Detecting an Invisibly Decaying Higgs Boson at a Hadron Supercollider

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We demonstrate that an invisibly decaying Higgs boson with standard model coupling strength to $t\bar{t}$ can be detected at the CERN Large Hadron Collider for masses $\lesssim 250$ GeV.

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Perhaps the most fundamental mission of future high energy hadron supercolliders such as the CERN Large Hadron Collider (LHC) is the detection of Higgs boson(s). While many production/decay modes have been studied in the past, an invisibly decaying Higgs boson (h) has not been thoroughly studied. Dominance of the decays of a Higgs boson by invisible channels is possible, in particular, in supersymmetric models. If R parity is conserved, decays to $\tilde{\chi}_1^0\tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ is the lightest supersymmetric particle, can be dominant [1]. Indeed, in the minimal supersymmetric model $\tilde{\chi}_1^0\tilde{\chi}_1^0$ dominance is possible for both the lightest CP-even Higgs boson and the CP-odd Higgs boson. In supersymmetric models with spontaneously broken R parity, the dominant decay mode of the lightest scalar Higgs boson is predicted to be $h \to JJ$, where J is the (massless) Majoron [2]. J interacts too weakly to be observed in the detector. In such models, the decays of the second lightest scalar Higgs boson can also be predominantly invisible, the two most important modes being JJ and $hh(\to JJJJ)$ [3].

Two possible detection modes for an invisibly decaying Higgs boson can be envisioned at a hadron collider. Associated Zh production was considered in Ref. [4], with the rough conclusion that a viable signal for $h \to I$ (I being any invisible channel) can be detected for $m_h \lesssim 150$ GeV provided the hZZ coupling is standard model (SM) strength and $B(h \to I) \sim 1$. In this Letter, we consider associated production of top quark plus top antiquark plus Higgs boson. We find that if the top quark is not too light ($m_t \gtrsim 130$ GeV) and if $B(h \to I) \sim 1$, then a viable signal for $h \to I$ can be extracted for $m_h \lesssim 250$ GeV when the $ht\bar{t}$ coupling is of SM strength. Clearly, the Zh and $t\bar{t}h$ modes are complementary in the sense that they rely on the vector boson vs fermion couplings, respectively, of the Higgs boson. For a CP-even Higgs boson, which has both types of coupling, both modes tend to be viable, but for a CP-odd Higgs boson the ZZ coupling is absent at tree level and only the $t\bar{t}h$ mode studied here could lead to a visible signal.

Our procedure is quite simple. We trigger on $t\bar{t}h$ events by requiring that one of the t's decay to a lepton (e or μ) with $p_T > 20$ GeV and $|\eta| < 2.5$, which is isolated from other jets and leptons by $\Delta R = 0.3$. In order to single out events containing a $t\bar{t}$ pair, we also demand that at least one of the b quarks be vertex tagged. The efficiency and purity of b tagging was studied by the Solenoidal Detector Collaboration (SDC) [5]. Based on this study, we assume that any b jet with $|\eta| < 2$ and $p_T > 30$ GeV will have a 30% probability (independent of p_T) of being vertex tagged, provided there is no other vertex within $\Delta R_V = 0.5$. (It may turn out that 30% is too conservative a number; the SDC TDR (Technical Design Report) b-tagging efficiency can be increased by looking for the lepton associated with a semileptonic b decay.) Misidentification backgrounds are not significant so long as the probability to tag (i.e., misidentify) a light quark or gluon jet as a b jet under these same conditions is of order 1%, and the corresponding number for c-quark jets is of order 5%. Jets with p_T below 30 GeV are assumed not to be tagged.

To further single out the $t\bar{t}$ events of interest, we demand that there be three or more jets with $p_T > 30$ GeV and $|\eta| < 2.5$ that are isolated from all other jets by at least $\Delta R = 0.7$ [6]. (One of these jets is allowed to be the tagged b jet.) The invariant mass of each pair of jets, M_{jj}, is computed and at least one pair *not containing the tagged b quark* is required to have $m_W - \Delta m_W/2 \le M_{jj} \le m_W + \Delta m_W/2$. In addition, we combine any pair of jets satisfying this criterion with the tagged b jet(s) and compute the three-jet invariant mass, M_{bjj}. We demand that $m_t - \Delta m_t/2 \le M_{bjj} \le m_t + \Delta m_t/2$ for at least one bjj combination. Together, these two cuts greatly reduce the likelihood that the second top in a $t\bar{t}$ event can decay leptonically and satisfy all our criteria. The results to be presented employ values of $\Delta m_W = 15$ GeV and $\Delta m_t = 25$ GeV. Only a small fraction of signal events are eliminated by such mass cuts for typical jet and lepton energy resolutions [7], whereas the reducible backgrounds are significantly decreased.

