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Prospects for observing an invisibly decaying Higgs boson in the $t\bar{t}H$ production at the LHC

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Abstract. The prospects for observing an invisibly decaying Higgs boson in the $t\bar{t}H$ production at LHC are discussed. An isolated lepton, reconstructed hadronic top-quark decay, two identified b-jets and a large missing transverse energy are proposed as the final state signature for event selection. Only the standard model backgrounds are taken into account. It is shown that the $t\bar{t}Z$, $t\bar{t}W$, $b\bar{b}Z$ and $b\bar{b}W$ backgrounds can individually be suppressed below the signal expectation. The dominant source of background remains the $t\bar{t}$ production. The key for the observability will be an experimental selection which allows further suppression to be achieved of the contributions from the $t\bar{t}$ events with one of the top quarks decaying into a tau lepton. Depending on the details of the final analysis, an excess of the signal events above the standard model background of about 10% to 100% can be achieved in the mass range $m_H = 100$–$200\,\mathrm{GeV}$.

1 Introduction

While several production and decay modes of the Higgs boson have already been studied in the past [1], the invisibly decaying Higgs boson has not yet been exhaustively discussed in the search scenarios of the LHC experiments. There are however many different and reasonable theoretical ideas which implicate an invisibly decaying Higgs boson. These motivations include models with light neutralinos, spontaneously broken lepton number, radiatively generated neutrino masses, additional single scalar(s), or right handed neutrinos in the extra dimensions. For a nice recent overview, see e.g. [2].

Some theoretical studies have already some time ago addressed the question of how to look for the evidence of an invisible Higgs decay. In [3] the use of the WH/ZH production mode was suggested and roughly evaluated. This analysis have been recently revised in [4]. The observation of the invisibly decaying Higgs boson in the associated $t\bar{t}H$ production has been proposed in [5]. Prospects for the observability of this decay mode in vector boson fusion production has been proposed and evaluated in [6]. The aforementioned options have recently been revisited in [7], where the results from the more experiment-specific analyses were reported.

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In this paper the prospects for the observation of an invisibly decaying Higgs in the $t\bar{t}H$ production are revised. The evidence will be an excess of very exclusively selected events with a single isolated lepton, a large missing transverse energy, two identified b-jets and one reconstructed top quark in the hadronic decay mode. Such a signature requires very dedicated work on understanding the systematic sources originating in both physics and detector simulation. Currently, all these aspects can certainly not be covered. The aim of this paper is rather to evaluate possible sources of the standard model backgrounds and to identify the dominant contributions thereof.

2 Signal and background processes

The proton–proton collisions at 14 TeV center-of-mass energy are simulated, using the matrix element based generator AcerMC [9] and general purpose generators PYTHIA [10] and HERWIG [11] for event generation.

The signal events, $gg, q\bar{q} \to t\bar{t}H$, are generated with the PYTHIA event generator. No model for the invisibly decaying Higgs is assumed; the only postulate is that the Higgs boson is *invisible* to the detector. The latter is equivalent to assuming a 100% branching ratio of the Higgs boson to invisible particles and its coupling to the $t\bar{t}$ pair is set equal to the standard model prediction. In addition, any assumptions on the mass/spin of the invisible decay products are omitted. The signal production in the mass range 100–200 GeV is analyzed.

For simulation of the computationally demanding $2 \to 4$ background processes the presented study benefits from the availability of the matrix element implementations and efficient phase-space modeling in the AcerMC generator. Events generated with the matrix elements of AcerMC are further evolved through the QCD shower algorithms and eventually hadronized using the shower evolution provided by PYTHIA. In addition, the top-quark decays in the matrix element processes generated by AcerMC are handled by PYTHIA. The CTEQ5L parton density functions [8] and the default settings of the initialization parameters for PYTHIA and HERWIG are used. The cross-sections for signal and background processes are specified in Table 1.

The proposed analysis relies on identifying the top-quark pair production in the association with the invisibly decaying object and the lepton–hadron[1] decay mode of the top-quark pair, where an isolated lepton will trigger an experiment. In the initial step of the event selection one requires two identified (tagged) b-jets, at least two additional jets in the central detector region and a large missing transverse energy. The possible background processes are those which involve a top-quark pair or b-quark pair production associated with the W- or Z-boson.

Table 1. Cross-section for signal and background processes. Branching ratios are included only for the hard processes $W \to \ell\nu$, $Z \to \nu\nu$ and $Z/\gamma^* \to \ell\ell$ decays (three families of neutrinos and two families of leptons). For W-bosons originating in top-quark decays all decay channels are allowed. For the $Z/\gamma^* \to \ell\ell$ the cutoff $m_{\ell\ell} > 10$ GeV is set. In the signal simulation the strength of the Higgs coupling to the top quark is assumed to be the equal to the standard model prediction

Process	Generator	σ ($\sigma \times$ Br)
$t\bar{t}H$	PYTHIA	
$m_H = 100$ GeV		910 fb
$m_H = 120$ GeV		520 fb
$m_H = 140$ GeV		320 fb
$m_H = 160$ GeV		210 fb
$m_H = 200$ GeV		100 fb
$t\bar{t}Z$, $Z \to \nu\nu$	AcerMC	190 fb
$t\bar{t}$	PYTHIA, HERWIG	490 000 fb
$t\bar{t}W$, $W \to \ell\nu$	AcerMC	140 fb ($\times$ 3)
$b\bar{b}W$, $W \to \ell\nu$	AcerMC	73 000 fb
$b\bar{b}Z$, $Z/\gamma^* \to \ell\ell$	AcerMC	61 400 fb

$gg, q\bar{q} \to t\bar{t}$

This irreducible continuum background is generated both with the PYTHIA and the HERWIG generator. As the implementations of the QCD showering/hadronization models are different in PYTHIA and HERWIG, it is considered as very interesting to study the consistency of the estimates from both event samples, while the same initial cross-section is assumed[2].

