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* Invited Talk presented at *Workshop on Physics at Current Accelerators and the Supercollider*, Argonne National Laboratory, 6/2–5/93

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ABSTRACT

We study the production and detection of the standard-model Higgs boson at the Fermilab Tevatron. The most promising mode is WH and ZH associated production followed by leptonic decay of the weak vector bosons and $H \to b\bar{b}$. It may be possible to detect a Higgs boson of mass m_H = 60–80 GeV with 1000 pb^{-1} of integrated luminosity.

The evidence is overwhelming that the electroweak interaction is described by an $SU(2)_L \times U(1)_Y$ gauge theory, spontaneously broken to $U(1)_{EM}$. However, the precise mechanism which breaks the electroweak symmetry is unknown. The simplest mechanism is the standard Higgs model, in which the symmetry is broken by the vacuum-expectation value of a fundamental scalar field. This model predicts the existence of a scalar particle, the Higgs boson, with fixed couplings to other particles, but of unknown mass. The search for this particle constitutes the baseline in our search for phenomena associated with the electroweak-symmetry-breaking mechanism.

The current lower bound on the mass of the Higgs boson is about 60 GeV, from the process $Z \to Z^*H$ at LEP [1] (Z^* denotes a virtual Z boson). This bound is limited by statistics and backgrounds, and is unlikely to improve significantly. The next extension in reach will be provided by LEP II, beginning in 1995, which will explore up to a Higgs-boson mass of about 80 GeV via $Z^* \to ZH$ [2]. Much higher masses will be explored by the CERN Large Hadron Collider (LHC) and the U.S. Superconducting Super Collider (SSC), which can reach as high as m_H = 800 GeV via the processes $gg \to H$ and $V^*V^* \to H$ ($V = W, Z$) [3].

Conspicuously absent from this discussion is the Fermilab Tevatron $p\bar{p}$ collider. It is generally assumed that the Tevatron cannot probe the electroweak-symmetry-breaking mechanism. However, there are two reasons why this is an appropriate time to study the possibility of searching for the Higgs boson at the Tevatron. First, the Tevatron is operating with high luminosity, and it now seems possible that 100 pb^{-1} of integrated luminosity will be delivered to each of the two detectors by the end of 1994. Furthermore, with the Main Injector, a five-fold increase in luminosity will be obtained, yielding 1000

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pb^{-1} of integrated luminosity per detector by the end of the century, and perhaps more. Second, it has been demonstrated that vertex detection is feasible in a hadron-collider environment. This allows the detection of secondary vertices from the decay of b quarks, which is vital for searching for the decay $H \to b\bar{b}$.

In this report we study the production of the Higgs boson in association with a W or Z boson at the Tevatron [4]. The leptonic decay of the W or Z boson provides a trigger for the event and suppresses the backgrounds. In the mass range of interest, the standard Higgs boson decays predominantly to $b\bar{b}$, and vertex detection must be used to separate b jets from light-quark jets. This process has been extensively studied for the LHC [5] and SSC [6, 7, 8, 9, 10], but no similar study has been undertaken for the Tevatron. While the analysis is similar to that of the LHC/SSC in many respects, it differs in several important ways. This report summarizes the work on the standard Higgs boson in Ref. [11].

Associated production with a W or Z boson is relatively more important at the Tevatron than at the LHC/SSC. The leptonic decay of the W or Z boson (including $Z \to \nu\bar{\nu}$) provides a trigger for the event, and suppresses backgrounds. The WH process has already been used at the Tevatron to eliminate a very light Higgs boson [12]. As we will show, at least 1000 pb^{-1} will be required to search for a more massive Higgs boson at the Tevatron. Thus we make cuts to simulate the acceptance of an upgraded CDF/D0 detector that one can envision existing by the time the Main Injector is operating.

