PHYSICAL REVIEW D VOLUME 34, NUMBER 3 1 AUGUST 1986

Overcoming a critical background to Higgs-boson detection

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(Received 24 March 1986)

We show that it may well be possible to overcome the jjW background to Higgs-boson detection in mixed hadronic-leptonic final decay channels, while maintaining substantial event rates, even for Higgs-boson masses as high as 1 TeV.

I. INTRODUCTION

The most essential element of the standard $SU(2)_L \times U(1)$ model of electroweak interactions which remains to be confirmed is the Higgs mechanism for symmetry breaking. Establishing this component of the model requires finding the Higgs boson. As is well known the H couplings are completely determined in the standard model (SM) but m_H is nearly unrestricted. If H is light, $m_H < 100$ GeV, then its discovery at e^+e^- machines that are presently available or that will soon be available is straightforward.[1–3] If 100 GeV $< m_H < 2m_W$ then only extension of the CERN LEP II energy range, to as much as 300 GeV for m_H near $2m_W$, will allow discovery of the H at planned e^+e^- facilities. In addition, there is no known technique for observing the Higgs boson in this mass range at a hadron collider, such as the Superconducting Super Collider (SSC); assuming that m_t is smaller than $m_H/2$ the relatively background-free channels involving rare decay modes of H have too low an event rate.[2] The very important high-mass region, $m_H > 2m_W$, that will certainly not be probed by any planned e^+e^- facilities, may, however, be accessible to the SSC.[4] Certainly the SSC will have sufficient center-of-mass energy ($\sqrt{s} = 40$ TeV) to produce an H in this mass range. Problems with backgrounds and/or event rates have been the subject of several recent investigations and will be the focus of this paper.[5–9,3]

For $m_H > 2m_W$ the Higgs boson decays predominantly to W pairs or Z pairs. An obvious background arises from continuum pair production; it has been established for some time that the Higgs boson can be observed above this background.[4,9] However, other difficulties arise from the necessity of observing the W's or Z's in some particular decay mode. If both gauge bosons decay hadronically then the final state, consisting of 4 quark jets, has large backgrounds from pure QCD 4-jet production processes. If both gauge bosons decay purely leptonically then event rates are relatively low for the standard $L = 10^4$ pb^{-1} planned luminosity;[8] the mode $H \to Z(\to ee + \mu\mu) + Z(\to \nu\nu)$ appears to be the most promising.[10] Thus mixed hadronic-leptonic decay modes for the two gauge bosons have been proposed as the best means for probing both the Higgs boson and the W- and Z-pair continuum processes. Raw event rates are more than adequate.[4] However, it has recently become apparent that mixed QCD-electroweak processes involving the production of 2 jets together with a single W or Z gauge boson provide a severe background to such modes.[6,7] It was demonstrated in Ref. 6 that strong cuts could be imposed that would produce a reasonable signal-to-background ratio. Unfortunately, these cuts also produced very marginal event rates, especially at high m_H. In this paper we demonstrate that more optimal event selection is possible, which both maintains a reasonable signal-to-background ratio and reasonable event rates out to $m_H = 1$ TeV.

Because of the larger branching ratio for H decay to two W's (compared to two Z's) we will focus on the process

$$pp \to H \to W(\to l\nu) + W(\to q\bar{q}) \ . \tag{1}$$

The two sources of background are the continuum pair process

$$pp \to q\bar{q} \to W(\to l\nu) + W(\to q\bar{q}) \tag{2}$$

and the jet-jet-W backgrounds

$$pp \to \begin{cases} gq \to W(\to l\nu) + gq, \\ gg \to W(\to l\nu) + q\bar{q}, \\ qq \to W(\to l\nu) + qq, \\ q\bar{q} \to W(\to l\nu) + gg, \end{cases} \tag{3}$$

along with additional unlisted crossings thereof. (We presume that, for the light-quark modes to be considered, experimental discrimination between quark and gluon jets is not possible.)