$gg, q\bar{q} \to t\bar{t}Z, Z \to \nu\nu$

This irreducible resonant background is generated with the AcerMC matrix element generator.

$q\bar{q} \to t\bar{t}W, W \to \ell\nu$

This reducible background is generated with the AcerMC matrix element generator. In the implemented matrix element the W-boson from the hard process is forced to decay into a lepton and neutrino. As the required lepton can also be produced in the semi-leptonic top-quark decays, the hard-process W-boson could thus also decay hadronically; consequently the generated background is multiplied by an combinatorial factor 3 in the final results. This approximation is acceptable under the assumption that the acceptance is roughly comparable for events involving either a leptonic decay of the W-boson from the hard process or a leptonic decay of a W-boson from top-quark decays. This is an acceptable assumption as already the initial cross-section for this process is comparable with the signal values and the irreducible $t\bar{t}Z$ background predictions. Even with the combinatorial factor 3 included, the $t\bar{t}W$ background contribution is expected to be of the order of the $t\bar{t}Z$ contribution at most.

$gg, q\bar{q} \to b\bar{b}Z/\gamma^*, Z/\gamma^* \to \ell\ell \oplus$ jets

This reducible background is generated with the AcerMC matrix element generator. The Z/γ^* is required to decay into a lepton pair. This background process is considered to reproduce quite reliably the estimates from the inclusive "Z-boson $\oplus$ jets" production. The recent study in [12] has shown that the rates for $Zb\bar{b}$ events agree within 10% with the predictions of the more inclusive approach of generating $q\bar{q} \to Z$ hard processes and invoking a parton shower afterward. Requiring the reconstruction of one top quark in the hadronic mode, a large missing transverse energy and vetoing additional lepton will strongly suppress this background.

$q\bar{q} \to b\bar{b}W, W \to \ell\nu \oplus$ jets

This reducible background is generated with the AcerMC matrix element generator. The W-boson is required to decay to a lepton and a neutrino. This background represents the lowest limit of what is expected from the "inclusive

[1] The nomenclature *lepton–hadron* denotes one top quark decaying $t \to Wb \to q\bar{q}b$ and the other $t \to Wb \to \ell\nu b$, where ℓ stands for electron or muon

[2] The PYTHIA cross-section value is used throughout the analysis. The HERWIG cross-section prediction is lower by $\sim$ 17%, mainly due to the different implementation of αQCD

$W\oplus$ jets" production. The recent study in [12] has shown that the more inclusive, parton shower based estimates for events with two b-jets and one isolated lepton are not exceeding the matrix element results by more than a factor 2. Requiring the reconstruction of one top quark in the hadronic mode and a large transverse missing energy will suppress it strongly.

The list presented above, although quite exhaustive already, does not include different reducible backgrounds with one or two misidentified b-jets. From the experience of several studies done in [1], one does not expect these backgrounds to contribute more than 20–30% of the respective backgrounds with two true b-quarks.

In the presented analysis about 10^8 unweighted events were generated for the $t\bar{t}$ process with PYTHIA and HERWIG and about 10^6 for each of the background processes generated with AcerMC.

3 Simplified detector simulation

For the needs of this analysis a simplified version [13] of the fast simulation/reconstruction of the ATLAS detector at LHC was used. It reads generated events and provides reconstructed experimental observables: isolated leptons, jets, identified b-jets, transverse energy. Isolated leptons are reconstructed within the pseudo-rapidity range of $|\eta| < 2.5$; the same pseudo-rapidity coverage is possible for b-jet identification. Jets are reconstructed within $|\eta| < 5.0$. The transverse momentum thresholds are set for the trigger muon to 20 GeV, for the trigger electron to 25 GeV and the threshold for jet reconstruction is set to 15 GeV. Additional leptons are vetoed with the threshold of 6 GeV for a muon and 10 GeV for an electron.

The applied estimates are a 90% efficiency for lepton identification and reconstruction, about 80% efficiency for jet reconstruction and 60% efficiency for b-jet identification (with misidentification probability of 1% for light jets and 10% for c-jets). The resolution of the reconstructed missing transverse energy components is of the order of 6 GeV.

These performance figures are representative for the low luminosity operation of the ATLAS detector. More details about the detector performance and fast simulation/reconstruction can also be found in [1,14].

4 Analysis

The invisibly decaying Higgs boson production in association with two top quarks leads to a very distinct signature, namely the large missing transverse energy and an accompanying top-quark pair. Requiring a fully or partially reconstructed top-quark pair will allow for strong suppression of backgrounds from W or Z production, leaving the $t\bar{t}$ background as the dominant one. The (reducible) top-quark background production rate is enormous; the initial cross-section is by a factor 5×10^2–5×10^3 higher than the signal one. The only notable distinction between the signal events and the $t\bar{t}$ events should be a much larger missing transverse energy. Therefore, a selection which implies accepting the purest possible sample with fully reconstructed hadronic top-quark decay and partially reconstructed semi-leptonic top decay is proposed.

