$t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ —toward the measurement of the top-Yukawa coupling

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Received: 30 May 2007 / Revised: 13 August 2008 / Published online: 18 December 2008

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Abstract One of the main goals of the ATLAS experiment is to measure various Higgs boson couplings as accurately as possible. Such a measurement is mandatory for a full understanding of the Higgs sector. One of the most challenging measurements of the Higgs boson properties is the determination of the Yukawa coupling to the top quark. To complement the $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ channel, which is the most significant in the low Higgs mass region ($m_H \sim 120$ GeV), we introduce a feasibility study of the $t\bar{t}H$ channel with the Higgs decaying to a pair of τ leptons. The signal events were reconstructed using the full and the fast simulation of the ATLAS detector. It is shown that both the distributions and the number of expected events after the same cuts agree, and that we can use the fast simulation to complete the analysis. We obtain a significance of 1.6σ for the low luminosity condition (30 fb^{-1}) and $m_H = 120$ GeV, and 2.0σ for the high luminosity condition (300 fb^{-1}) and $m_H = 120$ GeV. The observability of Higgs boson in this channel is demonstrated to be very marginal, even in the absence of taking into account $t\bar{t} + \text{jets}$.

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1 Introduction

One of the most challenging measurements of the Higgs boson properties is the determination of the Yukawa coupling to the top quark. Theory predicts that fermion masses are generated via the interaction with the Higgs field. The fermion masses are therefore given by $m_f = g_{f\bar{f}H} \cdot v/\sqrt{2}$, where $g_{f\bar{f}H}$ is the Yukawa coupling of the Higgs boson to the fermion and v is the vacuum expectation value (VEV). The puzzle of the top mass being a few orders of magnitude

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larger than the masses of other fermions can be formulated in terms of the relation of the top Yukawa coupling to the couplings to other fermions. Therefore the measurement of the top Yukawa coupling is of extreme importance and will enable us to further investigate the mass generation mechanism.¹

Even if the Higgs boson mass is above the $t\bar{t}$ threshold the branching ratio $\text{BR}(H \rightarrow t\bar{t})$ would be low due to the open decay channels to the W and the Z boson pairs. Moreover, top quark decay modes with leptonic W decay contain neutrinos, which makes the full reconstruction of the Higgs boson difficult. Precision fits of the Standard Model indicate that the Standard Model Higgs boson mass² is below ~ 200 GeV [1], while in the MSSM a light Higgs boson mass is theoretically bounded to be below ~ 135 GeV [2–8]. The experimental lower bounds on the Standard Model and light MSSM Higgs boson are 114.4 GeV [9] and ~ 90 GeV [10], respectively. The most favorable Higgs boson scenario is a Standard Model like light Higgs boson with a mass around or below 130 GeV. Such a Higgs boson will not have an open decay channel to a top quark pair. So the only way to directly measure the Higgs boson coupling to the top quark is via its direct coupling to the top quark in the associated (with a top quarks pair) production process (see Fig. 1.1). The motivation to detect and measure the $pp \rightarrow t\bar{t}H$ process is therefore clear.

For a 120 GeV Higgs boson, a significant final state of the $t\bar{t}H$ channel is the one with the Higgs boson decaying to a b -quark pair. Here one can identify (“tag”) four b -jets, as well as fully reconstruct the signal. The feasibility of this channel was studied with ATLAS fast simulation [11] and gave promising results for the ATLAS low luminosity benchmark of 30 fb^{-1} . However, further studies indicate that the systematics of this channel prohibit it from being a discovery channel. This is confirmed by later studies by CMS [12]. To complement this study, we introduce in this work a feasibility study of the $t\bar{t}H$ channel with the Higgs boson decaying to a pair of τ leptons. The cross section times branching ratio is about an order of magnitude be-

Fig. 1.1 Feynman diagrams of the $t\bar{t}H$ production processes

¹Most extensions of the SM, in particular the MSSM, contain a SM like light Higgs boson that couples in a similar fashion to fermions. Thus, the importance of the precision measurement of the top Yukawa coupling remains valid.