In referring to the above processes we will adopt the convention that the phrase "jjW background" refers only to processes (3), and "WW continuum" refers only to the process (2). However, when speaking of the final state, we will frequently refer to the jjW mode that is common to all signal and background processes. When plotting cross sections we will include only the final states:

$$e^+\nu\bar{u}d, \quad e^+\nu\bar{c}s \ . \tag{4}$$

In discussing statistics, however, we include all of the light-quark jet modes,

$$e^+\nu\bar{u}d,\ e^+\nu\bar{c}s,\ \mu^+\nu\bar{u}d,\ \mu^+\nu\bar{c}s,$$
$$e^-\bar{\nu}u\bar{d},\ e^-\bar{\nu}c\bar{s},\ \mu^-\bar{\nu}u\bar{d},\ \mu^-\bar{\nu}c\bar{s}, \quad (5)$$

by multiplying the rates for the final states (4) with a factor of 4.

II. EVENT STRUCTURE AND CUTS

Among the refinements we shall include in the present investigation will be the elimination of the approximation made in our earlier work[6] (paper I) that the neutrino from the W decay could be reconstructed without ambiguity. We will explicitly incorporate the effects from the twofold ambiguity in neutrino reconstruction. Our procedure is outlined below.

(a) We presume that the overall transverse momentum of the jjW system is known with reasonable accuracy as a fraction of the transverse momenta of the jets and W. (We will impose cuts that require these to be substantial.) Thus our calculations are done in the approximation where the transverse momentum of the overall jjW system is neglected.

(b) We use the (measured) transverse momenta of the jets and charged lepton to determine $\mathbf{p}_T^\nu$.

(c) We determine the two possible values of p_L^ν ($L \equiv$longitudinal) consistent with the constraint $(p^\nu+p^l)^2=m_W{}^2$.

(d) If both solutions are physical then we choose that value of p_L^ν which yields the smaller rapidity for the jjW system in the proton-proton center of mass. (Our reasoning is that the H will tend to be produced most frequently with small rapidity.)

In practice we find that this algorithm yields the correct p^ν approximately 75% of the time for signal events. Even in those cases when the algorithm fails, the correct p^ν and incorrect p^ν solutions often differ by only a small amount. Thus the distributions we consider are not dramatically altered by the reconstruction process.

Once the full four-momentum p^ν is determined by this procedure the "reconstructed" WW-pair mass m_{WW} may be calculated along with other variables, such as the charged-lepton angle defined below.

In fact, before proceeding it is useful to define the variables that we will need in the remainder of the paper. These are the following.

(1) θ_l^* is the angle (as computed after reconstruction) of the charged lepton in the rest frame of the decaying W—defined with respect to the direction of $\mathbf{p}_W$ in the jjW center of mass. The lepton decay angle could also be defined with respect to $\mathbf{p}_W$ in the overall laboratory system. However, we have found that cuts are slightly more effective in terms of the angle defined above.

(2) $p_T^{\max}$, $p_T^{\min}$ are the magnitudes of the transverse momenta of the jets with the larger and smaller value of p_T, respectively.

(3) $y^l, y^{\max}, y^{\min}$ are the rapidities of the charged lepton, and of the jets with $p_T^{\max}$ and $p_T^{\min}$, respectively.

(4) m_{WW} is the reconstructed jjW final-state invariant mass which, for WW continuum and H decay processes, is the same as the reconstructed WW invariant mass.

(5) m_{jj} is the invariant mass of the jj system.

It will also be useful to define the ratios

$$r_T^{\max}=\frac{p_T^{\max}}{m_{WW}},\quad r_T^{\min}=\frac{p_T^{\min}}{m_{WW}}\ . \quad (6)$$

In I we showed that the transverse momenta of the 2 jets provided the most powerful means for separating signal from backgrounds. The jjW subprocess is strongly suppressed as the p_T's of the 2 jets are made large. In I we also investigated the distribution of events as a function of $\cos(\theta_l^*)$. We found the expected difference between the $\cos(\theta_l^*)$ shapes for Higgs-boson events versus background events; a $\sin^2(\theta_l^*)$ distribution for the longitudinal W from H decay versus a $[1+\cos^2(\theta_l^*)]$ distribution for the transversely polarized W produced via the jjW and WW background processes. In I we imposed a strong cut in $\cos(\theta_l^*)$ that enhanced the Higgs component. With neutrino reconstruction there is little change; the $\cos(\theta_l^*)$ distributions are very close to the naive functional forms given above, even in the presence of rapidity and strong transverse-momentum cuts. To illustrate this we plot, for $m_H=0.3$ 0.8 TeV, in Fig. 1 the cross section

