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# Using the hadronic multiplicity to distinguish real $W$'s from QCD jet backgrounds

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In order to study $WW$ scattering or the decay of a heavy standard-model Higgs boson in the TeV region, it is necessary to use the channel $W(\rightarrow l\nu)+W(\rightarrow \text{jets})$. However, techniques are required for suppressing the severe background from mixed electroweak-QCD production of $W$+jets. We demonstrate that the charged multiplicity of the events can provide an extremely useful tool for distinguishing a jet system originating via real $W$ decay from a jet system produced by the mixed electroweak-QCD processes. Analogous techniques will be useful for any process involving $W$'s$\rightarrow$jets, whenever the $W$ decaying to jets has $p_t \gg m_W$ and the primary background produces jets predominantly in a color-nonsinglet state; however the precise procedure must be optimized separately for each such process.

## I. INTRODUCTION

Probing the source of electroweak symmetry breaking is one of the most important goals of the next generation of colliders. In particular, we must ascertain the extent to which hadron colliders, such as the proposed Superconducting Super Collider (SSC) and CERN Large Hadron Collider (LHC), can be used to carry out the necessary studies, and determine what detector capabilities will be required in order to perform these studies. While there is no general agreement as to the mechanism responsible for electroweak (EW) symmetry breaking, it is essential to be able to explore experimentally the standard-model (SM) scenario in which the observable experimental remnant is a single neutral Higgs boson, denoted by $H$. Since the mass of the $H$ is not determined by the theory, we must develop techniques for its detection for all possible values of its mass $m_H$. Equally important, we must be able to eventually determine whether the $WW$ interaction in the TeV region is consistent with its perturbative prediction. At large $m_H$, above roughly 0.6 TeV (for $m_t=60$ GeV, a c.m. energy of $\sqrt{s}=40$ TeV, and a yearly integrated luminosity of $L_{\text{year}}=10^4$ $\text{pb}^{-1}$ of the SSC), the "gold-plated" mode of $H\rightarrow Z(\rightarrow l^+l^-)Z(\rightarrow l^+l^-)$ has too small an event rate[1] and one must turn to either

$$H\rightarrow Z(\rightarrow l^+l^-)Z(\rightarrow \nu\bar{\nu}) \tag{1.1}$$

or

$$H\rightarrow W(\rightarrow l\nu)W(\rightarrow q_1\bar{q}_2) \tag{1.2}$$

and

$$H\rightarrow Z(\rightarrow l^+l^-)Z(\rightarrow q_1\bar{q}_1)\ . \tag{1.3}$$

The former decay mode has a limited event rate and elimination of backgrounds from continuum $ZZ$ pair production and $Z$+jet production requires substantial cuts.[1] While it is possibly feasible to use the mode (1.1) to reach somewhat above 0.6 TeV, it is essential to be able to see a signal in the modes (1.2) and (1.3) in order to probe the TeV region.

As has been demonstrated[2,3] the background to the mode (1.2) from processes of the type

$$\begin{aligned}&qq\rightarrow qqW,\quad qg\rightarrow qgW,\\&gg\rightarrow q\bar{q}W,\quad q\bar{q}\rightarrow ggW\ ,\end{aligned} \tag{1.4}$$

which yield the same final state of $Wj_1j_2$ as (1.2) is extremely large if one merely constrains the mass of the $j_1j_2$ to be in the vicinity of $m_W$—typically $S/B \lesssim 0.01$. A number of techniques have been proposed for improving the ratio of signal to background. These techniques rely either on the specific event structure of the Higgs-boson decay, resulting from the longitudinal nature of the $W$ bosons produced in the decay,[4] or on tagging the forward spectator jets remaining after the $W$ fusion production of the Higgs boson.[5,6] The above purely partonic-level investigations were able to delineate cuts that yield signal-to-background ratios of order 1:1 with signals of the order of 100 events per SSC year for Higgs-boson masses of order 1 TeV. Monte Carlo studies that included many detector and resolution effects have been performed based on the first type of approach.[7,8] Preliminary conclusions are less favorable than the partonic level results, but indicate that a $3-5\sigma$ effect can be achieved.

In this paper, we wish to consider the possibility of going beyond jet-level cuts and discriminating between a jet system coming from the decay of a real $W$ and one coming from the mixed EW-QCD background processes of Eq. (1.4) on the basis of the multiplicity of hadrons that are produced in the underlying event. Clearly this type of discrimination requires a detector with the ability to count individual hadrons within the highly energetic jets of the event. Techniques for constructing such detectors have been considered in several of the summer workshops.[9,10] In Sec. II we will outline the reasons why this type of discrimination might be quite effective. In Sec. III we will present results based on the PYTHIA Monte Carlo program, which we employed because it has a reasonable approximation to the correct color structure and correlations in the final state. Section IV contains our conclusions.