Finally, to reveal the invisibly decaying Higgs boson, we determine the missing transverse momentum, $\mathbf{p}_T^{\rm miss}$, for the event and compute $M_{{\rm miss}\text{-}l}$, the transverse mass obtained by combining the transverse components of the missing momentum and the lepton momentum, $M^2_{{\rm miss}\text{-}l} \equiv (E_T^{\rm miss} + E_T^l)^2 - (\mathbf{p}_T^{\rm miss} + \mathbf{p}_T^l)^2$. The transverse missing momentum is computed by taking the incoming beam momenta and subtracting from their sum the momenta of all observable final state partons. (Any jet falling outside $|\eta| = 5$ is deemed unobservable.) In addition, a probabilistically fluctuating missing momentum from the underlying minimum bias event structure is included. And, as already noted, jet energy and momenta are smeared. The

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$t\bar{t}h$ events of interest are characterized by very broad distributions in $M_{\text{miss-}l}$ and E_T^{miss}. Cuts on both variables will be made.

There are several sources of background. The most obvious is the irreducible background from $t\bar{t}Z$ events in which $Z \to \nu\bar{\nu}$. This background will be denoted by $t\bar{t}Z$; its E_T^{miss} and $M_{\text{miss-}l}$ distributions are very much like those of the signal. The important reducible backgrounds all derive from various tails related to $t\bar{t}$ or $t\bar{t}g$ events. We shall artificially separate the $t\bar{t}(g)$ backgrounds into two components. The first, and most important, component is that where both top quarks decay leptonically, in which case only $t\bar{t}g$ events can possibly satisfy the cuts outlined earlier. We shall refer to this background as the $t\bar{t}g(\to l\nu l\nu)$ background. The $t\bar{t}h$ signal, irreducible $t\bar{t}Z$ background, and $t\bar{t}g(\to l\nu l\nu)$ background have in common the feature that their $M_{\text{miss-}l}$ and E_T^{miss} spectra are essentially independent of whether or not the b quarks from the t's decay semileptonically or purely hadronically. In the second component, only one t decays semileptonically. However, the $t\bar{t}(g)$ rate is so large that a not so insignificant number of events could survive our cuts simply due to the fact that there is at least one neutrino from the leptonically decaying W providing the trigger lepton, and perhaps additional neutrinos from B quarks that decay semileptonically. The background from $t\bar{t}$ plus $t\bar{t}g$ events, in which only one W coming from the t quarks decays leptonically, will be denoted by $t\bar{t}g(b\to l\nu)$.

The strategies required to control the $t\bar{t}g(\to l\nu l\nu)$ and $t\bar{t}g(b\to l\nu)$ backgrounds are more or less "orthogonal." The $t\bar{t}g(\to l\nu l\nu)$ background is easily reduced to a level below that of the $t\bar{t}Z$ background by a cut on E_T^{miss}. Once such a cut is made, however, the $t\bar{t}g(\to l\nu l\nu)$ background has a very long $M_{\text{miss-}l}$ tail and is not significantly reduced by cuts on this latter variable. Thus, the optimal E_T^{miss} cut is essentially determined by the $t\bar{t}g(\to l\nu l\nu)$ background. In the case of the $t\bar{t}g(b\to l\nu)$ background, if the only neutrino present is that from the single leptonically decaying W, then there is a very sharp Jacobian peak in $M_{\text{miss-}l}$ near the W mass. After including the off-shell W tail, this background still only populates $M_{\text{miss-}l}$ values below about 100 GeV. this fact provides the main motivation for employing a cut on $M_{\text{miss-}l}$. Of course, semileptonic b decays lead to a tail to the W-decay Jacobian peak in the $M_{\text{miss-}l}$ spectrum. This tail can be significant for $t\bar{t}g$ events (but is quite small for events in which there is no extra radiated gluon), and forces us to a somewhat higher cut on $M_{\text{miss-}l}$. However, it is easy to find an $M_{\text{miss-}l}$ cut which reduces the $t\bar{t}g(b\to l\nu)$ background to a negligible level while retaining much of the $t\bar{t}h$ signal (and $t\bar{t}Z$ background).