The focal point of the proposed selection is to suppress as much as possible the contribution from events with one $t \to \ell\nu b$ and another $t \to \tau\nu b$ decay, which results in the presence of a lepton and a large transverse missing energy in the event.

(1) An isolated lepton from the semi-leptonic decay of the one top quark is required to provide the trigger for these events. In addition, a veto on events with an additional isolated lepton is set in order to suppress the $Z/\gamma^* b\bar{b}$ background.

(2) Both b-jets have to be identified (tagged), which efficiently reduces background from the inclusive Z- or W-boson production.

(3) One top quark reconstructed in the hadronic decay mode $t \to \mathrm{jj}b$ is required. The best $\mathrm{jj}b$ combination is chosen from the set of possible permutations, the criteria being $m_{\mathrm{jj}} = m_W \pm 15\,\mathrm{GeV}$ and $|\eta^{\mathrm{jet}}| < 2.0$. Taking only the central jets for $W \to \mathrm{jj}$ reconstruction reduces the fraction of events with a "fake" reconstruction of "$W \to \mathrm{jj}$", where the jets originate in the initial or final state QCD radiation and not in the W-boson decay. We apply a W-mass constraint in order to re-calibrate the four-momenta of jets as this optimizes the resolution of the reconstructed $\mathrm{jj}b$ system. The $\mathrm{jj}b$ system is considered to reconstruct a top quark if $m_{\mathrm{jj}b} = m_t \pm 25\,\mathrm{GeV}$.

(4) It is not feasible, without further assumptions, to require a full reconstruction of the semi-leptonically decaying top quark in signal events. For such a reconstruction one needs information on the missing transverse energy from the W-boson decay. The latter is however not available, as both the leptonic W-boson decay and the Higgs boson decay itself contribute to the missing transverse energy in those events. Instead, we decided to explore the fact that the expected transverse mass of the lepton and $\not{E}_{\mathrm{T}}$ system, $m_{\mathrm{T}}(\ell, \not{E}_{\mathrm{T}})$, is much higher in the signal than in the $t\bar{t}$ background events; see Fig. 1. For the $t\bar{t}$ events, with the missing transverse energy coming predominantly from the $W \to \ell\nu$ decay, one can observe characteristic sharp end-point in the $\not{E}_{\mathrm{T}}$ distribution at about the W-boson mass. The tail in this distribution is contributed mostly by events with one $W \to \tau\nu$ decay or with both W-bosons decaying $W \to \ell\nu$. For selection we require $m_{\mathrm{T}}(\ell, \not{E}_{\mathrm{T}}) > 120\,\mathrm{GeV}$.

(5) A relatively large missing transverse energy of the system, $\not{E}_{\mathrm{T}} > 150\,\mathrm{GeV}$, is required.

(6) The signal-to-background ratio is enhanced by the additional requirement of the large transverse momenta in the reconstructed system, $\sum p_{\mathrm{T}}^{\mathrm{rec}} > 250\,\mathrm{GeV}$. The $\sum p_{\mathrm{T}}^{\mathrm{rec}} = \sum p_{\mathrm{T}}^{\mathrm{j}} + p_{\mathrm{T}}^{l}$ where the sum runs over the transverse momenta of reconstructed objects from top-quark decays: two b-jets, two light jets used for the reconstruction of the $W \to q\bar{q}$ decay and an isolated lepton. This further suppresses the backgrounds where true top quarks are not present, like $b\bar{b}Z$ and $b\bar{b}W$.