## II. HADRONIC MULTIPLICITY AND COLOR STRUCTURE

In this section we compare the underlying color structure for the Higgs-boson production reaction to that of the background reactions. Based on this comparison we demonstrate that there should be a substantial difference in the hadronic multiplicity (both in magnitude and distribution) between signal and background events. Let us begin by considering the color structure of the Higgs-boson production process

$$qq \rightarrow qqH \ , \tag{2.1}$$

where the $H$ is formed by the fusion of two virtual $W$'s one being emitted from one initial quark and the second from the other initial quark. We will assume that the Higgs boson decays to a pair of real $W$'s, one of which decays leptonically and the other of which decays to a $q_1\bar{q}_2$ pair. There are several components to the hadronic multiplicity emerging from the resulting partonic-level final state. These are illustrated in Fig. 1. We focus first on that associated with the $q_1\bar{q}_2$ pair. Initially, this pair is in a color-singlet state. Of course, were the $W$ very narrow and, hence, long lived, it would exit the interaction region prior to this decay and the $q_1\bar{q}_2$ pair would not be influenced by the other final-state particles present in the event. The $W$ would decay as if it were a pseudostable particle to a fixed set of final states with well-determined average multiplicity. In particular, the decay multiplicity would be the same for a $W$ at rest as for an energetic $W$.

However, the $W$ is, in fact, rather broad and will decay almost instantly, and it is thus necessary to consider the

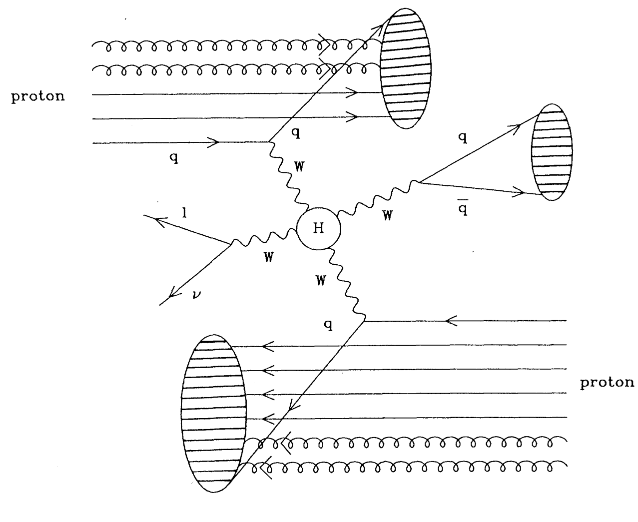


FIG. 1. An illustration of the color structure and resulting hadronic multiplicity for the $WW$-fusion Higgs-boson production reaction. The hatched areas indicate the color-singlet fragmentation zone leading to the final hadronization products. The Fock states of the incoming protons are pictured as containing gluons or an extra $q\bar{q}$ pair. More generally, there will be many such gluons and $q\bar{q}$ pairs in both incoming proton Fock states. The hard interaction allows these complicated Fock states to materialize and contribute a minimum-bias component to the hadronic final state. The beam and target Fock state plus $W$-emission spectator hadronic blobs combine to give a minimum-bias-type multiplicity plus a small additional amount determined by the scale $m_W$ of the spectator-quark–jet transverse momenta.

$q_1\bar{q}_2$ system in the same way as any pair of promptly produced jets in a color-singlet state. These jets can develop via gluon emission and gluon interactions with other jets in the final state. Considering the first such gluon, there are two possibilities: (i) if we picture the gluon emission or interaction as originating from one of the $W$-decay jets, one possibility is for it to communicate with the other jet of the $W$ decay; or (ii) it can connect with one of the final-state spectator jets in reaction (2.1) or with a beam or target remnant. Gluon connections of type (i) would occur even in the case of the decay of an isolated $W$; the jets associated with the decaying $W$ remain in an overall color singlet. The color factor for the associated amplitude squared diagram is large: $C_F=(N_c^2-1)/(2N_c)$. Gluon connections of type (ii) are required to change the color structure of the final state, and, if important, would imply that the development of the $W$ decay jets could not be considered in isolation from the rest of the hadronic process. But in the process being considered, a gluon-exchange diagram of type (ii) does not interfere with the lowest-order diagram at the amplitude squared level. One must go to order $\alpha_s^2$ at the amplitude squared level in order to find gluon connections that destroy the $W$ decay system's color-singlet nature. Relative to diagrams at order $\alpha_s^2$ for which the two emitted or virtual gluons act entirely within the original quark-antiquark $W$ decay system, the former color-singlet destroying diagrams have significant color-suppression factors of order $1/N_c$ or smaller. Thus, to leading order in $1/N_c$ the decaying $W$ remains isolated from the target and beam remnants, and retains its color-singlet nature. Let us ask if the available Monte Carlo programs correctly simulate this situation.