Thus, it is straightforward to find cuts on E_T^{miss} and $M_{\text{miss-}l}$ that are adequate for uncovering the invisibly decaying Higgs boson. Nonetheless, it may be useful to note that the $t\bar{t}g(\to l\nu l\nu)$ background could be suppressed further by demanding that all events contain only one identified *isolated* lepton. Although τ's will be difficult to identify, μ's can always be identified, and e's are easily identified so long as they are not too soft and are isolated. Reduction of the $t\bar{t}g(\to l\nu l\nu)$ background by a factor of order $\frac{1}{3}$ to $\frac{1}{2}$ could probably be achieved, with essentially no impact on the $t\bar{t}h$ signal (or $t\bar{t}Z$ background). Note that it is probably not advantageous to veto against nonisolated leptons (which can probably be done only for μ's in any case). Although such a veto would tend to suppress the already small $t\bar{t}g(b\to l\nu)$ background somewhat, it would also suppress the signal rate. The results in this paper do not make use of any type of second-lepton veto.

Our computations will not include $t\bar{t}jj$ backgrounds ($j=g$ or q). Such backgrounds are higher order in α_s and our normalization procedure (described later) is such that the $t\bar{t}+t\bar{t}g$ subprocesses should provide a good leading order estimate of the backgrounds from $t\bar{t}$ events including radiated jet(s). No new physical effects are introduced (for our cut procedures) by going beyond one extra jet.

We also will not explicitly compute $t\bar{t}W$ or $t\bar{b}W$ backgrounds. When the extra W decays leptonically, such processes will yield broad $M_{\text{miss-}l}$ and E_T^{miss} spectra. But these processes are higher order in the weak coupling constant than the leading order $t\bar{t}g(\to l\nu l\nu)$ background discussed earlier. The $t\bar{t}Z$ background can be significant since the Z can decay to automatically invisible $\nu\bar{\nu}$ final states, whereas $t\bar{t}W$ events are only a background if the explicit W decays via $W\to l\nu$ and the ν carries most of the W momentum. In addition, the rate for $t\bar{t}W$ events is proportional to $q'\bar{q}$ luminosities, which are much smaller at the LHC than the gg luminosity responsible for $t\bar{t}Z$ production. The $t\bar{b}W$ process can be thought of in part as $t\bar{t}$ production in which an off-shell t "decays" to bW. Clearly, this will be substantially suppressed compared to the on-shell decay backgrounds that we examine. In addition, the M_{bjj} cut is even more effective in eliminating this background than in the case of the $t\bar{t}g(\to l\nu l\nu)$ and $t\bar{t}g(b\to l\nu)$ on-shell decay backgrounds.

A host of other backgrounds have been thought about and dismissed. For example, $WWgg$ events are suppressed by being electroweak in origin, by the need to mistag one of the g's as a b, and by a cut on $M_{\text{miss-}l}$ (note that only one W can decay leptonically if we are to get at least three jets and if two nontagged jets are to have mass near m_W).

We have employed exact matrix element calculations for all the subprocesses. All the production reactions we consider are dominated by gg collisions. We have employed distribution functions for the gluons evaluated at a momentum transfer scale given by the subprocess energy. It is well known that QCD corrections are substantial for gg initiated processes. For example, for the $gg\to t\bar{t}$ process the QCD correction K factor has been found to be of the order of 1.6 for our choice of scale [8]. Computations of the K factors for the other reactions we consider are not yet available in the literature. We will assume that they are of the same magnitude. Our precise procedures follow. Rates for the $t\bar{t}h$ and $t\bar{t}Z$ processes have been multiplied by a QCD correction factor of 1.6. In the case of $t\bar{t}(g)$ we have incorporated the K factor as follows. We have generated events without an extra gluon ($t\bar{t}$ events) and have also generated events with an extra gluon ($t\bar{t}g$ events) requiring that the p_T of the extra gluon be >30 GeV. For this cutoff one finds $\sigma(t\bar{t}g) \sim 0.6\sigma(t\bar{t})$. Thus, if the two event rates are added together without cuts an effective K factor of 1.6 is generated. As already described, explicitly allowing for an appropriate number of $t\bar{t}g$ events is important in properly estimating the backgrounds to our $M_{\text{miss-}l}$ distribution. Our procedure should yield an upper limit on the number of events with an extra gluon having $p_T > 30$ GeV and therefore potentially providing a background source due to extra radiated jets in association with $t\bar{t}$ production. The gluon distribution functions we have employed are the D0′ distributions of Ref. [9].

