Higgs-boson decay to one real and one virtual W boson

E. W. N. Glover

CERN, Geneva, Switzerland

J. Ohnemus and Scott S. D. Willenbrock

Physics Department, University of Wisconsin, Madison, Wisconsin 53706

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We study the decay $H \rightarrow WW^*$ at future hadron colliders. If the top quark is heavy, $m_t > m_H/2$, the decay $H \rightarrow WW^* \rightarrow (l\bar{\nu})(\bar{l}\nu)$ yields an observable signal at the Superconducting Super Collider for $140 \text{ GeV} \lesssim m_H < 2M_Z$. The cluster transverse mass of the final-state leptons allows a rough estimate of the Higgs-boson mass.

An intermediate-mass ($M_Z \lesssim m_H < 2M_W$) Higgs boson decays most frequently to the heaviest available fermion-antifermion pair. It was long thought that this was likely to be the top quark, based on early data from the CERN $Spp\bar{S}$ collider, which suggested $30 < m_t < 50 \text{ GeV}$ (Ref. 1). This led to a great deal of pessimism regarding the capability of future hadron colliders, such as the Superconducting Super Collider (SSC) or the CERN Large Hadron Collider (LHC), to search for such a Higgs boson, due to the overwhelming background from QCD-produced top-quark pairs.²

The possibility now exists that the top quark is heavier than was originally thought,³ and that the top-quark decay mode of the Higgs boson is kinematically forbidden. If this is the case, the dominant decay mode of the intermediate-mass Higgs boson is to bottom quarks. Unfortunately, this is *also* overwhelmed by the QCD production of bottom-quark pairs.⁴

Unlike the top-quark decay mode, the partial width of the Higgs-boson decay to bottom quarks is rather small, due to the suppressed coupling ($gm_b/2M_W$). This opens up the possibility that other decay modes of the Higgs boson may have significant branching ratios. Since the number of intermediate-mass Higgs bosons produced per year at the SSC is about 10^6 , even rare decay modes will yield a large number of events. Decays to $\tau^+\tau^-$ (Refs. 5–8), $\gamma\gamma$ (Refs. 5–10), $Z\gamma$ (Refs. 7, 8, and 11), ZZ^* (Refs. 7, 8, 12, and 13), and WW^* (Refs. 7, 12, and 13) (the asterisks indicate a virtual particle) have been considered in the literature.

In this paper we examine in detail the decay of the intermediate-mass Higgs boson to one real and one virtual W boson, $H \rightarrow WW^*$. This was first suggested as a signal for the intermediate-mass Higgs boson in Ref. 12. It was further explored in Ref. 7, which concentrated on the scenario in which the W boson decays hadronically and the W^* leptonically. Subsequent work showed, as was conjectured in that paper, that the background from $W^* + 2$ jets, where the jets fake a real W boson, is overwhelming.^{14,15} We therefore concentrate on the leptonic decay of both the W and W^* :

$$pp \rightarrow H \rightarrow WW^* \rightarrow (l\bar{\nu})(\bar{l}\nu).$$

The final state is $l\bar{l}$ (where l denotes an electron or muon) plus missing energy (due to the loss of two neutrinos). Note that the charged leptons need not be the same type.

Since the signal is purely leptonic, the irreducible backgrounds are of electroweak strength and are thus less severe than QCD backgrounds. However, the information carried away by the two neutrinos makes a reconstruction of the Higgs-boson mass from the invariant mass of the decay products impossible. Nevertheless, we will show that the signal is observable above the background at the SSC for $m_H \gtrsim 140 \text{ GeV}$, and that it is possible to obtain a rough estimate of the Higgs-boson mass from the cluster-transverse-mass distribution.

The differential decay rate for the three-body decay $H \rightarrow WW^* \rightarrow W(l\bar{\nu})$ is given in Ref. 12. Since we will make cuts on the final-state leptons, we need the full four-body decay rate $H \rightarrow WW^* \rightarrow (l\bar{\nu})(\bar{l}\nu)$, as depicted in Fig. 1. A simple calculation yields ($x_W = \sin^2\theta_W$)

$$d\Gamma = 2 \left[\frac{4\pi\alpha}{x_W} \right]^3 \frac{M_W^2}{m_H} p_1 \cdot p_4 p_2 \cdot p_3 |D(W^+)|^2 |D(W^-)|^2 \\ \times \prod_{i=1}^4 \frac{d^3p_i}{(2\pi)^3 2E_i} (2\pi)^4 \delta^4 \left(p_H - \sum_{i=1}^4 p_i \right),$$

FIG. 1. The Feynman graph for the decay $H \rightarrow WW^* \rightarrow (l\bar{\nu})(\bar{l}\nu)$, with the lepton momenta labeled.

where $D(W^\pm)$ denotes the denominator of the W -boson propagators, and the momenta are defined in Fig. 1. This equation is valid for both on- and off-shell W bosons. It is amusing to note that the squared amplitude for this four-body decay is simpler than the corresponding expression for the three-body decay. This is due to the simplifications introduced by the presence of massless spinors in the final state.