In all the Monte Carlo programs, a produced $W$ is treated as decaying with a fixed multiplicity determined by treating the $q_1\bar{q}_2$ final state as a color singlet and using the $1\rightarrow 2$ branching probabilities for quark and gluon emissions to develop appropriate parton-level radiation. The amount of radiation is controlled by the maximum amount of virtuality allowed, which is set by the $W$ mass. Clearly this prescription agrees with the theoretical picture to leading order in $1/N_c$. Thus the $W$ hadronic multiplicity will remain completely characteristic of the $W$ (in particular, of its mass) as if it were a long-lived particle.

Let us now turn to the other colored jets in the final state of a typical $WW$ fusion production event (see Fig. 1). There are the two spectator jets left behind by the virtual $W$ emissions, and there are the beam and target remnants to consider. Typically the spectator jets have transverse momenta of order $m_W$ and substantial rapidity. As far as the color structure of the Born-level production process itself is concerned, the target and beam spectator jet systems, each consisting of a spectator quark and a hadron remnant, are separately in a color singlet. If there is no color communication between these two systems then each would radiate and hadronize on its own. The amount and distribution of the radiation and hadronization is clearly dependent on the complexity of the target and beam remnants. If these were simple coherent jets one could view the beam and target jet systems as $3\bar{3}$ jet pairs with invariant mass set by the transverse momentum of the spectator quark which is typically of order $m_W$. This would allow for a very limited amount of additional radiation associated with the spectator quarks and beam and/or target remnants. However, in reality each of the interacting $W$'s is generally just one object in a complicated Fock state of the incoming hadron. The interaction should allow the remainder of the Fock state to materialize and its hadronization products will generally populate the full rapidity range between the maximum possible rapidity and the rapidity at which the $WW$ fusion interaction takes place. The spectator quark jet with $p_t \sim m_W$ will be color connected to some component of this remnant Fock state and will produce additional radiation and hadronization at large rapidity characterized by an energy and/or mass scale of order $m_W$. Combining the beam and target system hadronizations will yield a final state that strongly resembles the standard minimum-bias component of a typical soft hadronic interaction plus additional hadronization at large rapidity coming from the spectator quarks. Effects of color communication (gluon exchange) between the beam and target jet systems are not likely to significantly alter this multiplicity picture.

What do the Monte Carlo programs do? The Monte Carlo program with color structure and radiation most closely matched to QCD expectations is HERWIG (Ref. 11). However, the $W$ processes of interest to us have not yet been implemented there.[12] As a result, the Monte Carlo program that we have actually used for our numerical work is PYTHIA (Ref. 13). In it the final-state radiation for the $WW$ fusion process derives from a number of sources.[14] First, every event is accompanied by minimum-bias-type radiation associated with the beam and target remnants. Second, the two spectator quarks are allowed to radiate without regard to their matching color partners, the virtuality of the radiation source being determined by the scale of the hard $WW$ fusion subprocess, that is by the Higgs-boson mass. We have argued above that this is not the correct scale to employ; it will lead to an overestimate of the amount of radiation emanating from the spectator quark jets. However, most of the hadrons produced by this radiation are at large rapidity and will fall outside the detector that we shall consider in later sections. In any case, employing the scale $m_W$ for the quark spectator radiation could only increase the difference between background and signal multiplicities that we shall find in our Monte Carlo work.

Let is now turn to a discussion of theory and Monte Carlo implementation of the background processes. First, we remind the reader that the Monte Carlo programs actually generate the $W+$jets events of interest by first generating a $W+j$, $2\rightarrow 2$ event, and then producing any further jets as part of the radiation process itself. This is done in leading-pole approximation, and thus neglects interference between subprocess *diagrams.* Indications are[15] that, after the first-level cuts on rapidity and mass of the jets system, this results in a factor of 2 or 3 error in the cross section. Our concern, however, is the multiplicity, for which we would hope not to make so large an error. Since the $qg\rightarrow qgW$ partonic subprocess is the largest, it is useful to keep it in mind as we proceed. The Monte Carlo programs can generate such a $W+$jets event in several ways. For instance, the underlying subprocess might be $qg\rightarrow Wq$ followed by a hard radiation of the final $q$ to $qg$. Note that even when the latter two jets are produced with an invariant mass of the order of $m_W$, they are never in a color singlet, and the radiation of the two-jet system cannot be considered in isolation.