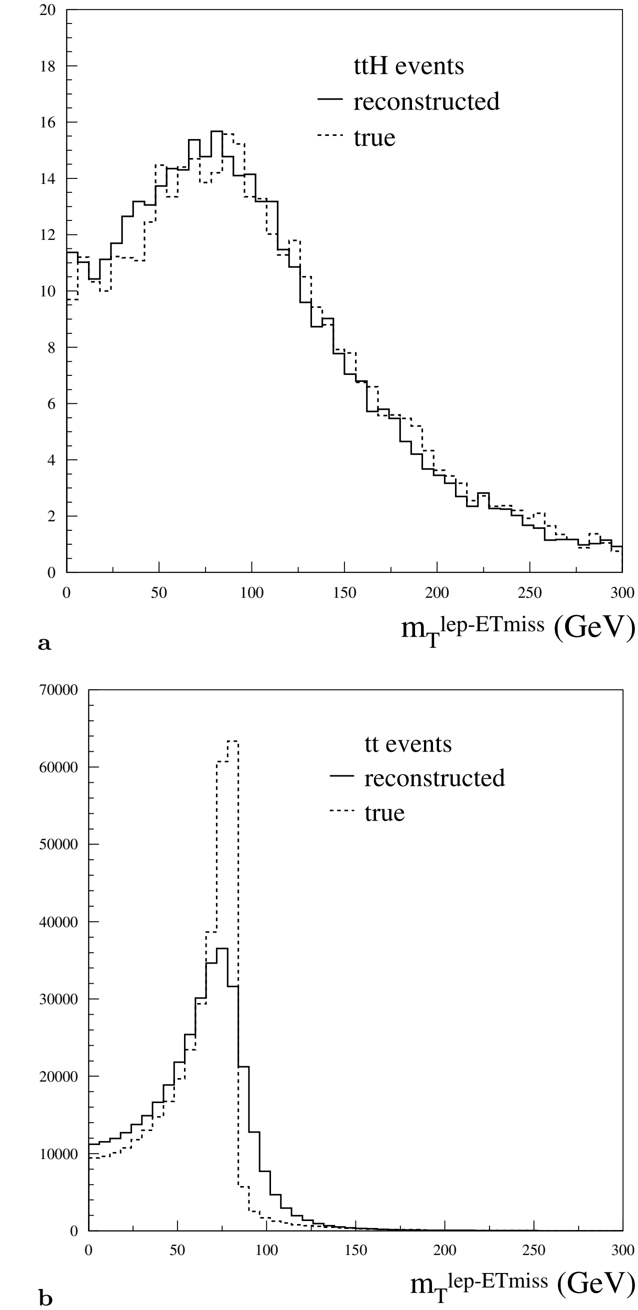


Fig. 1a,b. Reconstructed transverse mass of the lepton and $\not{E}_{\mathrm{T}}$ system in the $t\bar{t}H$ events (top plot) and in the $t\bar{t}$ events (bottom plot). The dashed line denotes the distributions calculated from the true invisible energy of the primary products of W-boson decays in these events, obtained by using the generator level information. The distributions are normalized to the number of events expected for an integrated luminosity of $30\,\mathrm{fb}^{-1}$

(7) Finally, further enhancement of the signal-to-background ratio can be achieved by the additional requirement on the cone separation, R_{jj}, between jets which were used for the $W \to \mathrm{jj}$ reconstruction, $R_{\mathrm{jj}} < 2.2$.

In Table 2 the selection criteria and cumulative acceptances from signal and dominant background processes are specified. The selection cutoff $\not{E}_{\mathrm{T}} > 150\,\mathrm{GeV}$ is quite loose and certainly can be optimized further. The cumulative acceptance for signal events after these cuts is about 0.3%. The acceptance is indeed very similar for the $t\bar{t}H$ signal events at $m_H = 120\,\mathrm{GeV}$ and for the $t\bar{t}Z$ background events. The cumulative acceptance for the $t\bar{t}$ process is of $7.6 \cdot 10^{-6}$ for PYTHIA events and $1.2 \cdot 10^{-5}$ for HERWIG events.

Table 2. The cumulative acceptances for the specified selection criteria. Efficiencies for b-tagging and lepton identification are included. The generation of the event samples was discussed in Sect. 2. A Higgs boson mass of 120 GeV is assumed for signal events. Only the dominant background sources are listed

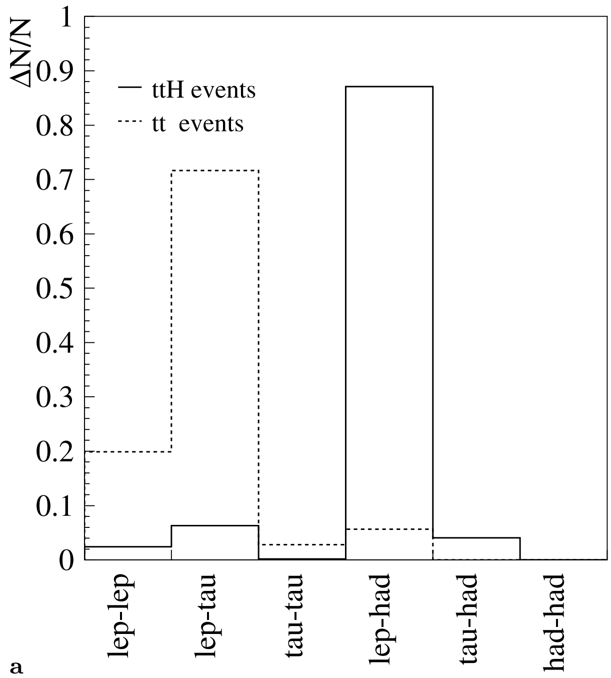
Process	$t\bar{t}H$ PYTHIA	$t\bar{t}Z$ AcerMC	$t\bar{t}$ PYTHIA	$t\bar{t}$ HERWIG
Trigger lepton	22%	22%	22%	22%
2 b-jets + 2 jets	5.0%	4.8%	4.9%	5.2%
rec. t-quark (jjb)	2.6%	2.4%	2.4%	2.6%
$m_{\mathrm{T}}^{\ell \not{E}_{\mathrm{T}}} > 120\,\mathrm{GeV}$	0.87%	0.93%	$4.1 \cdot 10^{-4}$	$5.2 \cdot 10^{-4}$
$\not{E}_{\mathrm{T}} > 150\,\mathrm{GeV}$	0.41%	0.53%	$2.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-5}$
$\sum p_{\mathrm{T}}^{\mathrm{rec}} > 250\,\mathrm{GeV}$	0.40%	0.51%	$2.0 \cdot 10^{-5}$	$3.2 \cdot 10^{-5}$
$R_{\mathrm{jj}} < 2.2$	0.28%	0.35%	$7.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$

After performing the selection, about 70% of the $t\bar{t}$ events comes from the lepton–tau[3] decay and 20% from the lepton–lepton decay of the top-quark pair in the PYTHIA sample with compatible fractions also found in HERWIG events. In these two cases the jj$b$ combination is thus made from the ISR/FSR jets and not from the true $W \to q\bar{q}$ decays. These events could hopefully be suppressed further by implementing a tau-jet veto and with more stringent requirements in the $t \to \mathrm{jj}b$ reconstruction. The cumulative acceptance for the $t\bar{t}$ background is found to be about 50% higher for events generated with the HERWIG than with the PYTHIA generator. The signal events in contrast contain only a $\sim 10\%$ fraction of lepton–tau and lepton–lepton decays; the relative fractions of signal and $t\bar{t}$ background events are shown in Fig. 2.