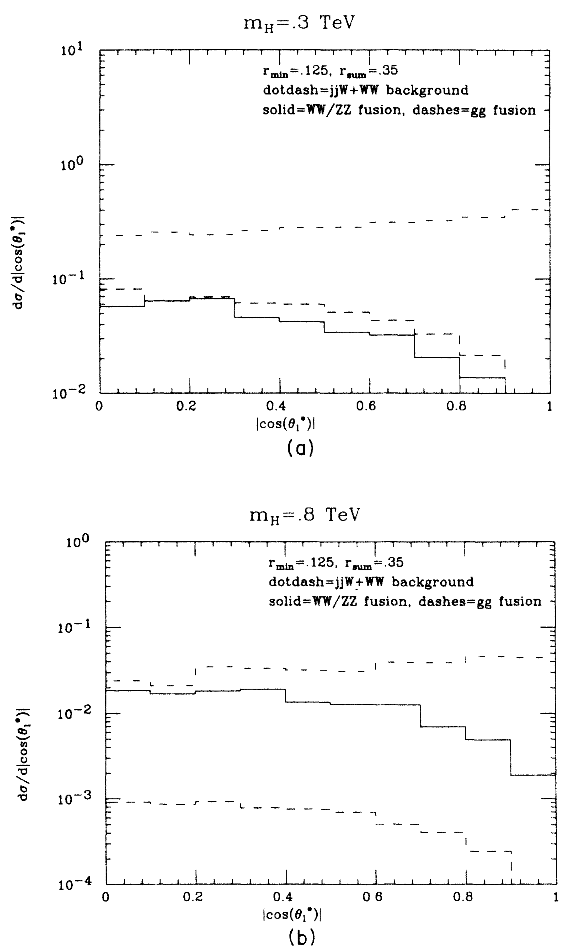


FIG. 1. The angular distribution $d\sigma/d\,|\cos(\theta_l^*)|$ for the sum of the WW and jjW backgrounds and for the Higgs-boson events produced by both gg fusion and WW/ZZ fusion. We plot these distributions for $m_H=0.3$ TeV in (a) and for $m_H=0.8$ TeV in (b), with cuts as outlined in the text. Only the modes (4) are included.

$d\sigma/d\,|\cos(\theta_l^*)|$ subject to the cuts listed below.

(i) A cut on the invariant mass m_{WW}:

$$m_H-\Delta m_H/2<m_{WW}<m_H+\Delta m_H/2\,, \quad (7)$$

where

$$\Delta m_H=\max(0.05m_H,\Gamma_H)\,. \quad (8)$$

(ii) A restriction on the invariant mass of the 2-jet system, m_{jj}:

$$0.975m_W<m_{jj}<1.025m_W\,, \quad (9)$$

corresponding to requiring the jj system to have approximately the W mass within 5% resolution.

(iii) A restriction on the transverse momenta of the 2 jets:

$$r_T^{\min}>r_{\min},\quad r_T^{\min}+r_T^{\max}>r_{\text{sum}}\,, \quad (10)$$

with $r_{\min}=0.125$ and $r_{\text{sum}}=0.35$—these turn out to be fairly optimal.

(iv) A cut on the rapidities of the observed particles:

$$|y^l|,|y^{\max}|,|y^{\min}|<4\,. \quad (11)$$

The WW-pair and jjW backgrounds rise slowly as a function of $|\cos(\theta_l^*)|$. In contrast the WW/ZZ-fusion[11] and gg-fusion[12] components of the H signal tend to be flat out to $|\cos(\theta_l^*)|=0.5$, and decrease sharply thereafter. We note that these behaviors are not strongly dependent on the p_T cuts of Eq. (10). Thus, in all subsequent calculations we will impose the restriction

$$\text{(v)}\quad |\cos(\theta_l^*)|<0.5 \quad (12)$$

as a means of reducing, somewhat, the background while retaining most of the true Higgs-boson events. This is weaker than the cut imposed in paper I. A stronger cut would only slightly improve the signal-to-background ratio while cutting the signal event rates by a factor of 2. While this gain in event rate will be helpful, the main increase relative to paper I will come from optimizing the p_T cuts.