A typical example of the color structure of a background event is that obtained for the $qg\rightarrow Wq$ example. Such an event is pictured in Fig. 2. As in the case of the signal there are several components to the final-state hadronization. First, consider that arising from the high-$p_t$ quark jet. This quark must be paired with an antitriplet, that is part of the beam or target remnants, in order to make a primordial color-singlet linked pair. Since the quark has $p_t$ of order the Higgs-boson mass, the typical invariant mass of the color-singlet linked-pair system will be much larger than $m_W$. The amount of radiation associated with the jet will on the average be correspondingly larger than that associated with real $W$ decay. Only for those relatively rare cases where the outgoing $q$ jet radiates a secondary $q'\bar{q}'$ pair, such that the secondary $q'$ is very soft and the remaining fast-moving $q\bar{q}'$ pair is in a color-singlet state, can one expect limited multiplicity for the background event. The next final-state hadronization

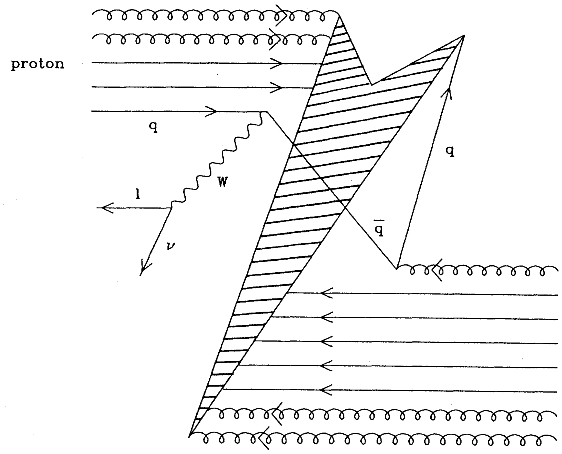


FIG. 2. Same as Fig. 1 for the $qg \to qW$ background reaction, where the final $q$ is that explicitly labeled in the figure. The color structure requires a complicated communication between beam and target remnants and the quark jet (with transverse momentum of order $m_H/2$), resulting in a minimum-bias multiplicity component plus a large amount of hadronization associated with the radiation from the colored quark jet.

component to consider is that arising from the complicated Fock states of the incoming hadrons. Even though these must have some color communication due to the nature of the subprocess being considered (unlike in the signal reaction), the dominant effect of these remnants will be to create a minimum-bias hadronization component that is quite similar to that in the signal reaction. The final component to hadronization for this reaction is that arising from initial-state radiation from the quark and gluon initiating the $qg \to Wq$ subprocess. Such radiation typically yields a small addition to the wings of the final quark jet multiplicity pattern. Overall, we see that the major difference between the hadronization for the background reaction and that for the signal reaction is at small rapidity where the high-$p_t$ quark jet in the background is expected to yield large multiplicity as compared to the limited multiplicity coming from the decaying $W$ of the signal. The other background subprocesses listed in Eq. (1.4) will yield similar results whenever the jet pair that mimics the $W$ is not in a color singlet. While it is impossible for the jet pair to be in a color singlet in the $qg \to qgW$ reaction just discussed, it is not impossible in some of the other cases. However, these other subprocesses are much less important, and in addition, production of a jet pair in a color singlet is a rather rare occurrence being suppressed by a factor of at least $1/N_c$.

As in our discussion of the signal reaction, we must consider the influence of strong-interaction corrections to these subprocess-level considerations. Regarding higher-order corrections, it has been argued[16] that the leading effects for soft radiation corrections to high-$p_t$ jet radiation can be included by requiring that radiation take place in such a way that at every branching the secondary jets have smaller angles with respect to their source jets than the opening angle characterizing the preceding branching. This effect should also be included when considering the two jets from a real color singlet $W$; however, the angular ordering prescription is such that the two jets from the $W$ will still radiate uninfluenced by their surroundings. The first level at which corrections to this procedure develop is when one includes the nonsoft (strictly speaking, non-strongly-ordered) corrections contained in the next-to-leading corrections.

Let us now consider the procedure employed in PYTHIA. There, the final quark in the underlying example subprocess of $gq \to Wq$, is allowed to radiate independently of the beam and target fragments. The amount of radiation is controlled by the hard subprocess scale, which is set by the transverse momentum of the final $q$ or $W$; the latter, in turn, is of order the Higgs-boson mass for the cuts that we shall impose. The virtuality scale set in this way is rather similar to that which would be obtained using any given detailed color structuring, differences being of the same order as higher-order-correction uncertainties in determining the appropriate scale. After the first $g$ is radiated from the final quark, subsequent radiations are performed in PYTHIA using the angular-ordering procedure. PYTHIA also incorporates a minimum-bias component to the hadronization associated with the subprocess and a form of initial-state radiation. Perhaps the most delicate aspect of a Monte Carlo program such as PYTHIA concerns the relatively rare events, mentioned earlier, in which the primary jet emits secondary jets, one of which is slow and has the correct color such that the remaining fast-moving jets are in a color singlet. It is clearly important that the Monte Carlo generate such configurations with correct probability. A detailed comparison of the results from PYTHIA (which as described above uses a leading-log QCD approach for generating secondary jets) and exact analytic calculations would be required to check this point, but is beyond the scope of this paper.

Overall, aside from the $WW$-fusion spectator-radiation-scale problem of PYTHIA, it would appear that this Monte Carlo program will give a faily good characterization of the radiation for a given event, accurate in leading order and with the most important next-to-leading corrections included. Thus, we now proceed to a quantitative analysis of the extent to which the Monte Carlo does indeed yield a substantially different hadronic multiplicity for the background processes as compared to the signal reaction with a real hadronically decaying $W$, once other kinematic cuts appropriate to isolating the Higgs-boson decays of interest have been made.