The branching ratio for the $H \rightarrow WW^*$ decay (summed over all possible W -boson final states) may be found in Ref. 12. It is nearly unity for Higgs-boson masses above the real W -boson pair threshold (in which case both W bosons are real) and below the real Z -boson pair threshold, i.e., $2M_W < m_H < 2M_Z$. As the Higgs-boson mass descends below $2M_W$, the $H \rightarrow WW^*$ branching ratio falls off rapidly since one of the W bosons is forced increasingly far off mass shell. However, even for $m_H = 120$ GeV, the $H \rightarrow WW^*$ branching ratio is still as large as 5%.

As noted earlier, the difficulty with detecting an intermediate-mass Higgs boson at future hadron colliders is not the rate of production, but the large backgrounds. We must therefore consider processes which mimic the Higgs-boson final state, $\bar{l}l$ plus missing energy. Standard-model backgrounds are

- (a) $pp \rightarrow Z^*, \gamma^* \rightarrow \bar{l}l$,
- (b) $pp \rightarrow Z^*, \gamma^* \rightarrow \tau\bar{\tau} \rightarrow (l\bar{\nu}_\tau)(\bar{l}\nu_\tau)$,
- (c) $pp \rightarrow ZZ \rightarrow (\bar{l}l)(\nu\bar{\nu})$,
- (d) $pp \rightarrow WW \rightarrow (l\bar{\nu})(\bar{l}\nu)$.

We now discuss each of these backgrounds in turn.

Ordinary Drell-Yan production of lepton pairs (electrons or muons) (a) is not accompanied by missing energy, so we may eliminate this background by simply imposing a cut on the minimum missing transverse momentum $\not{p}_T$. We therefore demand $\not{p}_T > 20$ GeV. Furthermore, note that the Drell-Yan produced leptons are always of the same type, whereas the signal may have same- or different-type leptons.

τ -lepton pairs (b) where each τ lepton decays leptonically, provide a real background to the Higgs-boson signal, where the missing energy is provided by four neutrinos. Fortunately, this background may be eliminated by a judicious choice of cuts, as was shown in Ref. 16. The τ leptons are produced most copiously at the Z -boson pole ($Z \rightarrow \tau\bar{\tau}$) and near the photon pole (i.e., at low invariant mass). We will now discuss the cuts which eliminate these two sources of τ leptons.

The τ leptons from Z -boson decay are very relativistic, and thus their decay products continue in the direction of the parent τ lepton. The final-state leptons are therefore nearly back to back in the transverse plane. We may eliminate this source of τ leptons by imposing a cut on the angle in the transverse plane between the final-state leptons $\Delta\phi(\bar{l}l)$. We choose $\Delta\phi(\bar{l}l) < 160^\circ$, following Ref. 16.

The τ -lepton pairs with low invariant mass yield final-state leptons with little energy. We may therefore eliminate these τ leptons by imposing a cut on the minimum transverse momentum of the final-state leptons, p_T . We

choose $p_T(l), p_T(\bar{l}) > 20$ GeV, again following Ref. 16.

The above arguments assume implicitly that the τ -lepton pairs are produced with little transverse momentum. We may enforce this requirement by demanding that there is no large transverse-momentum jet in the process. It was shown in Ref. 16 that it is sufficient to reject events which contain jets with $p_T > 20$ GeV.

The background from Z -boson pair production (c) can be eliminated by rejecting events in which the invariant mass of the lepton pair is equal to M_Z . In a small fraction of events, the Z boson that decays into charged leptons is far off shell and is not rejected by the above cut. However, such events are greatly suppressed by the Z -boson propagator and can be safely neglected. Furthermore, this background does not contribute to different-type lepton events.

The dominant background to the Higgs-boson signal is real W -boson pair production from quark-antiquark annihilation (d) followed by leptonic decay of each W boson. It is difficult to introduce cuts to reduce this background without also reducing the signal. We will therefore consider it to be the irreducible background to the Higgs-boson decay to one real and one virtual W boson.