Consider the decay of the Higgs boson to a $b\bar{b}$ pair. To suppress the Wjj and Zjj background, we must require that at least one of the jets be identified as coming from a b quark. We require $|\eta_b| < 2$ for the b and $\bar{b}$ rapidity to simulate the coverage of the vertex detector, and we further require the rapidity, transverse momentum (p_T), and isolation cuts listed in Table 1. The resulting cross sections are shown in Fig. 1, including all branching ratios ($\ell = e, \mu$) and the +25% QCD correction (in the $\overline{MS}$ scheme with $\mu = M_{VH}$) [13]. The WH process contributes to the ZH cross section when the charged lepton from the W decay is missed; the ZH process contributes only a small amount to the WH cross section, when one of the charged leptons from $Z \to \ell\bar{\ell}$ is missed.

Table 1: Acceptance cuts used to simulate an upgraded CDF/D0 detector.

$\|\eta_b\| < 2$	$p_{Tb} > 15$ GeV
$\|\eta_\ell\| < 2.5$	$p_{T\ell} > 20$ GeV
$\not{p}_T > 20$ GeV	(for $W \to \ell\bar{\nu}, Z \to \nu\bar{\nu}$)
$\|\eta_j\| < 2.5$	$p_{Tj} > 15$ GeV
$\|\Delta R_{b\bar{b}}\| > 0.7$	$\|\Delta R_{b\ell}\| > 0.7$

The principal backgrounds are $Wb\bar{b}$ [14, 6, 10, 15, 16] and $Zb\bar{b}$ [15, 17], WZ [18] and ZZ [19] followed by $Z \to b\bar{b}$, and $t\bar{t}$ production. The $Wb\bar{b}$ and $Zb\bar{b}$ backgrounds are shown in Fig. 1, assuming a $b\bar{b}$ invariant-mass resolution equal to a typical two-jet invariant-mass resolution. We assume $\Delta E_j/E_j = .80/\sqrt{E_j} \oplus .05$ for the jet energy resolution, which corresponds to approximately $\Delta M_{jj}/M_{jj} = .80/\sqrt{M_{jj}} \oplus .03$ for the two-jet invariant-mass resolution. We integrate the background over an invariant-mass bin of size $\pm 2\Delta M_{jj}$ centered at m_H, which contains nearly all the signal events. The invariant-mass resolution may be degraded somewhat since about forty percent of all events have at least one neutrino from semileptonic b decay. The signal-to-background ratio is of order unity, and is better for ZH

than WH because the HZZ coupling is bigger than the HWW coupling by M_Z^2/M_W^2. Recall that at the LHC/SSC the ZH signal is swamped by $gg \to Zb\bar{b}$ [6]. This is not the case at the Tevatron; $q\bar{q} \to Zb\bar{b}$ is slightly larger than $gg \to Zb\bar{b}$, due to the decreased gluon luminosity.

The background processes WZ and ZZ, with $Z \to b\bar{b}$, populate the region between about 80 and 100 GeV. The cross sections, including the QCD corrections (+33% for WZ [18], +25% for ZZ [19] in the $\overline{MS}$ scheme with $\mu = M_{VV}$), are shown in Fig. 1; they are comparable to the signal, and increase the background in this region. These backgrounds could be calibrated using the purely leptonic decays of the gauge-boson pairs.

The top quark is also a potential background. The process $t\bar{t} \to W^+W^-b\bar{b}$ mimics the WH signal if one W goes undetected. We assume a coverage for jets of $|\eta_j| < 2.5$ and $p_{Tj} > 15$ GeV, and reject events with additional jets.† With this coverage, the dominant $t\bar{t}$ background occurs when the charged lepton from a W decay goes outside the coverage of the detector. We make the additional requirement that the transverse mass of the observed charged lepton plus the missing p_T be less than M_W, which is always true for the signal. This cut reduces the background by about a factor of two. This background is shown in Fig. 1(a) for $m_t = 150$ GeV; it is far less troublesome than the direct $Wb\bar{b}$ background. The top quark is also a background to the ZH signal, with $Z \to \nu\bar{\nu}$, if both W's are missed. This background is shown in Fig. 1(b); it is negligible. In both cases, the top-quark background decreases for a heavier top quark. The top-quark background is a much worse problem at the LHC/SSC.‡