## III. MONTE CARLO ANALYSIS

In this section we present a detailed analysis of the predictions of PYTHIA 4.8 for the multiplicity of a Higgs $W$+jets decay final state, in comparison to the mixed EW-QCD $W$+jets background. We will analyze the two cases in a parallel fashion. We will later mention a similar analysis of the same channels involving $Z$'s. A more exhaustive study of hadronic decays of $W$'s and $Z$'s can be found in Ref. 17. We will set the stage by showing in Fig. 3 simulated Monte Carlo events of the two cases in a hypothetical SSC detector described in detail later. Charged tracks with $p_t > 0.5$ GeV and calorimeter cell with $E_t > 0.5$ GeV are shown. Figure 3(a) is a Higgs-boson event and Fig. 3(b) is a mixed EW-QCD event. In the first case, one of the $W$'s decays leptonically and the other hadronically, while in the second case, the real $W$ decays leptonically. It is obvious that the mixed EW-QCD event Fig. 3(b) has much larger charged multiplicity. One should also note that the high-$p_t$ $W$ jet of Fig. 3(a) is collimated much more tightly than the QCD jet of Fig. 3(b), which resembles a broad fan. We shall here focus exclusively on the case of $m_H = 1$ TeV. For a moderate $m_t = 60$ GeV choice for the top-quark mass, the production of a SM Higgs boson of this mass is dominated by $WW$ fusion processes. The Higgs-boson events were Monte Carlo–generated subject to the criteria $850 < M_{WW} < 1350$ GeV, and the background was generated as $W$+jet events with $850 \text{ GeV} < M_{W\,\text{jet}} < 1350$ GeV. Of course, ideally one should impose these criteria after reconstruction; for this first analysis, however, we have simply imposed them at the event-generation level. In addition, we assume for the entire analysis a perfect detector with coverage in rapidity between $-2.5 \le Y \le 2.5$ for tracking, calorimeter, and muon detectors. For the calorimeter, a conservative resolution of $\sigma_E/E = 0.15/\sqrt{E}$ for the electromagnetic part and $\sigma_E/E = 0.50/\sqrt{E}$ for the hadronic part is assumed ($E$ in GeV), with cells of size $\Delta\eta = 0.05$ and $\Delta\phi = 0.063$ ($\eta$ and $\phi$ being pseudorapidity and azimuthal angle, respectively). The tracking chamber was assumed to be of the kind proposed in Ref. 9 which allows the determination of the charged multiplicity with high reliability down to momenta of the order of 0.5 GeV or less. We will quote event rates for a standard SSC operating year with integrated luminosity of $10^4$ pb$^{-1}$, but the reader should keep in mind that the multiplicity results will hold at any luminosity. In the case of the signal reaction we scaled our results to a production cross section of $\sigma(H \to W^+W^-) = 0.45$ pb. Such scaling is necessary since PYTHIA does not contain the full gauge-invariant amplitude[18] for $WW \to WW$, and thus puts more cross section in the high $M_{WW}$ tail, that we cut away, than the full amplitude would predict. However, differences in the shape of the $M_{WW}$ spectrum in the 850–1350-GeV band that we retain are small. Scaling of our background results is also necessary since, as in most of these studies, the statistics on the background sample is about a factor 25 smaller than the rates expected for one SSC year.