²The upper limit strongly depends on m_{top} .

low that of the $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ channel, and the τ tag efficiency is lower than the b -tag efficiency, yet, preliminary studies indicated that combining several final state topologies, there might be a significant contribution from this channel. However, a significant amount of work was invested in improving the τ tagging in the fast simulation and make it as realistic as possible. In this paper we describe in detail the $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ analysis. The cross section and the various topologies are described in Sect. 2. The Monte Carlo simulations are presented in Sect. 3. The analysis objects, i.e. electron and muon identification, and the b , τ and light jet reconstruction are described in Sect. 4. We then describe the signal selection criteria in Sect. 5. Fast simulation high luminosity results are given in Sect. 6. Systematic uncertainties are discussed in Sect. 7 and the background normalization from the data is described in Sect. 8. The results are summarized in Sect. 9.

2 Cross section and topologies

Recent calculations were used for the $t\bar{t}H$ cross section and the branching ratios of $H \rightarrow \tau^+\tau^-$ [13–15]. The cross section times the branching ratio of $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ is shown in Table 2.1 and Fig. 2.1. Throughout this paper we used leading order (LO) calculations for the cross section for both signal and background processes. The accuracy of the signal cross section is improved when next-to-leading order QCD corrections are calculated [16], which lead to a K-factor of 1.2, and an estimated accuracy of 20% from variations of the scale. One can clearly see that the cross section drops as the Higgs boson mass increases.

A priori, since each top quark can decay to a b quark accompanied either by two jets (bjj) or by a lepton and a neutrino ($bl\nu$), and each τ can decay hadronically ($\tau_j\nu$) or leptonically ($l\nu\nu$), nine channels are possible. Only muonic or electronic decays of the top are considered, and therefore $l = e, \mu$. Table 2.2 shows the nine channels, their relative fraction, and the number of expected events (for 30 fb^{-1} and $m_H = 120$ GeV). Since we consider here only the low luminosity benchmark (30 fb^{-1}) it is clear that only channels 1, 2, 4, 5 and 6 have enough signal events to proceed with the analysis. However, channel 1, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow bj\bar{j}\bar{b}jj\tau_j\bar{\nu}_\tau\tau_j\nu_\tau$, is purely hadronic

Table 2.1 Cross sections [13, 14] for the $t\bar{t}H$ production, Branching Ratios [15] for $H \rightarrow \tau^+\tau^-$, and $\sigma \times \text{BR}(H \rightarrow \tau^+\tau^-)$

m_H (GeV)	σ (fb)	$\text{BR}(H \rightarrow \tau^+\tau^-)$	$\sigma \times \text{BR}$ (fb)
110	894	0.076	68.27
120	692	0.068	47.32
130	541	0.054	29.12

Table 2.2 Final states and Branching Ratios for the $t\bar{t}H^0 \rightarrow t\bar{t}\tau^+\tau^-$. The number of events and number of reconstructed events, where reconstructed events here denotes those that satisfy the low luminosity trigger conditions (see Table 4.4) and the topology requirement, for 30 fb^{-1} and $m_H = 120 \text{ GeV}$ are also given. We consider only channels 2, 4 and 5 in the following sections

	Channel	$t\bar{t}H^0 \rightarrow t + t + \tau + \tau$	BR	No of events ($30 \text{ fb}^{-1}, m_H = 120 \text{ GeV}$)	No of reconstructed events
Group 1	1	$b\bar{b}j + b\bar{b}j + \tau_j\nu + \tau_j\nu$	19%	270.2	9.54
	2	$b\bar{b}j + b\bar{b}j + \tau_j\nu + \ell\nu\nu$	20%	284.4	30.91
	3	$b\bar{b}j + b\bar{b}j + \ell\nu\nu + \ell\nu\nu$	6%	85.3	3.25
Group 2	4	$b\bar{b}j + b\bar{\ell}\nu + \tau_j\nu + \tau_j\nu$	12%	170.6	8.82
	5	$b\bar{b}j + b\bar{\ell}\nu + \tau_j\nu + \ell\nu\nu$	13%	184.9	13.94
	6	$b\bar{b}j + b\bar{\ell}\nu + \ell\nu\nu + \ell\nu\nu$	3%	42.7	7.15
Group 3	7	$b\bar{\ell}\nu + b\bar{\ell}\nu + \tau_j\nu + \tau_j\nu$	2%	28.4	0.73
	8	$b\bar{\ell}\nu + b\bar{\ell}\nu + \tau_j\nu + \ell\nu\nu$	2%	28.4	1.8
	9	$b\bar{\ell}\nu + b\bar{\ell}\nu + \ell\nu\nu + \ell\nu\nu$	1%	14.2	1.4