A similar procedure for the decay angle in the hadronic channel is not useful. The p_T cuts on the jets lead to substantial distortion of the angular distributions and signal and backgrounds have similar shapes.

The main focus of this paper will be upon optimizing the p_T cuts of Eq. (10) given the restrictions (7), (9), (11), and (12). Once these have been found we will then present full m_{WW} distributions and discuss a number of additional issues. In order to optimize the values of $r_{\min}$ and r_{sum} we have generated events for both signal and backgrounds, subject to (7), (9), (11), and (12), and binned them as a function of the transverse-momentum ratios $r_T^{\max}$ and $r_T^{\min}$. We focus on two representative Higgs-boson masses: $m_H=300$ and 800 GeV. In Fig. 2 we present three-dimensional plots of the signal and background cross sections as functions of $r_T^{\max}$ and $r_T^{\min}$. In Figs. 2(a) and 2(d) we exhibit the sum of the WW-pair and jjW background contributions. In Figs. 2(b) and 2(e) we give the gg-fusion contributions to the H signal and in Figs. 2(c) and 2(f) we present the WW/ZZ-fusion results. The two sources of H production lead to similar r_T correlations, while the background is strikingly different. In particular, the background events accumulate near the $r_T^{\min}=0$ line over a range of $r_T^{\max}$. In contrast the H events accumulate along a line of constant $r_T^{\text{sum}}=r_T^{\min}+r_T^{\max}$. By simultaneously imposing minimum values on r_T^{sum} and $r_T^{\min}$ we may eliminate a large portion of the background while retaining most of the actual Higgs-boson events. This is, of course, the motivation for considering cuts of the form (10). We have systematically searched for the best $r_{\min}$ and r_{sum} and found that, for the two Higgs-boson masses considered, the values

$$r_{\min}=0.125,\quad r_{\text{sum}}=0.35 \quad (13)$$

are very close to optimal. In what follows we shall retain the restriction (10) with parameters (13).

Before continuing we give the background and signal cross sections that are obtained with the restrictions (7), (9), (11), (12), and (10) with values (13). These include all the modes (5). At $m_H=0.8$ TeV we find

$$\sigma_{\text{signal}}=4.0\times10^{-2}\ \text{pb},\quad \sigma_{\text{background}}=6.0\times10^{-2}\ \text{pb}\,. \quad (14)$$

At $m_H=0.3$ TeV we obtain

$$\sigma_{\text{signal}}=0.256\ \text{pb},\quad \sigma_{\text{background}}=0.48\ \text{pb}\,. \quad (15)$$

It is also of interest to give the decomposition of $\sigma_{\text{background}}$ in terms of the various contributing subprocesses. These are in the ratio

$$(qg\to qgW+\bar{q}g\to\bar{q}gW):(gg\to q\bar{q}W):(qq\to qqW+q\bar{q}\to q\bar{q}W+\cdots):(q\bar{q}\to ggW)=\begin{cases}5.1{:}0.68{:}0.26{:}0.29, & m_H=0.3\ \text{TeV},\\ 4.6{:}0.10{:}0.13{:}0.85, & m_H=0.8\ \text{TeV}.\end{cases} \quad (16)$$

Note that only the $gg\to q\bar{q}W$ (and at a much lower rate, $q\bar{q}\to q\bar{q}W$) subprocess produces a final state that is indistinguishable from the true W-pair decay mode, and that its contribution to the total jjW background is small. Thus if vertex detection, etc., could be used to identify the heavy flavor mode, $jjW=btW$, the jjW background could be greatly reduced, provided that losses in mass resolution and ability to perform cuts are not too great. This subject is currently under investigation by the W/Z/Higgs-boson and heavy-flavor working groups.[13] Considerable skepticism is warranted given the results of Ref. 14, in which Higgs-boson mass reconstruction in the process $pp\to HW\to t\bar{t}W$ was attempted with little success. In the current situation the transverse momenta of the b and t quarks would be greater and some improvement over Ref. 14 should be possible. In any case, it is clearly of importance to continue our study of the light-quark modes and their associated backgrounds.