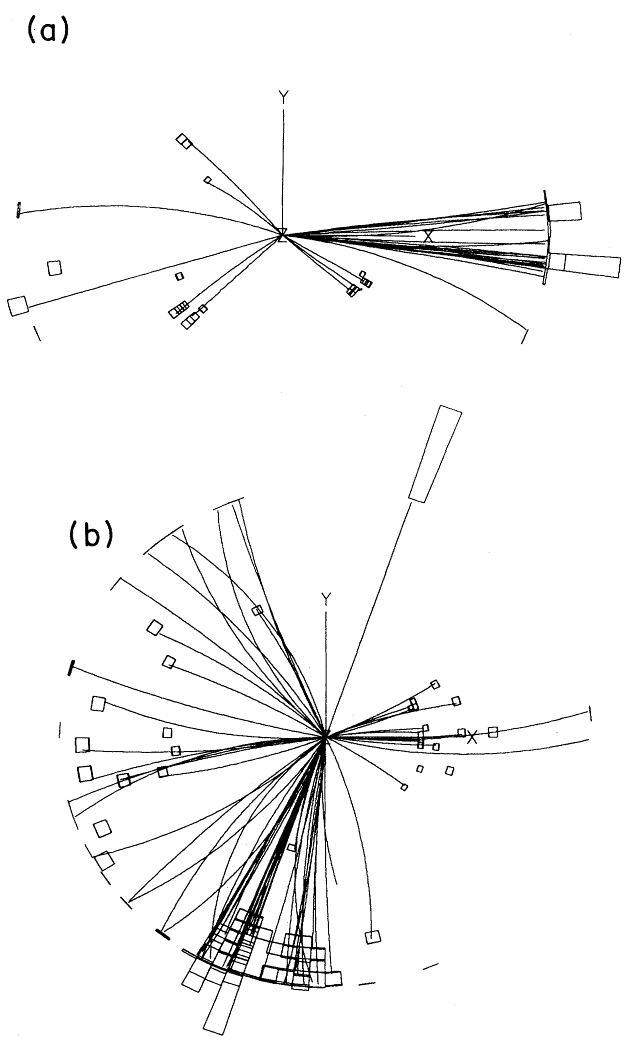


FIG. 3. Event display which shows charged tracks with $p_t \ge 0.5$ GeV and calorimeter cells with $E_t > 0.5$ GeV in $|Y| < 2.5$ together with the isolated lepton from the $W$ decay. (a) Higgs boson$\to W^+W^+$ event with $M_{WW} = 1230$ GeV, $N_{\text{ch}} = 33$, and $m_j = 73$ GeV. (b) Mixed EW-QCD event with invariant mass $M_{W\,\text{jet}} = 1280$ GeV, $N_{\text{ch}} = 73$, and $m_j = 82$ GeV.

The initial event sample obtained contains 1000 events of the type

$$H \to W^{\pm}(\to l^{\pm}\nu) + W^{\mp}(\to \text{jets}) \tag{3.1}$$

and 100 000 events from the

$$W^{\pm}(\to l^{\pm}\nu) + \text{jets} \tag{3.2}$$

background processes. Here $l$ stands for both muons and electrons because we assume a detector which will allow tracking of both electrons and muons, and we made a $p_t$ cut on the leptons from the $W$ decay of $p_t > 20$ GeV. We next subject these events to a jet-finding algorithm, using the ISAJET 5.38 GETJET subroutine. The basic idea of the analysis is to reconstruct the hadronically decayed $W$ as one jet in a relatively limited solid-angle cone of the calorimeter. This is motivated by the observation that high-momentum $W$'s are more highly collimated than QCD jets of the same mass and that restricting the extent of the jet will suppress the QCD background. Our parameter selection for GETJET reflects this approach: we choose (i) $(E_c)_{\text{cut}} = 0.5$ GeV, (ii) $(E_J)_{\text{cut}} = 100$ GeV, and (iii) $\Delta R = 0.5$ where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Before any analysis is done, any cell with total energy below $(E_c)_{\text{cut}}$ is discarded. The parameter $(E_J)_{\text{cut}}$ is the minimum transverse energy $E_t$ of a jet with a cone of size $\Delta R$ around the cell with the largest $E_t$.

The number of jets obtained are 1365 for the Higgs-boson decays and 186 000 for the background process (3.2). The distribution of masses $m_j$ of these jets is shown in Fig. 4 for masses above 40 GeV. In the window from $70 < m_j < 90$ GeV there are 580 signal jets (solid line) and 6700 background jets (dotted line), implying $S/B = 1/11.5$ and a $7\sigma$ effect. This is already a remarkable result, given that the $S/B$ ratio is $\lesssim 0.01$ if one simply looks for two jets at the parton level with mass between 70 and 90 GeV. As alluded to above, the procedure of looking at the $W$ as a single well-collimated jet inside a cone of appropriately chosen size $\Delta R$ eliminates a large fraction of the background. In particular, much of the background in which two parton jets combine to have invariant mass in the vicinity of $m_W$ arises when the jets have rather unequal energies but are widely enough separated in angle to have a large invariant mass. In contrast, the longitudinally polarized $W$ from the Higgs boson tends to decay to two jets of fairly equal energy with narrow angular separation. Thus this GETJET procedure is closely related to the procedure of Ref. 4 where events in which one of the jets forming the fake $W$ is much softer than the other are discarded.

Although the above result is already very significant, in a convincing analysis one would ask for better signal/background discrimination. To this end, we look at the charged-event multiplicity as a way to distinguish between $W+W$ and $W+$QCD jets events. (The total multiplicity would be a better parameter, but we believe it will be difficult to determine the neutral multiplicity.) We define the charged multiplicity $n_{ch}$ in the context of a precision tracking device covering $\pm 2.5$ units of rapidity and having the capability to track charged particles with a transverse momentum $p_t$ greater than a cutoff value which is of the order $p_t = 0.5$ GeV. In Fig. 5 we show the charged event multiplicity $n_{ch}$ for the process (3.1) [Fig. 5(a)] and for reaction (3.2) [Fig. 5(b)], respectively, including only tracks with $|Y| < 2.5$ and $p_t > 0.5$ GeV. The two distributions are very different, as predicted in Sec. II, having mean values of $\bar{n}_{ch} = 32$ and 76, respectively. With a cut at $n_{ch} < 40$, 78% of the signal is retained and 93% of the background is eliminated. This cut results in Fig. 4(b), which shows in the $W$ mass region (70 GeV $< m_j <$ 90 GeV) the improved signal/background ratio $456/490 = 0.93$.