Fig. 2.1 Cross section times Branching ratio, $\sigma \times \text{BR}$, for the $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ process as a function of the m_H (see Table 2.1)

with a small amount of missing energy and suffers from large $t\bar{t}$ and QCD backgrounds. Likewise, channel 6, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\bar{\ell}\nu_\ell \bar{b}jj\ell\nu_\ell \bar{\nu}_\tau \ell\bar{\nu}_\ell \nu_\tau$, suffers from a huge irreducible $Zt\bar{t} \rightarrow \ell^+\ell^-t\bar{t}$ background.³ We therefore consider in this analysis only channels 2, 4 and 5.

3 Monte Carlo

The complexity of the physics events to be analyzed at the LHC and the diversity of the detectors to be integrated into ATLAS make it an absolute necessity to provide an accurate detector simulation program, with which the detector response to various processes can be evaluated in detail. The complete simulation is performed in several stages. The input for the simulation comes from the event generators after a particle filtering stage. Data objects representing the Monte Carlo truth information from the generators are read by the simulation and processed. Hits produced by the simulation can be directly processed by the digitization algorithm

³We applied the Z -mass veto, i.e. we cut-off events with $75 < m_Z < 105 \text{ GeV}$, but $Zt\bar{t} \rightarrow \ell^+\ell^-t\bar{t}$ background was still prevailing.

and transformed into Raw Data Objects (RDOs). Alternatively they can be sent first to the pile-up⁴ algorithm and then passed to the digitization stage. RDOs produced by the simulation data-flow pipeline are used directly by the reconstruction processing pipeline [17].

Since ATLAS is a huge and complicated detector, and we are interested in the high energy processes, full simulations are heavily CPU time consuming, in particular for events with high particle multiplicities.⁵ Studies of physics channels of interest and the associated backgrounds usually require the generation and simulation of millions of events. This is not feasible with the full simulation of the ATLAS detector. Therefore, a fast simulation program, ATLFast [18], was developed in which the detector response was parametrized as a function of the transverse momentum $p_T = \sqrt{p_x^2 + p_y^2}$ and $\eta = -\ln(\tan\theta/2)$, where $\theta = p_z/|\vec{p}|$.

3.1 Signal generation

Signal events were generated using PYTHIA 6.226 [19] with Tauola⁶ 2.6 [20] turned on. To get a manageable sample size, events were accepted if they passed a one-lepton filter, where an electron or a muon was required to have a $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$. The efficiency of the filter was $\sim 60\%$ for the signal. We did not apply any cut on jet p_T at generator level. For the full simulation analysis, events that have passed the filter were simulated with GEANT4 (Athena version 9.0.4), then digitized and reconstructed using Athena 10.0.1. For the fast simulation we

⁴We use pile-up for high luminosity study only.

⁵For the channel $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$, ~ 20 minutes are required to fully simulate one event.

⁶The TAUOLA package was developed for the accurate simulation of τ -lepton decays.

Table 3.1 The number of generated events (column 5) and $\sigma \times \text{BR}$ (LO) for various background processes. The last two processes were used as background sources for channel 2 only