Considering the relative fractions of the tau–lepton events in the signal and background, one can assume that the inter-jet cone separation, R_{jj}, might provide some additional separation power; the R_{jj} for signal and $t\bar{t}$ background events are given in Fig. 2. Subsequently, a loose cut of $R_{\mathrm{jj}} < 2.2$ was applied; the final efficiencies are listed in Table 2.

It can reasonably be assumed that the R_{jj} cut is the one most sensitive to the modeling of ISR and FSR jets, which in certain regions of phase space might not be adequately described by the parton shower generators such as PYTHIA or HERWIG. Nevertheless, since the efficiency

[3] The *lepton–tau* label denotes one top quark decaying $t \to Wb \to \ell\nu b$ and another $t \to Wb \to \tau\nu b$, where ℓ stands for electron or muon. The *lepton–lepton* decay labels events with both top quarks decaying $t \to Wb \to \ell\nu b$. Finally, the *lepton–hadron* decay labels events with one top quark decaying $t \to Wb \to \ell\nu b$ and another $t \to Wb \to q\bar{q}b$



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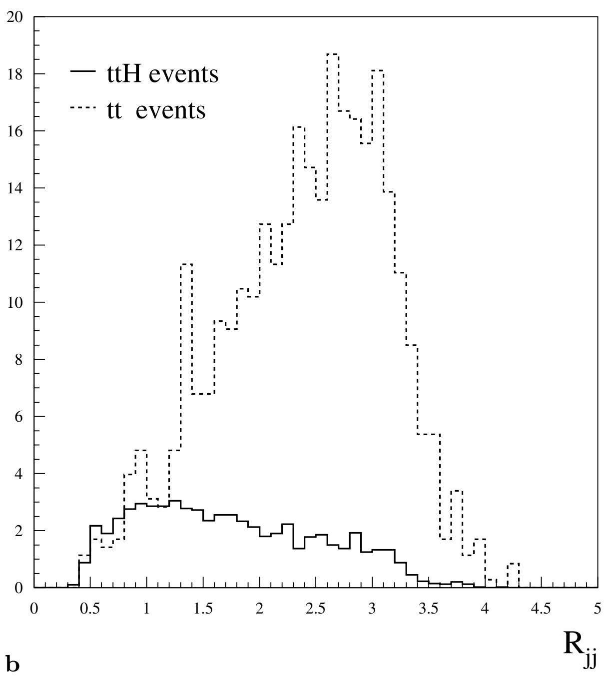
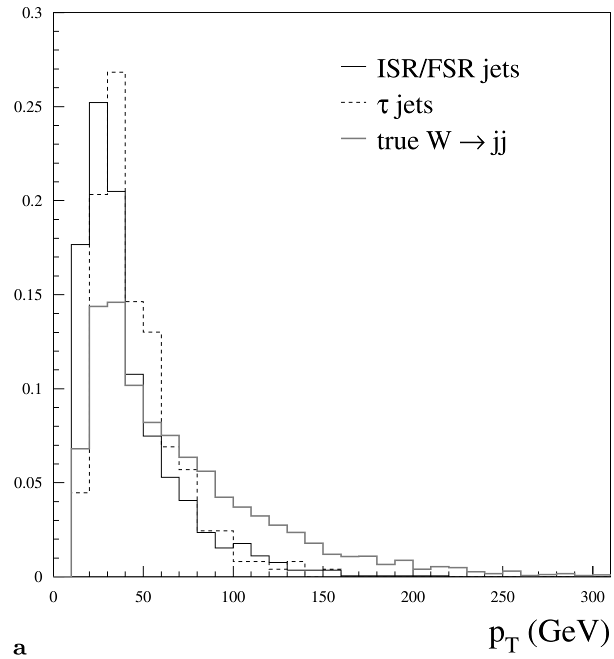


b

Fig. 2a,b. The relative fractions of the $t\bar{t}$ decay modes are listed for signal and $t\bar{t}$ background simulated with PYTHIA (top plot). The $R_{\rm jj}$ cone separation between jets used in the $W \to$ jj reconstruction; the distributions are normalized to the number of events expected for an integrated luminosity of $30\,{\rm fb}^{-1}$ (bottom plot)



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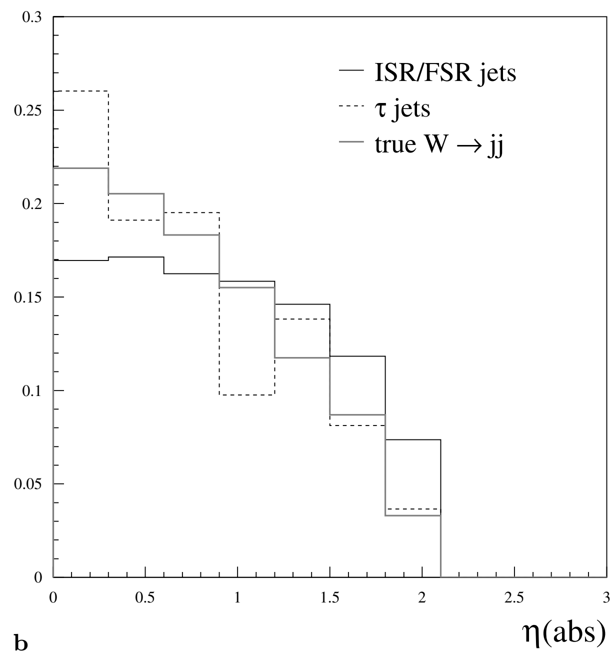

b

Fig. 3a,b. Reconstructed transverse momenta $p_{\rm T}$ (top plot) and the rapidity (absolute value) η (bottom plot), of the two light jets used in the $W \to q\bar{q}$ reconstruction, originating either in the ISR/FSR, $W \to \tau\nu$ or true $W \to$ jj decays in the $t\bar{t}$ background. The distributions are normalized to one

for the $R_{\rm jj}$ cut is nearly identical for the $t\bar{t}$ backgrounds produced by PYTHIA and HERWIG (c.f. Table 2), it is assumed that the cut is robust enough to be included. Due to its clear physics content it should remain valid also when more accurate simulations of the $t\bar{t}\oplus$jets background become available.