In this Letter, we focus on results for the LHC. Some preliminary discussion is useful. First, we note that a plot of the $M_{\text{miss-}l}$ event rate spectrum for the $t\bar{t}h$ signal as compared to that for the sum of the $t\bar{t}Z$, $t\bar{t}g(\to l\nu l\nu)$, and $t\bar{t}g(b\to l\nu)$ backgrounds shows great similarity in shape for the signal and background once $M_{\text{miss-}l}$ is large enough that the $t\bar{t}g(b\to l\nu)$ background is small. For $M_{\text{miss-}l} \gtrsim 150$ GeV, signal and background both fall very slowly as $M_{\text{miss-}l}$ increases. This similarity implies the need for an accurate determination of the expected background level. The importance of a cut on M_{bjj} is illustrated in Fig. 1. There, we compare the M_{bjj} distribution shapes for the $m_h = 100$ GeV signal (the $t\bar{t}Z$ background would yield a similar M_{bjj} plot) and the (primary reducible) $t\bar{t}g(\to l\nu l\nu)$ background at $m_t = 140$ GeV; in the figure we have required $E_T^{\text{miss}} > 200$ GeV and $M_{\text{miss-}l} > 250$ GeV. The $t\bar{t}h$ signal exhibits a strong peak near m_t, whereas the bulk of the $t\bar{t}g(\to l\nu l\nu)$ background populates much higher M_{bjj} values.

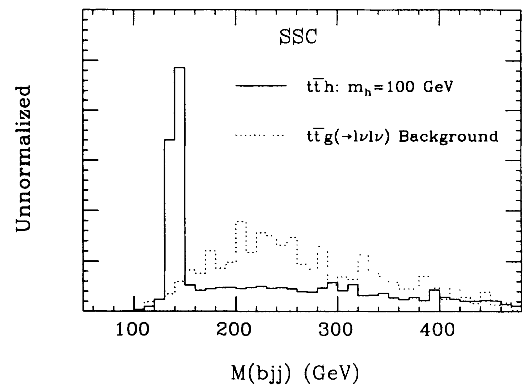

FIG. 1. Distribution shape in M_{bjj} for the $m_h = 100$ GeV signal (solid) compared to that for the $t\bar{t}g(\to l\nu l\nu)$ background (dashed), at $m_t = 140$ GeV. We have taken $\Delta m_W = 15$ GeV, and required $E_T^{\text{miss}} > 200$ GeV and $M_{\text{miss-}l} > 250$ GeV.

In order to quantify the observability of the Higgs boson signals, we have estimated the number of LHC years required for a $N_{\text{SD}} = 5$ sigma significance of the signal compared to background for $B(h\to I) = 1$. The statistical significance N_{SD} is computed as $S/\sqrt{B}$. For any given integrated luminosity, S is the total $t\bar{t}h$ event rate and B the total $t\bar{t}Z + t\bar{t}g(\to l\nu l\nu) + t\bar{t}g(b\to l\nu)$ event rate, with $E_T^{\text{miss}} > 200$ GeV and $M_{\text{miss-}l} > 150$ GeV (and all other cuts) imposed. The required number of years as a function of m_h for various m_t values appears in Table I. Also given (in parentheses) is the associated number of signal events (S). The associated number of background events (B) can be obtained from the relation $B = S^2/25$.

From the table, it is immediately apparent that detection of an invisibly decaying Higgs boson should be possible within 1 to 2 LHC years for $m_t \gtrsim 130$ GeV and $m_h \lesssim 200$–250 GeV if (as assumed in these calculations) its coupling to $t\bar{t}$ is of standard model strength. (The required number of years for non-SM coupling is obtained simply by dividing the results of Table I by the ratio of the $t\bar{t}$ coupling strength to the SM strength, raised to the fourth power.) For $m_h \gtrsim 300$ GeV, the $t\bar{t}h$ event rate drops to a lower level such that more than 2 LHC years are required. However, it is rather unlikely that invisible decays would be dominant for a Higgs boson with mass above 200 GeV or so.

The $M_{\text{miss-}l}$ and E_T^{miss} cuts chosen for Table I are probably near optimal. If the $M_{\text{miss-}l}$ cut is strengthened to $M_{\text{miss-}l} > 200$ GeV, the $t\bar{t}g(b\to l\nu)$ background becomes completely negligible, but the $t\bar{t}h$ (and $t\bar{t}Z$) event rates are cut by about 25% while the $t\bar{t}g(\to l\nu l\nu)$ background falls only slightly; as a result, the time required to achieve a 5 sigma effect typically increases by (15–25)%. As not-

TABLE I. Number of 100 fb^{-1} years (signal event rate) at LHC required for a 5σ confidence level signal, with cuts specified by (see text) $E_T^{\text{miss}} > 200$ GeV, $M_{\text{miss-}l} > 150$ GeV, $\Delta m_W = 15$ GeV, and $\Delta m_t = 25$ GeV. $B(h\to I) = 1$ is assumed.