Process	Decay	Generator	$\sigma \times \text{BR}$	Generated No of events	Filter efficiency
$t\bar{t}$	$t\bar{t} \rightarrow bj\bar{j}b\bar{j}j$	PYTHIA	224 pb	2.5×10^7	12%
$t\bar{t}$	$t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$	PYTHIA	215 pb	2.4×10^7	60%
$t\bar{t}$	$t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}\ell\nu_\ell$	PYTHIA	52 pb	1.2×10^7	80%
$gq \rightarrow Zt\bar{t}$	$Z \rightarrow \tau^+\tau^-, \ell^+\ell^-$	AcerMC	7.5 fb	5×10^4 (each)	88% $Z \rightarrow \tau\tau$
$q\bar{q} \rightarrow Zt\bar{t}$	$t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$		3.8 fb	5×10^4 (each)	98% $Z \rightarrow \ell^+\ell^-$
$gq \rightarrow Zt\bar{t}$	$Z \rightarrow \tau^+\tau^-, \ell^+\ell^-$	AcerMC	3.7 fb	5×10^4 (each)	45% $Z \rightarrow \tau\tau$
$q\bar{q} \rightarrow Zt\bar{t}$	$t\bar{t} \rightarrow b\tau\bar{\nu}_\tau bjj$		1.9 fb	5×10^4 (each)	94% $Z \rightarrow \ell^+\ell^-$
$gq \rightarrow Zt\bar{t}$	$Z \rightarrow \tau^+\tau^-, \ell^+\ell^-$	AcerMC	12.25 fb	10^5 (each)	37% $Z \rightarrow \tau\tau$
$q\bar{q} \rightarrow Zt\bar{t}$	$t\bar{t} \rightarrow bj\bar{j}b\bar{j}j$		6.2 fb	10^5 (each)	94% $Z \rightarrow \ell^+\ell^-$

used ATLAST implementing the Fast Shower [21] and including the Tau-algorithm. We have produced 10^5 events for $m_H = 110, 120$, and 130 GeV each, and for different topologies as shown in Table 2.2. 2×10^4 events with $m_H = 120$ GeV were generated with the full simulation.

3.2 Background generation

The most relevant background processes with the corresponding cross-sections are listed in Table 3.1. $t\bar{t}$ events were generated with PYTHIA, while for the $Zt\bar{t}$ processes, AcerMC 2.4 [22, 23] was used for the generation, and PYTHIA for the hadronization. Events were required to satisfy the one-lepton filter mentioned above. The 1-lepton filter efficiencies are shown in the last column of Table 3.1.

We also studied the MC@NLO generator for $t\bar{t}$ events, and found differences with PYTHIA that do not affect this analysis. We note that the properties of $t\bar{t}$ events can be extracted from the actual ATLAS data relatively soon after start-up of the experiment, and that understanding this background is crucial before any signal for new particles can be claimed.

Note that for this feasibility study we have chosen to use only a $t\bar{t}$ background Monte Carlo. A refinement of the analysis would require the inclusion of a dedicated $t\bar{t} + \text{jets}$ Monte Carlo.

4 Event reconstruction

The $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ channel contains a large variety of objects that can be reconstructed with the ATLAS detector, and could serve as an excellent tool to test the reconstruction. In this section we will describe the reconstruction within the full and fast simulation of all ingredients of the relevant channels.

4.1 Lepton reconstruction

We consider here electrons and muons as leptons. Our goal is to identify those that originate in t -quark or τ -lepton.

Electron identification In the full simulation, electron candidates are reconstructed from the calorimeter and tracking system information. A likelihood function calculated from several quantities (see Appendix A) [24], based on single electron and single pion samples, and defined as

$$L_e = \frac{\text{weight}_{\text{EM}}}{(\text{weight}_{\text{EM}} + \text{weight}_\pi)} \quad (4.1)$$

is used to identify electrons.⁷ In addition, calorimeter and track isolation is applied. In order to determine the efficiency of the identification, electron candidates are labeled as MC-isolated if they contain a true electron within a cone of $\Delta R = 0.2$, where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, and if this true electron is isolated from other MC-particles.⁸ They are labeled as MC-non-isolated if they contain a true electron within a cone of $\Delta R = 0.2$, but this true electron is not isolated from other MC-particles. Further on, they are labeled as MC- τ if they contain a τ_{had} ⁹ within a cone of $\Delta R = 0.2$. Finally, if they contain a pion within a cone of $\Delta R = 0.2$, they are labeled as MC- π .

Figure 4.1 shows the distribution of the electron identification likelihood L_e for MC-isolated electrons (blue solid line), MC-non-isolated electrons (green dash-dotted line), MC- τ (red dotted line), and MC- π (black dashed line) in

⁷In order to reject photons, the likelihood is set to zero if there is no associated track.

