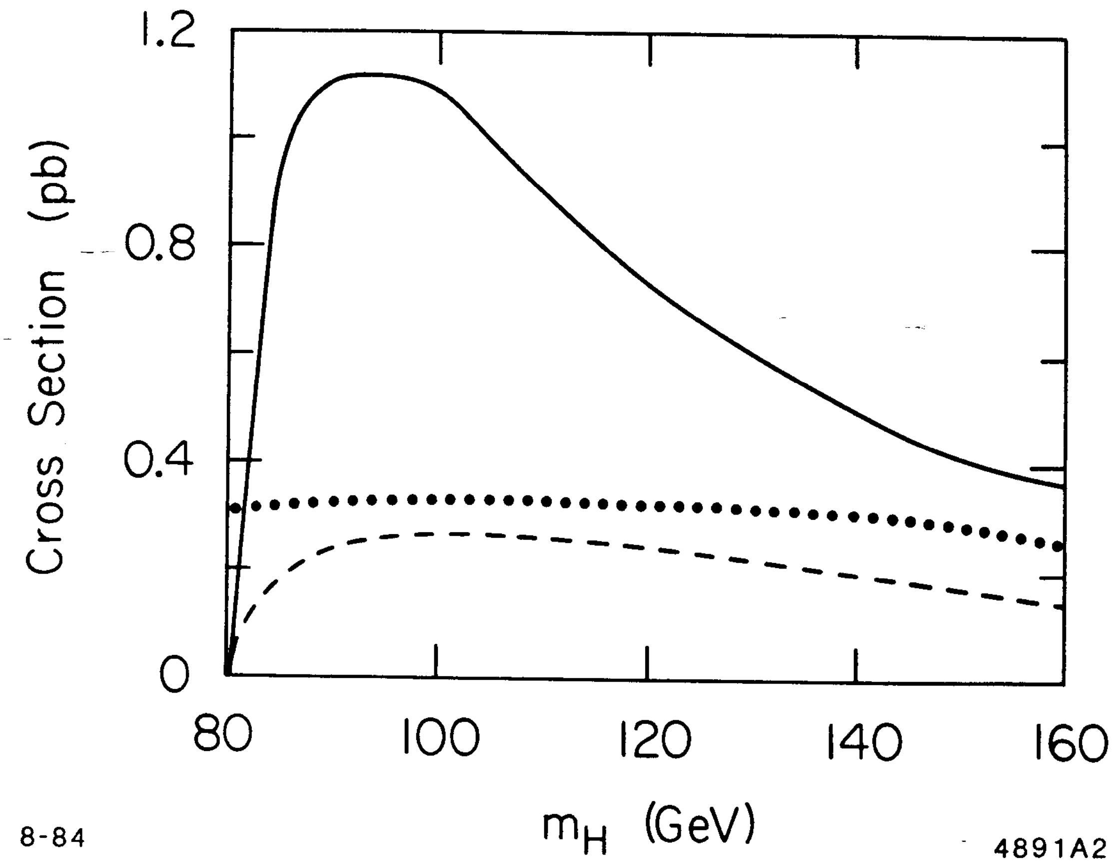
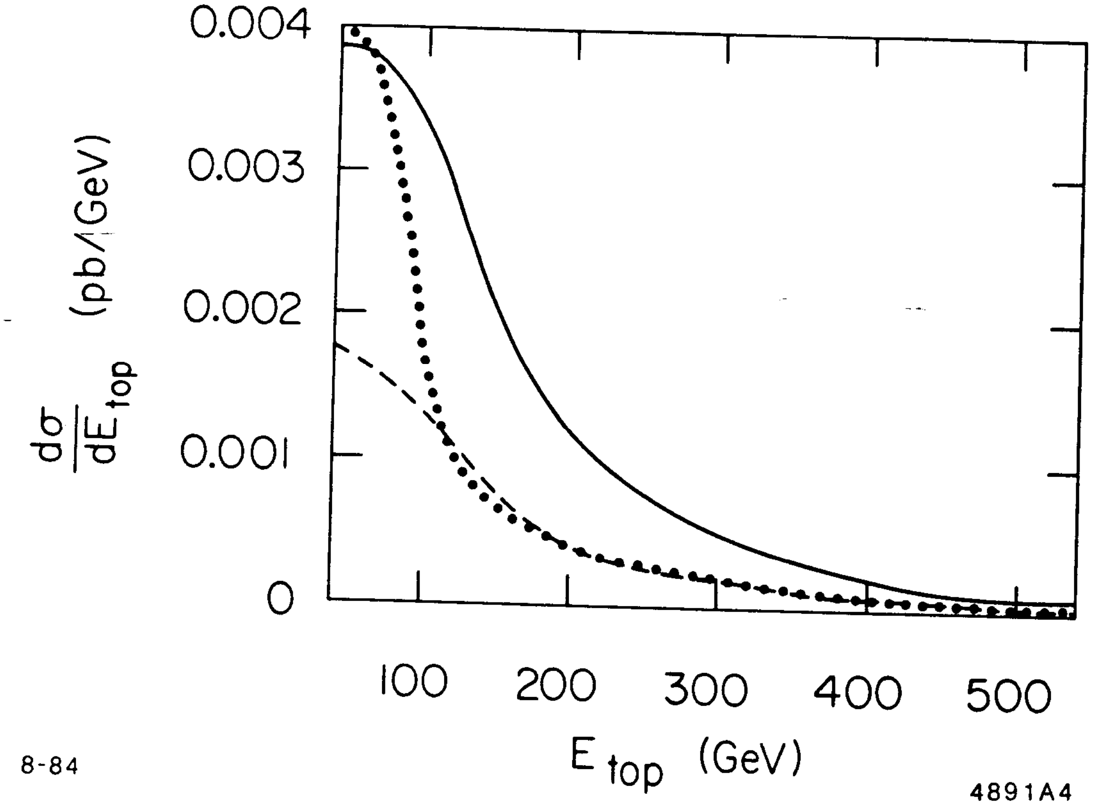
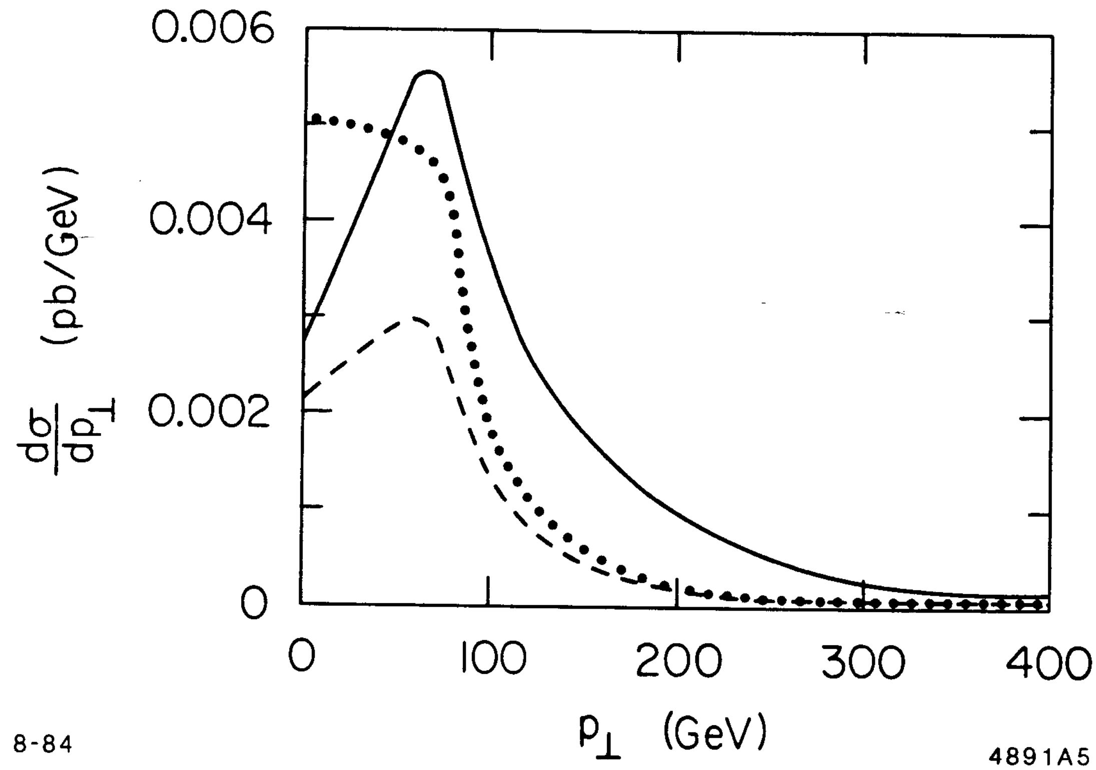


Fig. 2



0.004
0.003
0.002
0.001
0
100
200
300
400
500
dσ/dE top (pb/GeV)
E top (GeV)
8-84
4891A4

Fig. 3



0.006
0.004
0.002
0
$\frac{d\sigma}{dp_\perp}$ (pb/GeV)
0
100
200
300
400
$p_\perp$ (GeV)
8-84
4891A5

Fig. 4