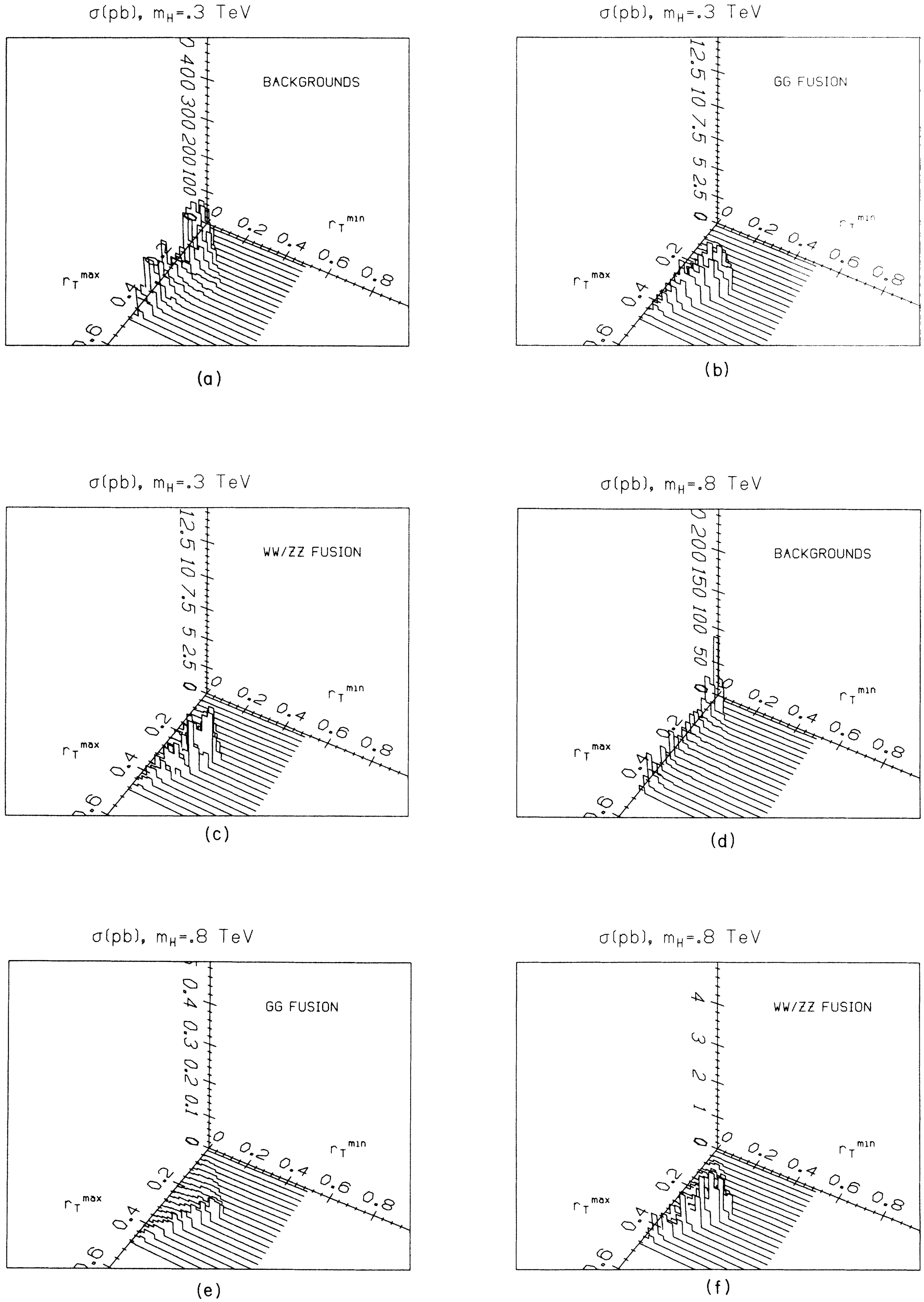


FIG. 2. Cross sections for the final states (4) subject to cuts (7), (9), (11), and (12) from (a) $WW+jjW$ backgrounds, (b) gg-fusion Higgs-boson production, (c) WW/ZZ-fusion Higgs-boson production—all at $m_H=0.3$ TeV. These same cross sections for $m_H=0.8$ TeV appear in (d), (e), and (f), respectively.

III. MASS PLOTS AND ELIMINATION OF SYSTEMATICS

In order to further assess the significance of the enhancements of Eqs. (14) and (15) we will first plot the cross sections as a function of m_{WW} and then discuss means for eliminating systematic uncertainties in the background. In Fig. 3 we exhibit the cross sections $d\sigma/dm_{WW}$ for the various background and H signal contributions. We also display the combined cross sections. From these plots it is clear that the H signal provides a distinct enhancement to the cross section in the vicinity of $m_{WW}=m_H$. However, the enhancement is only 50% in the $m_H=0.3$ TeV case. For $m_H=0.8$ TeV the H creates a 100% excess, but spread over a large range of m_{WW}. Thus in both cases a systematic uncertainty in the normalization of the background could make observation of the H signal uncertain.

These m_{WW} distributions also show that the restriction (7) is not maximally efficient at high m_H. The $m_H=0.8$ TeV curve peaks at $m_{WW}=0.86$ TeV, rather than at m_H. Thus by taking an asymmetric cut about m_H, at high mass, a further increase in signal-to-background ratio could be obtained. In discussing elimination of the systematic uncertainty in the jjW background below we shall adopt the restriction

$$0.75\ \text{TeV} < m_{WW} \tag{17}$$

for the $m_H=0.8$ TeV case, while retaining (7) at $m_H=0.3$ TeV. The restriction (17) leads to the results

$$\sigma_{\text{signal}}=4.9\times10^{-2}\ \text{pb},\quad \sigma_{\text{background}}=4.8\times10^{-2}\ \text{pb}; \tag{18}$$

i.e., the Higgs-boson signal is slightly larger relative to (14) while the background is now smaller. With this type of asymmetric cut we estimate that our techniques can be extended to $m_H=1$ TeV. Roughly, at high m_H, the background and signal are equal for $m_{WW}\geq m_H$. At $m_{WW}=1$ TeV we thus estimate that the cross sections for background and signal are a factor of 4 below the values of (18), see Fig. 3(b).