⁸MC refers to the truth information. An MC-truth electron is isolated if the energy within a cone of $\Delta R = 0.4$ around it is less than 10 GeV.

⁹ τ_{had} is defined as the sum of the hadronic products of the τ -lepton.

the generated signal sample. We tag a particle as an electron if the $L_e > 0.92$. This cut was chosen in order to optimize efficiency of the electron identification and purity of the samples.

In order to determine whether the electron is isolated we apply two criteria—calorimeter and track isolation. Figure 4.2(a) shows the sum of the transverse momenta of

Table 4.1 Rejection of the non-electrons. Rejection is defined as a number of rejected candidates for each one accepted

Sample	Rejection
Total	180
π	1340
τ	270
MC-non-isolated e	37

Fig. 4.1 The likelihood [24] used for the electron identification for MC-isolated electrons (blue solid line), MC-non-isolated electrons (green dash-dotted line), MC- τ (red dotted line), and MC- π (black dashed line). The likelihood is calculated on the full signal sample. The distributions are not normalized

Fig. 4.2 Track (a) and calorimeter (b) isolation, i.e. the energy deposited in a cone of $\Delta R = 0.2$ around an electron track, calculated from tracks (a) and the energy deposited in a cone of $\Delta R = 0.2$ around an electron cluster, calculated from the calorimeter cells (b), for MC-

charged tracks in the Inner Detector in a cone of $\Delta R = 0.2$ around an electron candidate track. We required that this sum is less than 5 GeV. Figure 4.2(b) shows the additional calorimeter energy in a cone of $\Delta R = 0.2$ around the electron candidate. We required that this additional calorimeter energy is less than 5 GeV.

The obtained electron selection efficiency is $\sim 82\%$ with a purity of more than 95%. Rejection ratios are calculated from the full $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ sample and they are given in Table 4.1.

Following these results, the electron identification efficiency for the fast simulation is set to 85%.¹⁰

Muon identification In the full simulation, the muon identification is done using the combined muon reconstruction (see [17]). Additionally, it is required that the muon track is isolated. To determine the efficiency of the muon identification, all MC muons originating in a W -boson from the decay of t -quark or a τ -lepton are labeled as MC-isolated, while those coming from other sources are considered as MC-non-isolated.

Figure 4.3 shows the sum of the transverse momenta of charged tracks in the Inner Detector in a cone of $\Delta R = 0.2$ around a muon candidate track for a MC-isolated (blue solid line) and a non MC-isolated (red dashed line) muon. We required that this sum is less than 10 GeV.

The obtained efficiency is $\sim 85\%$. Accordingly, this efficiency is applied in the fast simulation for isolated muons.

¹⁰The total number of tagged electrons includes also fake electrons (that do not originate in MC-isolated electrons). In order to have the same total number of tagged electrons we set the efficiency to 85% rather than 82%.

isolated electrons (blue solid line), MC-non-isolated electrons (green dash-dotted line), MC- τ (red dotted line), and MC- π (black dashed line). The distributions are areas normalized to unity

Fig. 4.3 Track isolation, i.e. the energy deposited in a cone of $\Delta R = 0.2$ around muon track, calculated from tracks for MC-isolated muons (blue solid line) and MC-non-isolated muons (red dashed line). The distributions are areas normalized to unity

4.2 Jet reconstruction

We use a seeded cone algorithm in $\eta - \phi$ coordinates, with a fixed cone radius of $\Delta R = 0.4$, for jet reconstruction in the full and fast simulation. We merge two jets if their overlapping energy is more than 50% of the least energetic jet energy. We also add to the jet a non-isolated muon if found within a cone of $\Delta R = 0.4$ around the jet axis. We require that every jet has a transverse momentum $p_T > 15$ GeV. More details can be found in [25].