The distributions of the rapidity and transverse momentum of the two light jets used in the $W \to q\bar{q}$ reconstruction in contrast do not exhibit a significant difference when originating either in true $W \to$ jj events, $W \to \tau\nu$ or in the initial or final state radiation but for an expected tendency to higher rapidities and lower transverse momenta, typical for the ISR/FSR jets. The obtained distributions for the $t\bar{t}$ background are shown in Fig. 3.

Table 3. Expected numbers of events for an integrated luminosity of 30 fb^{-1} and selection as specified in Table 1. Efficiencies for b-tagging and lepton identification are included. (PY) and (HW) denote the results for the $t\bar{t}$ events generated with PYTHIA and HERWIG respectively. Also shown is the separate contribution to the $t\bar{t}$ background from the lepton–hadron events

Process	No. of events
$t\bar{t}H$,	
$m_H = 100$ GeV	60
$m_H = 120$ GeV	45
$m_H = 140$ GeV	30
$m_H = 160$ GeV	25
$m_H = 200$ GeV	15
$t\bar{t}Z$	20
$t\bar{t}W$	20
$t\bar{t}$ (all)	115 (PY), 190 (HW)
(only lepton–hadron)	15 (PY), 30 (HW)
$b\bar{b}W$	5
$b\bar{b}Z/\gamma^*$	5

The expected numbers of events for an integrated luminosity of 30 fb^{-1} are given in Table 3. Several values of the Higgs boson masses are studied, while assuming the standard model production cross-sections.

Taking as an example the results for the $t\bar{t}$ background obtained with the PYTHIA generator, the signal-to-background ratio is about 39% for a Higgs boson mass of 100 GeV and about 9% for a Higgs mass of 200 GeV. The total number of expected events from all backgrounds but the $t\bar{t}$ one is on the level of the signal itself. It is evident that in case the "fake" reconstructions could be eliminated in the $t\bar{t}$ events, the signal-to-background ratio could be brought to e.g. 90% for the $m_H = 120$ GeV, without changing thresholds on the $\not{E}_T$.

In Fig. 4 the expected final (post-selection) distribution of the $\not{E}_T$ and $\sum p_T^{\rm rec}$ is shown for a Higgs mass of 120 GeV. One can clearly see that the shape of the $\not{E}_T$ distribution is much steeper for the $t\bar{t}$ events than for the signal ones. In addition, the shape of the $\sum p_T^{\rm rec}$ distribution is different for both classes of events and in fact the applied threshold 250 GeV is shown to be rather low. One may also expect that the shape of the $\sum p_T^{\rm rec}$ (or analogous) distributions will be sensitive to the Higgs boson mass, thus allowing for the extraction of that information with some precision, limited by the signal-to-background ratio.