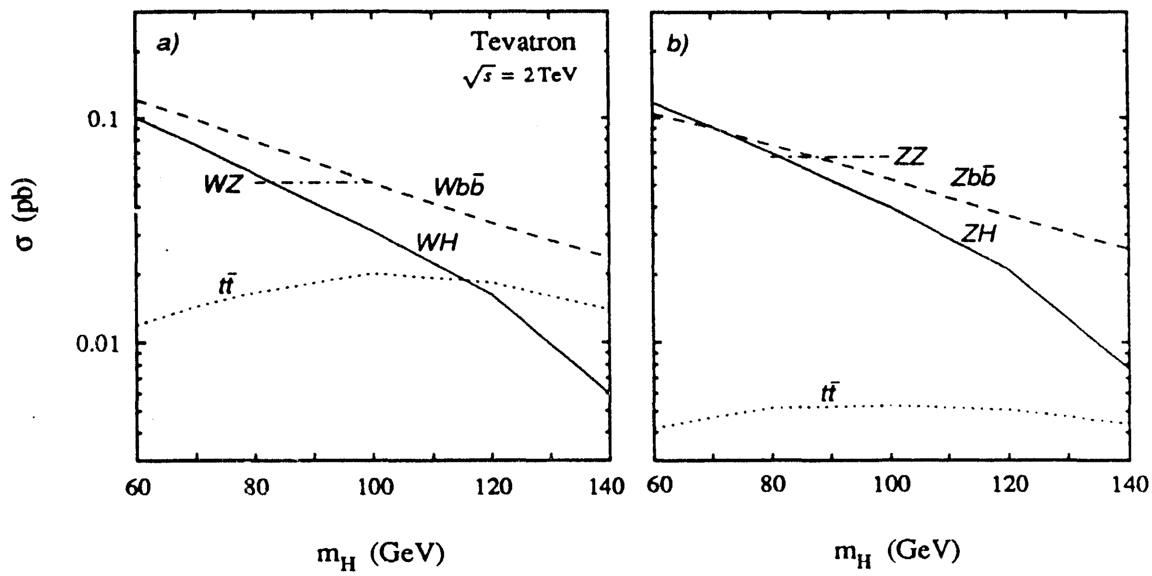

Fig. 1 - Cross section and backgrounds for a.) WH and b.) ZH production, followed by $H \to b\bar{b}$ and $W \to \ell\bar{\nu}$, $Z \to \ell\bar{\ell}, \nu\bar{\nu}$, versus the Higgs-boson mass. The cuts which have been made to simulate the acceptance of the detector are listed in Table 1. The backgrounds are from $Wb\bar{b}$ and $Zb\bar{b}$, WZ and ZZ followed by $Z \to b\bar{b}$, and $t\bar{t} \to W^+W^-b\bar{b}$ with one W missed (for WH) or with both W's missed (for ZH, $Z \to \nu\bar{\nu}$).

† Rejecting events with additional jets decreases the signal somewhat. This reduction can be minimized by increasing the minimum p_T of the additional jets, without greatly increasing the background.

‡ The top-quark background at the SSC was considered by R. Kauffman in Ref. [9].

Another serious background is $Wc\bar{c}$ and $Zc\bar{c}$. Since the charm-quark lifetime is comparable to that of the bottom quark, these events can also produce a displaced vertex, and could as much as double the background. Final states with a single charm quark, such as $W^-c\bar{s}$, can also contribute to the background if only one jet is required to have a displaced vertex. In Ref. [7, 8] the charm-quark background was suppressed by demanding that the b quark decay semileptonically, with lepton momentum transverse to the b jet of at least 1 GeV. Due to the modest number of signal events, one may not be able to afford such a cut at the Tevatron. Perhaps another method can be found.