We want to emphasize that the multiplicity cut is essentially independent of other cuts on kinematic variables, including cuts that favor longitudinally polarized $W$'s and as such is truly complementary to many previous Monte Carlo analyses of the heavy-Higgs-boson problem. In fact, using the multiplicity to discriminate against the non-$W$ background enables us to have an unbiased sample of reconstructed $W$'s with which to measure the $W$ polarization (see below). Of course, as described earlier, the $\Delta R$ procedure favors longitudinally polarized real $W$ decays over backgrounds, but the cut is much milder and the bias introduced is much less than that for the cut procedure followed in Ref. 4. Indeed, the multiplicity analysis allows very efficient cuts, which leaves us with an order of magnitude more signal events than in previous heavy-Higgs-boson analyses.

A similar analysis, again described in detail elsewhere,[17,19] aims at measuring the $W$ polarization due to the scalar nature of the Higgs boson. Again, the $W$ jet is being reconstructed in a limited cone in the calorimeter [$\Delta R = 1$ and $(E_J)_{cut} = 100$ GeV], but then the additional requirement is imposed that two jets subject to a smaller $E_t$ cutoff can be found inside the large jet with matching invariant mass. We find, not surprisingly, that, in this case too, a similar multiplicity cut improves the signal/background ratio by a factor 10 to about 3 with about 200 signal events left.

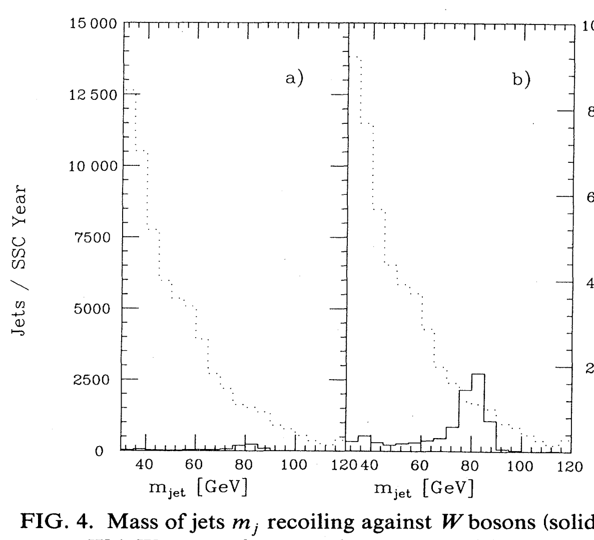


FIG. 4. Mass of jets $m_j$ recoiling against $W$ bosons (solid histogram: $W+W$ events from a Higgs boson with 1-TeV mass, dotted histogram: $W+$QCD jets events with 1 TeV mass, both normalized to one SSC year), (a) all events, (b) events with $n_{ch} < 40$.

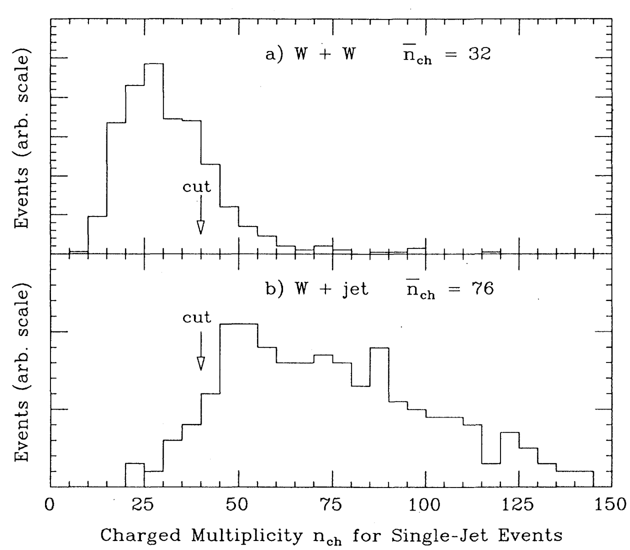


FIG. 5. Charged multiplicity $n_{ch}$ in events containing leptonically decaying $W$ bosons in $pp$ collisions (PYTHIA 4.8): (a) $W+W$ events from the decay of a Higgs boson with 1-TeV mass and (b) $W+$QCD jets events with 1-TeV mass.

One could ask to what extent our requirement is justified that the tracker be able to reconstruct tracks down to $p_t = 0.5$ GeV. To check this, we have changed the lower cutoff on the track $p_t$ from 0.5 GeV to 1 GeV and 2 GeV, respectively. We then have applied the multiplicity cut to retain 80% of the signal. The signal/background ratio deteriorated by a factor of 0.8 and 0.7 when raising the $p_t$ cutoff from $p_t = 0.5$ GeV to $p_t = 1$ GeV and $p_t = 2$ GeV, respectively. Because the multiplicity cut discriminates against the soft component of the event, the lower the $p_t$ cutoff, the more effective will be the multiplicity cut.