Let us now turn to a straightforward technique for

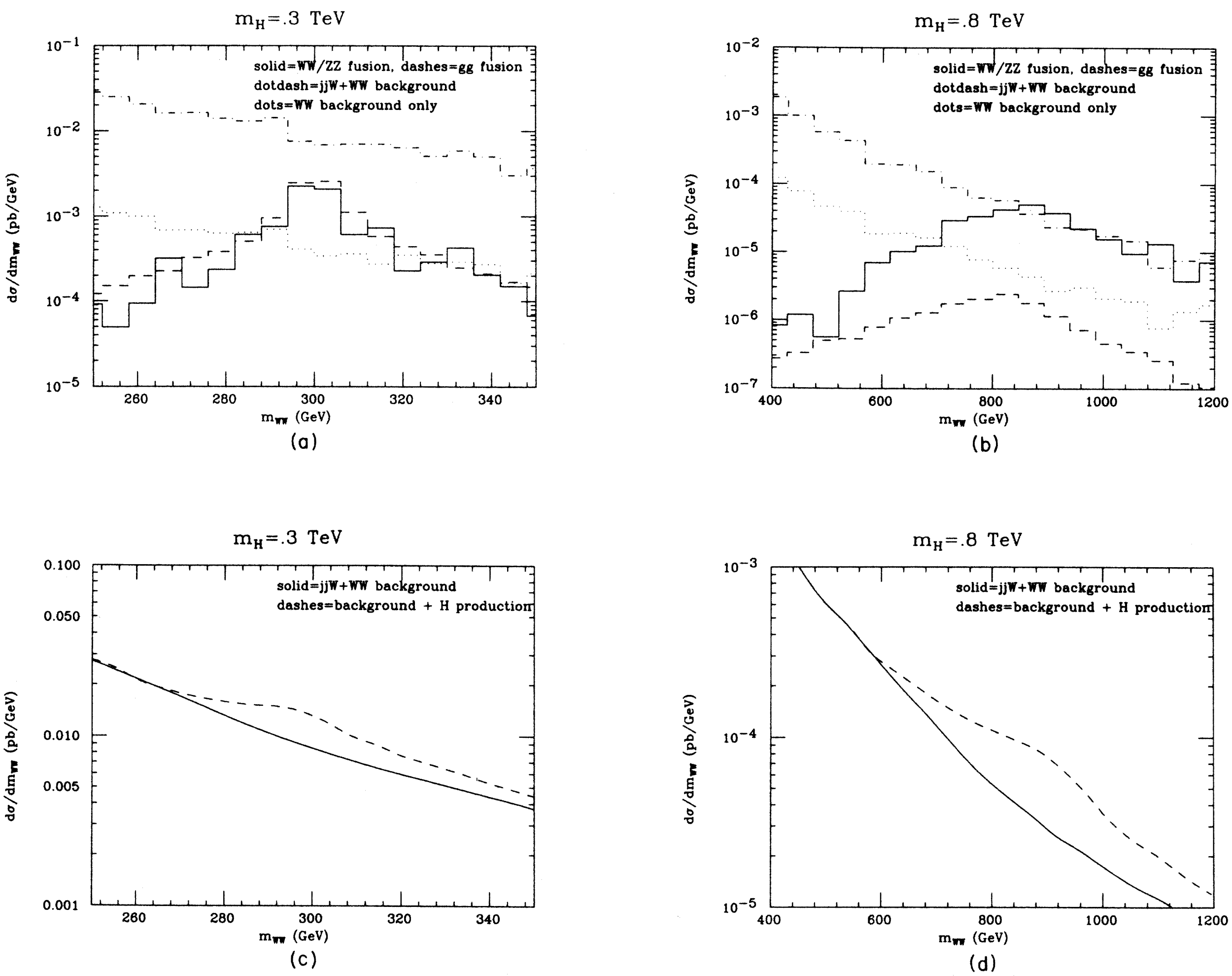
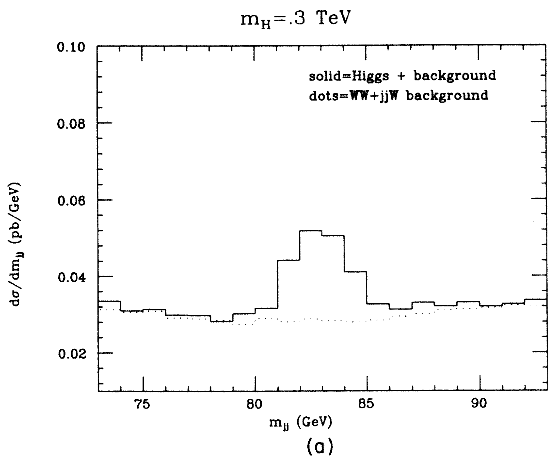


FIG. 3. We present cross sections for the mode (4) subject to cuts (9), (11), (12), and (10) [with values (13)] as a function of m_{WW}. In (a) and (b) we plot separately the results for WW continuum, jjW background combined with WW continuum, H production via gg fusion, and H production via WW/ZZ fusion—at $m_H=0.3$ TeV and $m_H=0.8$ TeV, respectively. In (c) and (d) we compare the total background in the absence of H production to the total cross section including both background and H production contributions, for these same values of m_H.