Light jet reconstruction In the present analysis, light jets are important for the W -boson reconstruction. Therefore, it is necessary that they are well reconstructed and calibrated. We consider a jet as a light one if it is not tagged as a b -jet or as a τ -jet, both in the full and the fast simulation.

b jet reconstruction The b -tagging, i.e. identification of the jets originating in b -quarks, is one of the most important aims of the reconstruction software. In the full simulation of the ATLAS detector, this is done by several algorithms that exploit the long lifetime of B-hadrons. We use the ‘3D + secondary vertex’, or so-called SV2 algorithm, which combines track impact parameters in three dimensions and secondary vertices in jets into one likelihood function. This likelihood is shown in Fig. 4.4, where labeled¹¹ b -jets are represented with the blue solid line, labeled c -jets with the brown dashed line and light jets with the red dotted line. We tagged a jet as a b -jet if $W_{SV2} > 3$. The obtained average efficiency, calculated on the $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ where t -quark and τ -lepton decayed freely, is 60%, with a rejection of 57 against light jets, and 7 against c -jets. The average purity is 89%.

¹¹We label jets if they contain a corresponding (b or c) parton within a cone of $\Delta R = 0.4$ around the jet axis.

Fig. 4.4 The resulting likelihood function for the SV2 algorithm for labeled b -jets (blue solid line), labeled c -jets (brown dashed line) and light jets (red dotted line). All distributions are normalized to unity

Table 4.2 Cut values on the τ -Likelihood as a function of the p_T of the jet in the fully simulated events

p_T range (GeV)	Cut value
<30	3
(30, 45)	3
(45, 60)	2
(60, 80)	2
(80, 120)	2
>120	0

In the fast simulation, b -jet tagging is done via a parametrization.¹² We set our efficiency to 60%. The corresponding default rejections are 35 against light jets and 7 against c -jets, with an average purity of 84%.

τ jet reconstruction Excellent τ -tagging is crucial for this analysis. For the tau-tagging in the full simulation, we take $\Delta R = 0.4$ cone jets as input, and calculate a likelihood from several calorimetric and track quantities (see Appendix B and [26]). As mentioned above, we use the whole $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ sample¹³ to establish efficiencies and rejections against the light jets. Figure 4.5 shows the τ -Likelihood for different p_T ranges of the labeled (blue solid line) and non labeled (red dashed line) τ -candidates.¹⁴ The values where we cut on the likelihood, determined with the crossing points of the two histograms, depend on the p_T of the jet (see Table 4.2). Additionally, we ask that the ratio of

¹²Currently, the b -tag performance in the full simulation is found to be better than in the fast one.

¹³Whole $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ means that top decays to e or μ (top decays to tau are not included in this), and τ can decay freely.

¹⁴A jet is labeled as a τ jet if there is a τ Monte Carlo (MC) hadronic jet with transverse momentum $p_T > 10$ GeV and pseudorapidity $|\eta| < 2.5$ within $\Delta R < 0.3$ from the jet axis. A τ MC hadronic jet is a pseudo particle defined by the sum of all hadronic τ decay products. These definitions hold for both the fast and full Monte Carlo.

Table 4.3 Cut values on the τ variables, R_{EM} and F_{Iso} , as a function of the p_T of the jet in the fast simulation

p_T range (GeV)	R_{EM}	F_{Iso}
<30	0.14	0.3
(30, 45)	0.13	0.27
(45, 60)	0.12	0.26
(60, 80)	0.1	0.26
(80, 120)	0.095	0.24
>120	0.09	0.23

the hadronic energy and the sum of the p_T of all tracks is larger than 0.1.¹⁵ In the fast simulation it is possible to use a parametrization [26] or an algorithm-based method. We used our own algorithm. With our algorithm, a jet is considered as a tagged τ -jet if (a) it has 1 or 3 charged tracks; (b) the isolation fraction (see Appendix B) satisfies $F_{\text{Iso}} < F_{\text{Iso}}^0(p_T)$ where $F_{\text{Iso}}^0(p_T)$ is determined by the crossing point of the labeled and non-labeled F_{Iso} for a given p_T ; (c) the electromagnetic radius (see Appendix B) satisfies $R_{\text{EM}} < R_{\text{EM}}^0(p_T)$ where $R_{\text{EM}}^0(p_T)$ is determined by the crossing point of the labeled and non-labeled R_{EM} for a given p_T . The cut values are given in a Table 4.3. Figure 4.6 shows the efficiency (a), the rejection of the non- τ -jets (b), and the purity and contamination (c) for the fully simulated signal events (blue full line), for those with our fast τ -algorithm applied (red dotted line), and for those with the parametrization (magenta dashed line), all of them calculated on the full $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ sample.