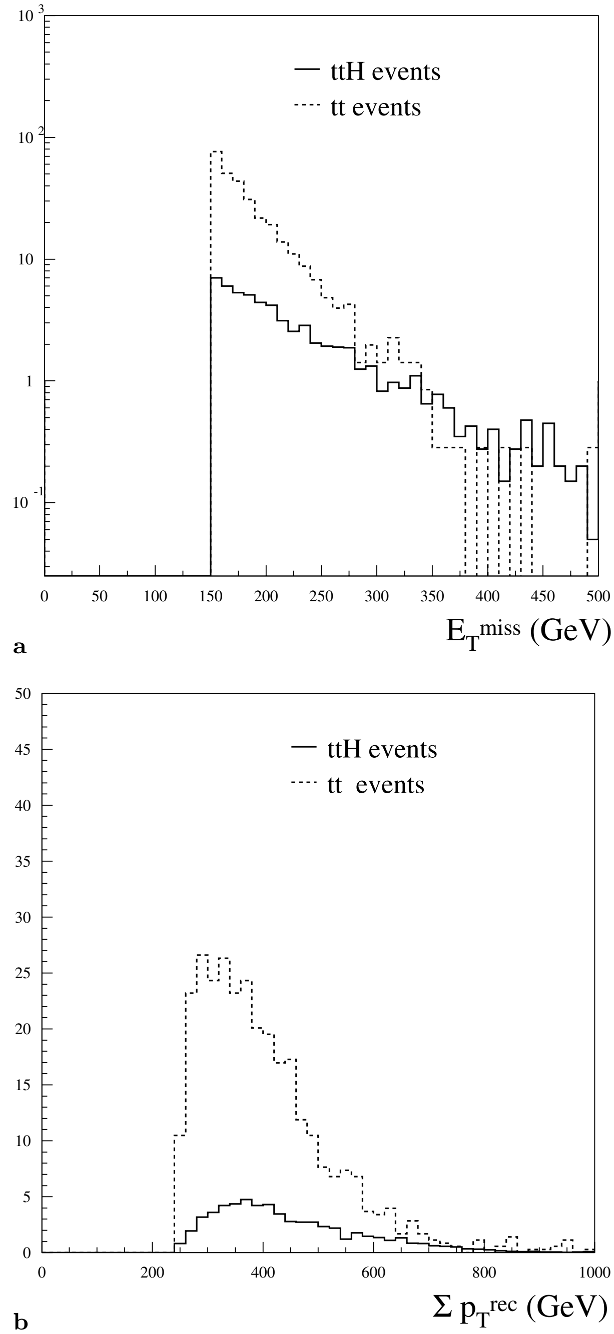

Fig. 4a,b. Reconstructed missing transverse energy $\not{E}_T$ (top) and sum of the transverse momenta of reconstructed objects $\sum p_T^{\rm rec}$ (bottom). The solid line denotes the ttH signal with $m_H = 120$ GeV, the dashed one the $t\bar{t}$ background prediction. The distributions before the last selection step specified in Table 1 are shown. The distributions are normalized to the number of events expected for an integrated luminosity of 30 fb^{-1}

One can certainly increase the signal-to-background ratio by increasing thresholds on the $R_{\rm jj}$,$\not{E}_T$, $\sum p_T^{\rm rec}$ or other reconstructed visible observables, like e.g. the total transverse momenta of the top-quark and lepton system, $P_T^{\rm rec}$, or the transverse momenta of the top quark, $p_T^{\rm top}$. Taking as the reference the distributions shown in Fig. 5, increasing the threshold on the $\not{E}_T$ to about 250 GeV would result in increasing the signal-to-background ratio (only the $t\bar{t}$ background) to about 1, while still keeping the expected number of signal events to about 20.

One can also increase the signal-to-background ratio by further optimizing the selection criteria, e.g. by asking

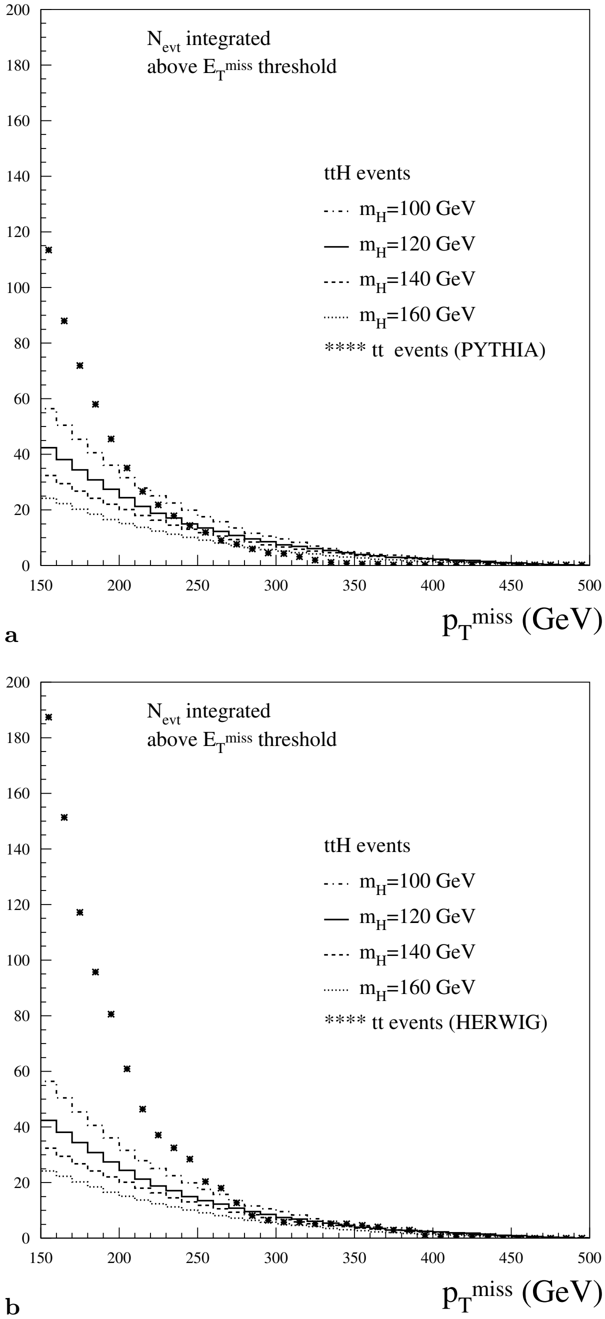

Fig. 5a,b. Integrated number if events from the ttH signal with m_H = 100, 120, 140, 160 GeV (histograms) and the $t\bar{t}$ background (stars) as a function of the $\not{E}_T$ threshold. The results for $t\bar{t}$ events simulated with PYTHIA (top) and HERWIG (bottom) generators are shown. The distributions are normalized to the number of events expected for an integrated luminosity of 30 fb^{-1}

for an isolation in the azimuthal angle of the $\not{E}_T$ direction from the reconstructed jets, the reconstructed top quark or the isolated lepton. It has been checked that a moderate isolation requirement, $\delta\phi > 0.4$, can improve the signal-to-background ratio by 20–30% at the price of reducing signal rates by a comparable amount.

Nevertheless, in our opinion, the key point for the signal observability remains the experimental efficiency for reducing the fake $W \to q\bar{q}$ reconstruction and thus the contribution from the $t\bar{t}$ events with lepton–tau and lepton–lepton decays.