m_t (GeV)	m_h (GeV) 60	100	140	200	300
110	1.3 (24)	2.0 (31)	2.8 (36)	5.2 (49)	15.8 (86)
140	0.2 (18)	0.4 (23)	0.6 (30)	1.5 (47)	4.3 (80)
180	0.2 (24)	0.3 (31)	0.5 (44)	1.6 (76)	5.2 (139)

ed earlier, weakening of the $E_T^{\rm miss}$ cut causes a significant increase in the $t\bar{t}g(\rightarrow l\nu l\nu)$ background relative to signal. Strengthening this latter cut to $E_T^{\rm miss} > 250$ GeV improves S/B, but at a sacrifice of signal, which makes h discovery statistically more difficult.

Of course, the $N_{\rm SD}$ values quoted assume that the normalization of the expected background will be well determined by the time the experiments are performed. This will require a good understanding of the missing energy tails as they actually appear in the detectors, calculation of the higher-order QCD corrections that we have only estimated, and accurate knowledge of the parton (especially gluon) distribution functions. With the availability of data from the DESY ep collider HERA, and through the analysis and study of $t\bar{t}$ events in the actual detectors, we believe that uncertainties in the relevant backgrounds can be brought down to the 20% level by the time adequate luminosity has been accumulated that an invisible Higgs boson signal would become apparent.

Remaining questions include the following. Will the efficiency of b tagging at the LHC, given the many overlapping events expected, be as great as assumed here based on the SDC detector study? Will the missing-energy tails from overlapping events be significant? Will it be possible to build sufficiently hermetic detectors given radiation damage issues, and so forth? Our results are sufficiently encouraging that the LHC detector collaborations should study carefully the impact of these issues upon this detection mode.

Our studies have been performed for an h that is a CP-even Higgs boson mass eigenstate. The $t\bar{t}h$ rates would be somewhat different as a function of m_h for a mixed CP or CP-odd eigenstate. However, we do not anticipate that the results for such cases would differ very much from those obtained here.

We have demonstrated that at the LHC a hermetic detector with the ability to tag b-quark jets should allow detection of an invisibly decaying Higgs boson with a $t\bar{t}h$ associated production rate comparable to that of a SM Higgs boson. Allowing for several years of running at canonical luminosity, such detection should be possible for $m_h \lesssim 200$–250 GeV.

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[1] See, for instance, K. Greist and H. E. Haber, Phys. Rev. D **37**, 719 (1988); A. Djouadi, J. Kalinowski, and P. M. Zerwas, Z. Phys. C **57**, 569 (1993); and J. L. Lopez, D. V. Nanopoulos, H. Pois, X. Wang, and Z. Zichichi, Phys. Rev. D **48**, 4062 (1993).

[2] J. C. Romao, F. de Campos, and J. W. F. Valle, Phys. Lett. B **292**, 329 (1992); A. Joshipura and S. Rindani, Phys. Rev. Lett. **69**, 3269 (1992); see also G. Jungman and M. Luty, Nucl. Phys. **B361**, 24 (1991), and B. Brahmachari *et al.*, Phys. Rev. D **48**, 4224 (1993).

[3] J. C. Romao, J. L. Diaz-Cruz, F. de Campos, and J. W. F. Valle, Report No. FTUV-92-39, 1992 (to be published).

[4] S. Frederiksen, N. Johnson, G. Kane, and J. Reid, SSCL Report No. 577, 1992 (unpublished).

[5] E. L. Berger *et al.*, Solenoidal Detector Collaboration Technical Design Report No. SDC-92-201, SSCL-SR-1215, 1992 (unpublished), p. 4.15–4.16.

[6] For b's that decay hadronically the jet momentum is taken to be that of the b quark; for b's that decay semileptonically, the jet momentum is computed by omitting the momentum carried by the neutrino.

[7] We employ $\delta E/E = 0.5/\sqrt{E\,({\rm GeV})} \oplus 0.03$ for jets and $\delta E/E = 0.2/\sqrt{E\,({\rm GeV})} \oplus 0.01$ for leptons. The very first step of our analysis is to smear the energies of all leptons and jets using these resolutions.

[8] P. Nason, S. Dawson, and R. K. Ellis, Nucl. Phys. **B303**, 607 (1988). See also W. Beenakker *et al.*, Phys. Rev. D **40**, 54 (1989).

[9] A. D. Martin, R. G. Roberts, and W. J. Stirling, Report No. RAL-92-078, 1992 (to be published).