One must also consider the Wjj and Zjj backgrounds, where the jets come from light quarks [20, 21, 22, 23, 24, 25, 26]. Applying the same acceptance cuts and invariant-mass resolution as before, we find that these cross sections are about one hundred times as large as the $Wb\bar{b}$ and $Zb\bar{b}$ backgrounds.[§] Excellent light-quark-jet/b-jet discrimination will be required to eliminate this background. The Wjj and Zjj backgrounds are much more severe at the LHC/SSC because of the large gluon luminosity. They were eliminated in Ref. [7, 8] by demanding a semileptonic decay of a b quark, with lepton momentum transverse to the b jet of at least 1 GeV, as mentioned above.

The efficiency for detecting a displaced vertex from a b-quark jet is hoped to reach about 30 percent, or 50 percent to detect at least one displaced vertex per $b\bar{b}$ pair. We present in Table 2 the number of signal and background events with at least one displaced vertex for various values of the Higgs-boson mass for 1000 pb^{-1} of integrated luminosity. We assume a one percent misidentification of a light-quark (or gluon) jet as a b jet. The Wjj and Zjj backgrounds, as well as the single-charm background (which we have not included), could be eliminated completely by requiring a double b tag; however, the double-tag efficiency is only 10 percent. The significance of the signal is about the same as with a single tag. Additionally, one can tag b jets using semileptonic decays; however, this has an efficiency of only about 10 percent, with a one percent misidentification of light-quark jets. The number of signal events with at least one displaced vertex for m_H = 60–80 GeV may be enough to detect the Higgs boson at the Tevatron, especially if the light-quark jet misidentification can be reduced below one percent. One should keep in mind that LEP II will have already explored these masses by the time 1000 pb^{-1} is delivered. However, the confirmation of the Higgs boson at the Tevatron would be of interest since both the ZH (similar to LEP II) and WH processes could be detected. A Higgs boson of mass near the Z-boson mass will be difficult to separate from the WZ and ZZ backgrounds. A Higgs

[§]The Wjj and Zjj backgrounds were calculated using the code developed in Ref. [24].

Table 2: Number of signal and background events, per 1000 pb^{-1}, for production of the Higgs boson in association with a weak vector boson, followed by $H \to b\bar{b}$ and $W \to \ell\bar{\nu}$, $Z \to \ell\bar{\ell}, \nu\bar{\nu}$.

m_H (GeV)	WH/ZH	$Wb\bar{b}/Zb\bar{b}$	Wjj/Zjj
60	50/58	60/52	200/200
80	28/35	39/38	140/170
100	15/20	25/26	100/130
120	8/10	17/18	76/97
140	3/3.8	11/13	52/68

boson of mass in excess of the Z-boson mass would require increased integrated luminosity for discovery.

The search for the Higgs boson at the Tevatron is challenging, but is matched by the importance of the search. A Higgs boson in the range 80–140 GeV (the so-called intermediate-mass range) is also difficult for the LHC/SSC to discover. Studies at the LHC/SSC usually focus on the rare two-photon decay of the Higgs boson [27, 28]. It might be worthwhile to reconsider the $b\bar{b}$ decay mode at these machines [29, 30].

In Ref. [11] we have also studied the possibility of detecting a non-standard Higgs boson with suppressed couplings to fermions, dubbed the bosonic Higgs, via its enhanced two-photon decay mode. With just 100 pb^{-1} of integrated luminosity, it will be possible to detect such a particle, produced in association with a W or Z, with the weak vector bosons decaying leptonically or hadronically, up to $m_H = 100$ GeV. There may also be an observable signal from the weak-vector-boson-fusion process. The discovery of such a particle would have an enormous impact on our understanding of the electroweak-symmetry-breaking mechanism.

Acknowledgements

We are grateful for conversations with B. Blair, E. Boos, S. Dawson, E. Eichten, K. Ellis, S. Errede, G. Forden, S. Geer, H. Gordon, J. Gunion, T. Han, R. Kauffman, S. Kuhlmann, T. LeCompte, R. Lipton, T. Liss, F. Paige, S. Parke, S. Protopopescu, C. Quigg, A. White, and J. Yoh. This work was supported under contract no. DE-AC02-76CH00016 with the U.S. Department of Energy. S.W. thanks the Aspen Center for Physics where part of this work was performed. S.W. was partially supported by the Texas National Research Laboratory Commission.

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