5 Conclusions

The prospects for observing the invisibly decaying Higgs boson in the $t\bar{t}H$ production at LHC were discussed. The proposed analysis required one top quark reconstructed in the hadronic decay mode, an isolated lepton (electron, muon) from the decay of the second top quark and a large missing transverse energy. Evidence for the signal would be the observation of an excess of such events above the background. Expected excess can be on the level from 10% to even 100% or more, depending on the required threshold on the missing transverse energy and on the assumed Higgs boson mass. It can be expected that some sensitivity to the Higgs boson mass could be revealed by the hardness of the reconstructed visible part of the event, the $\sum p_T^{\text{rec}}$, P_T^{rec} or similar distributions. The signal observability should not degrade significantly for the high luminosity operation of the detectors. Thus, the sensitivity to the signal is expected to increase with increasing collected integrated luminosity.

The availability of the matrix element implementations for the $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}Z$ and $t\bar{t}W$ processes in the AcerMC generator allowed us to conclude that the total contribution from these background processes could be kept on the signal level or below.

The dominant standard model background comes from the $t\bar{t}$ production with one top quark decaying semi-leptonically into an electron or a muon and the second one into a tau lepton. It was also shown, by comparing results for the $t\bar{t}$ background generated with PYTHIA and HERWIG Monte Carlo, that for the final estimate one would have to study very carefully the systematics from the showering, hadronization and decays models. The key to reduce the $t\bar{t}$ background further will be the purest possible reconstruction of the top-quark hadronic decays ($t \to q\bar{q}b$), thus eliminating the events with the top quark decaying to a tau lepton ($t \to \tau\nu b$).

It was concluded that the final optimization of the observability potential demands a much more sophisticated experimental analysis than foreseen in the scope of this paper. Rather than increasing the threshold on the required missing transverse energy one should aim for the best possible suppression of the contribution from the tau-lepton events of the top-quark pair decays.

In Table 4 a comparison between the sensitivity to the invisible Higgs production in the $t\bar{t}H$ channel and in the $qq \to qqH$ vector boson fusion (VBF) published in [7] is given in terms of the sensitivity of the ξ^2 parameter:

$$\xi^2 = \frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}H)_{\text{SM}}} \times \text{Br}(H \to \text{inv}).$$

The parameter ξ^2, as defined in [7] and presented in Table 4, serves as an estimate of the branching fraction

Table 4. Expected sensitivities of ξ^2 for an integrated luminosity of $30\,\mathrm{fb}^{-1}$ and selection as specified in Table 1. In the first column the complete PYTHIA background prediction is considered and in the second column only the lepton–hadron $t\bar{t}$ decays are included. The third column lists the values from the VBF analyses given in [7], re-scaled for comparison to the integrated luminosity of $30\,\mathrm{fb}^{-1}$

Process	ξ^2 [%] ($t\bar{t}H$) all $t\bar{t}$	ξ^2 [%] ($t\bar{t}H$) (lep-had) $t\bar{t}$	ξ^2 [%] (VBF)
$t\bar{t}H$,			
$m_H = 100\,\mathrm{GeV}$	42.2	26.5	12.1
$m_H = 120\,\mathrm{GeV}$	55.7	27.4	10.3
$m_H = 140\,\mathrm{GeV}$	75.4	47.4	9.8
$m_H = 160\,\mathrm{GeV}$	95.6	60.2	9.9
$m_H = 200\,\mathrm{GeV}$	154.3	97.1	10.7

$\mathrm{Br}(H \to \mathrm{inv})$. It is derived from the fact that since the true $\sigma(t\bar{t}H)$ is also not known a priori, one is restricted to measuring the $\sigma(t\bar{t}H \to \mathrm{inv}) = \sigma(t\bar{t}H) \times \mathrm{Br}(H \to \mathrm{inv})$ and thus the $\mathrm{Br}(H \to \mathrm{inv})$ estimate has to be scaled by the ratio between the unknown cross-section and the standard model prediction $\sigma(t\bar{t}H)_{\mathrm{SM}}$. Table 4 lists the sensitivity limits of the ξ^2 which can be probed at the 95% confidence level. In the table the VBF limits have been re-scaled to the luminosity of $30\,\mathrm{fb}^{-1}$; in case the data point was not provided the nearest value was taken.

The presented limits of ξ^2 do not contain the estimates of the systematic uncertainties since the level of uncertainty about the background predictions is in our opinion still too large, as is evident from the difference between PYTHIA and HERWIG predictions for the $t\bar{t}$ background. It might well be that for more firm background estimates one might have to wait for the availability of NLO Monte-Carlo generators and/or tuning on the data itself. It is nevertheless evident that even if an efficient way to reject events with *fake* $W \to$ jj reconstruction (topological selection, tau-jet veto) is found the potential for invisible Higgs detection in the $t\bar{t}H$ channel is about a factor 2 to 3 less weaker than with the VBF channel [7] in the low-mass Higgs region while in the high-mass region the clear VBF dominance is evident. One has to stress, however, that the $t\bar{t}H$ channel does not require the implementation of an efficient forward jet trigger, essential for the VBF studies as stated in [7], and that with more stringent cut optimization it might still be possible to significantly increase the sensitivity listed in Table 4.

The associated Higgs production $t\bar{t}H$ already turned out to be very powerful for the $H \to b\bar{b}$ decay mode [15]. Establishing the observability in the same production mode and the complementary decay channel (if $H \to \mathrm{inv}$ is open the $H \to b\bar{b}$ is suppressed) will make this search very interesting in the range of intermediate strengths of both decays.

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