eliminating systematics in the background. The main jjW component of the background can be independently normalized by moving away from the W resonance in the jet-jet mass m_{jj}. In this way the WW continuum and H production contributions are greatly suppressed, whereas the jjW background, which is very slowly varying as a function of m_{jj}, remains essentially unchanged. We illustrate this in Fig. 4. In this figure, H production is clearly seen as an enhancement in $d\sigma/dm_{jj}$ as one passes through the region $m_{jj}=m_W$. Thus systematic uncertainties are not a severe problem, provided sufficient resolution in the jj invariant mass can be achieved. With this in mind it is not unreasonable to quote the statistical level of the enhancements due to Higgs-boson production, following from Eqs. (14), (15), and (18). At a yearly integrated luminosity of $L=10^4$ pb^{-1} we obtain 16σ, 37σ, and 22σ effects, respectively. Note that even though the signal-to-background ratio is larger for the 0.8-TeV Higgs boson, the numbers of events are such that the nominal statistical significance of the 0.3-TeV Higgs-boson signal is greater. Following the procedure outlined for the 1-TeV Higgs boson we obtain, roughly, a 10σ enhancement of Higgs-boson signal over background.



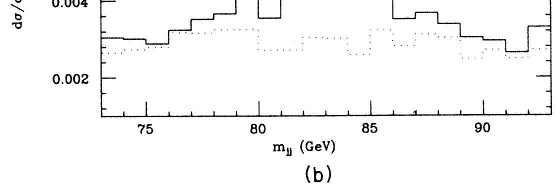


FIG. 4. We plot the cross section $d\sigma/dm_{jj}$ at $m_H=0.3$ TeV in the modes (4), subject to the restrictions (7), (11), (12), and (10) [with values (13)] for backgrounds and H production contributions. In (a) we present the 0.3-TeV results for the sum of the jjW and WW continuum backgrounds, together with the sum of these backgrounds and the gg and WW/ZZ-fusion contributions to the Higgs-boson signal. In (b) these same curves are given for the 0.8-TeV case.

IV. CONCLUSIONS

In conclusion we have shown that observation of the Higgs boson at the SSC in the mixed hadronic-leptonic decay modes of Eq. (5) is quite likely to be possible despite the presence of a severe jjW background from mixed QCD-electroweak processes. In order to achieve a reasonable signal-to-background ratio and a reasonable event rate we have used the r_T cut procedure of Eqs. (10) and (13). Elimination of systematic uncertainties in the background, which could otherwise make observation of the Higgs-boson enhancement uncertain, can be achieved by varying the jet-jet mass m_{jj} on and off the W resonance. The remaining uncertainties are as follows.

(1) Will it be possible to determine the transverse momentum of the jjW system with sufficient accuracy that neutrino reconstruction can be effectively performed?

(2) How well can the 2 jets be resolved in practice? At the parton level we have found that all events that fall within our cuts have $\Delta R_{jj}\geq 0.1$, where $\Delta R_{jj}=(\Delta y^2+\Delta\phi^2)^{1/2}$ is a typical measure of jet separation. ($\Delta\phi$ is the azimuthal separation between the partons in the transverse plane.) Experimental resolution in ΔR_{jj} is expected to be at least this good.[13] However, effects of hadronization of the partons remain to be investigated.

(3) Will the hadronization of the final-state jets, both from the subprocesses and from the beam and target spectator systems, obscure the p_T correlations that have allowed background reduction without catastrophic signal loss?

(4) How well can the jj invariant mass be reconstructed considering uncertainties in hadronization effects?

Question (1) is largely a matter of detector acceptance. In particular the spectator jets from the WW/ZZ-fusion mechanism must be observed in the detector. This will probably require hadronic calorimetry out to large rapidities. It will also be dangerous to have "cracks" leading to missing p_T. Questions (2), (3), and (4) are both theoretical and experimental in nature. Theoretically a reliable Monte Carlo simulation of jet fragmentation and hadronization is required in order to assess fully the development of the final state. Experimentally resolution and jet reconstruction will be a significant factor.

ACKNOWLEDGMENTS

We would like to thank F. Paige, M. Chanowitz, and A. Savoy-Navarro, and other members of the UCLA $W/Z/H$ working group, for valuable conversations. This work was supported by the Department of Energy.

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