In Ref. 17 an analysis of Higgs boson$\to ZZ$, similar to that we have performed here for Higgs boson$\to WW$, is presented where one $Z$ decays into electron or muon pairs and the other into hadrons. Again, an appropriate cut on the event multiplicity improves the signal-to-background ratio by about a factor 8, leaving about 90 signal events over 190 background events for a Higgs-boson mass of 800 GeV. This Higgs-boson channel has caught our attention for several different reasons (even though the rates are a factor of 5 to 6 smaller than the $WW$ channels discussed above). First, all the final particles are detected allowing unambiguous reconstruction of the Higgs-boson mass. Second, the polarization of the $Z$'s can be measured both in the lepton-pair and the two-jet channel. While for many events this is also true for the $W \to l\nu$ decays, the $Z \to l^+ l^-$ decays have the advantage that the lepton channel will yield resolution that is superior to that of the hadron channel. Third, the nonresonant background under the Higgs boson is smaller when compared to the resonance in the $ZZ$ channel than was the case in the $WW$ channel. Fourth, the $ZZ$ channel allows an independent confirmation of the signal in the $WW$ channel for Higgs-boson masses between $m_H = 600$ GeV and $m_H = 900$ GeV. Finally, and perhaps most important, if $m_t > m_W$ an additional source of background for $H \to W^+ W^-$ arises from $gg \to t\bar{t}$ followed by $t \to bW^+$ and $\bar{t} \to \bar{b}W^-$. The large magnitude of this background will make detection of $H \to W^+ W^-$ or study of $W^+ W^-$ scattering substantially more difficult. The $ZZ$ channel, in contrast, is not affected.

Of course, a large top-quark mass also increases the cross section for heavy-Higgs-boson production via the reaction $gg \to H$. For $m_t > 150$ GeV the gluon-fusion reaction is larger than $WW$ fusion all the way out to $m_H = 1$ TeV (Ref. 20). However, because of the colored nature of the fusing gluons, it is possible that the multiplicity cut will be less efficient in retaining this source of signal events. Nonetheless, the additional Higgs-boson cross section could only help the $ZZ$ channel signal.

Finally, we want to emphasize three points. First, even though there is an uncertainty in the absolute values of the mean multiplicities of the Higgs-boson production events and the mixed EW-QCD events (as discussed earlier), our analysis is valid as long as the true multiplicity distributions differ from the ones in the Monte Carlo generators only by a multiplicative factor or an additive constant. Second, it is important to note that this analysis assumed no event overlap; superimposing minimum-bias events on top of the high-$p_t$ events of interest could cause a deterioration of the effectiveness of our cuts. Third, it should be noted that the multiplicity cuts become increasingly efficient as the $W$+jets mass of interest becomes larger. This is because the hadronic multiplicity of the $WW$ signal reaction is to first approximation independent of the $W$+jets mass, whereas the $W$+jets background multiplicity increases as the $W$+jets mass increases. Correspondingly, of course, at low Higgs-boson mass, where the appropriate $W$+jets system mass is no longer much greater than $2m_W$, the multiplicity and $\Delta R$ "single-jet" cuts become relatively ineffective.

## IV. CONCLUSIONS AND DISCUSSION

We have shown that the color-linkage structure of the PYTHIA Monte Carlo program that we have employed for this study can be expected to yield relatively reliable predictions for the hadronic multiplicity associated with a $W$+jets final state, whether produced by Higgs-boson decay or by mixed EW-QCD processes. We then employed PYTHIA to explore quantitatively the differences between the Higgs-boson decay signal and the background events. In this Monte Carlo analysis, we reconstructed the jets from the $W$ in a limited solid-angle cone in the calorimeter, i.e., as one jet with $E_t > 100$ GeV and $\Delta R = 0.5$. The events containing QCD jets with masses close to the $W$ mass have distinctly different charged event multiplicities than the $WW$ events, allowing a background reduction by a factor of 12 and a signal-to-background improvement of a factor 10. We previewed a similar analysis of the $ZZ$ decay of the Higgs boson, where one $Z$ decays leptonically and the other $Z$ hadronically, and outlined the experimental advantages of this channel.

Overall, we show that the ability to measure the charged hadronic multiplicity associated with $W$+jets final states will provide an important additional tool for isolating production of real $W$'s from backgrounds. We have examined only the simplest use of such measurements. More generally, it is not inappropriate to speculate that hadronic multiplicity distributions can provide an important discriminator between signal and background for many new physics processes. The principle criteria that must be met are that the signal reaction must produce jets in a color-singlet state of well-defined mass; this mass must be much smaller than the transverse momentum required for these jets in the analysis; and the background processes must produce jets primarily in color-nonsinglet states.

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