Another potentially dangerous background is heavy-quark pair production followed by the semileptonic decay of each quark. This background is separable from the signal in principle due to the presence of additional particles in the final state. However, the cross section is very large, and it may be difficult to suppress this background sufficiently. This is a complicated issue which we shall not address here.

An intermediate-mass Higgs boson is produced from gluon fusion via a top-quark loop,¹⁷ and thus the cross section depends on the top-quark mass. Since we are assuming that the Higgs boson cannot decay to top quarks, we require $m_t \geq \frac{1}{2}m_H$. The cross section approaches a constant value in the limit that the top-quark mass is much greater than the Higgs-boson mass, and is roughly twice this value at $m_t = \frac{1}{2}m_H$ (Ref. 18). The uncertainty in the Higgs-boson production cross section due to the unknown top-quark mass is therefore only a factor of 2. For definiteness, we have chosen $m_t = 100$ GeV.

We show in Fig. 2(a) the transverse-momentum spectrum of the final-state lepton l for a variety of Higgs-boson masses, and for the background W -boson pair production process, for pp collisions at $\sqrt{s} = 40$ TeV (SSC). The rates shown are for only one lepton-type in the final state; i.e., we have not summed over the four combinations e^+e^- , $\mu^+\mu^-$, $e^+\mu^-$, and $e^-\mu^+$. We have imposed the cuts $\not{p}_T > 20$ GeV, $\Delta\phi(\bar{l}l) > 160^\circ$, and $p_T(l), p_T(\bar{l}) > 20$ GeV on both the signal and the background.

Figure 2(a) shows that the Higgs-boson decay to one real and one virtual W boson will produce an observable enhancement in the W -boson pair continuum at small lepton transverse momentum if the Higgs-boson mass is greater than about 140 GeV. The total number of events per year is large, roughly 10^3 , assuming the standard SSC luminosity of $10^{33}/\text{cm}^2\text{sec}$.

Figure 2(b) shows the cluster-transverse-mass distribution $M_T(\bar{l}l, \not{p}_T)$ defined by¹⁶

FIG. 2. (a) The lepton transverse-momentum distribution and (b) the cluster-transverse-mass distribution for the process $pp \rightarrow H \rightarrow WW^* \rightarrow (l\bar{\nu})(\bar{l}\nu)$ at the SSC for various Higgs-boson masses. The cuts $p_T(l), p_T(\bar{l}) > 20 \text{ GeV}$, $p_T > 20 \text{ GeV}$, and $\Delta\phi(l\bar{l}) < 160^\circ$ have been imposed. The background from W -boson pair production followed by the leptonic decay of each W boson is also shown.

FIG. 3. Same as Fig. 2, but at the LHC.

$$M_T^2(\bar{l}l, \not{p}_T) = \{ [|\mathbf{p}_T(l) + \mathbf{p}_T(\bar{l})|^2 + M^2(\bar{l}l)]^{1/2} + |\not{p}_T| \}^2 \\ - |\mathbf{p}_T(l) + \mathbf{p}_T(\bar{l}) + \not{p}_T|^2,$$

where $M(\bar{l}l)$ is the invariant mass of the charged leptons. Since there are two neutrinos in the final state, it is impossible to make a direct measurement of the Higgs-boson mass. However, the $M_T(\bar{l}l, \not{p}_T)$ distribution has a broad Jacobian peak with an end point at m_H , and thus supplies a rough estimate of the Higgs-boson mass. The cluster transverse mass is defined in such a way as to minimize the smearing of the distribution due to the intrinsic p_T of the Higgs boson.¹⁹

We show in Fig. 3 the same distributions at the LHC. The signal is about five times smaller than at the SSC. Furthermore, the signal-to-background ratio is worse. This is a consequence of the fact that the gluon luminosity (which is relevant for the signal) falls off more rapidly than the quark-antiquark luminosity (which supplies the background) for decreasing collision energy.

Our results complement those of Ref. 8, which concentrates on the intermediate-mass Higgs-boson decay modes $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$, where each Z boson decays leptonically. Reference 8 shows that these two modes can cover the mass region $100 \text{ GeV} \lesssim m_H < 2M_Z$, assuming the top-quark decay mode of the Higgs boson is forbidden. We have found that the decay $H \rightarrow WW^*$, where each W boson decays leptonically, yields an observable Higgs-boson signal in the mass range $140 \text{ GeV} \lesssim m_H < 2M_Z$. The former two decay modes have the advantage that they allow a reconstruction of the Higgs-boson mass from the invariant mass of the decay products, while the $H \rightarrow WW^*$ decay mode requires a less direct approach, such as the cluster-transverse-mass distribution, due to the loss of two neutrinos.

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