4.3 Missing energy reconstruction

In the full simulation there are several ways to calculate the missing energy [17]. The most common one is to sum up the energies from all calorimeter cells. Instead of calorimetric cells, reconstructed objects can be used as well. Finally, the energy of the muons calculated from the muon spectrometer is added. We use Topological clusters as input objects. Resolution in the signal channel (defined as $(E_{T_{\text{miss}}} - E_{T_{\text{miss}}(\text{MC})})/E_{T_{\text{miss}}}$ is 0.17. More details can be found in [25]. In the fast simulation missing E_T is calculated as following: all isolated objects are added (EM, muon, energy corrected jets), then non-isolated muons, then clusters non-associated with objects, then cells non associated with clusters.

4.4 W reconstruction

For the W reconstruction we used several approaches. In the first one we used a constrained fit to reconstruct the

Fig. 4.5 The value of the likelihood function for τ -labeled (blue solid line) and non-labeled (red dashed line) jets for different transverse momenta of the jet. All distributions are normalized to unity **Fig. 4.6** Dependence of the (a) τ -id efficiency, (b) rejection, and (c) purity and contamination on the p_T of the jet of the signal sample. Results are shown for the full simulation (blue solid line), for our fast simulation algorithm (red dotted line), and for the parametrization (magenta dashed line)

W -boson from the two light jets. In addition we developed a multivariate technique to reconstruct the whole $t\bar{t}$ system. This approach is described in the next paragraph.

¹⁵This cut removes non identified electrons.

4.5 Top reconstruction

In the first approach we reconstruct the hadronic t -quark as a sum of the reconstructed W ¹⁶ and b -jet. The combination that gives the invariant mass m_{bW} closer to m_{top} is chosen. We also tried to reconstruct the t -quark that decayed semileptonically.¹⁷ The reconstruction failed in 30% of the events when we assumed that the ν_ℓ carried the total missing momentum. The reconstruction failed in 20% of the events when we assumed that m_H was already measured, such that we reconstructed the total momentum of the τ -neutrinos and subtracted it from the total missing momentum in order to reconstruct the ν_ℓ . When we combined these two methods, the reconstruction failed¹⁸ in 13% of the events. Eventually, we dropped the reconstruction of the semi-leptonic top quark because it could not give us any distinguishable signal.

In the second method for the reconstruction of the $t\bar{t}$ system¹⁹ we use a multivariate technique based on the distributions of the correct and incorrect combinations of the $t\bar{t}$ system ingredients. For the discriminant variable we use $\ln(L_W)$, where L_W is defined as:

$$L_W = \frac{\prod \text{pdf}(V_{\text{true}})}{\prod \text{pdf}(V_{\text{fake}})}, \quad (4.2)$$

where the product runs over all discriminant variables V . The pdf is their probability density function, true denotes the reconstructed $t\bar{t}$ system that matches the MC $t\bar{t}$ system²⁰, and fake denotes the reconstructed $t\bar{t}$ systems that do not match the MC system. We use the mass(es)²¹ of the W -boson(s) and the t -quark(s), and distances between the reconstructed particles for the calculation of the likelihood. The combination with the maximal likelihood is chosen.²² In $\sim 70\%$ the maximal likelihood combination was

¹⁶We use a constrained fit for the W reconstruction.

¹⁷We tried this for the channels from the second group—4 and 5.

¹⁸Reconstruction failed when the solution for p_Z was not real number.

¹⁹ $t\bar{t}$ system is $bjjbjj$ for channel 2 and $bjjb\ell\bar{\nu}_\ell$ for channels 4 and 5.

²⁰For channels 4 and 5 the matching of the reconstructed $t\bar{t}$ system and the MC one requires that b -jet originating in hadronic (leptonic) decay of the t -quark has the corresponding b -parton within a cone of $\Delta R < 0.3$, that the reconstructed lepton is within $\Delta R < 0.2$ from the MC lepton from the semileptonically decaying t -quark, and that both jets are within $\Delta R < 0.3$ from the partons originating in the W -boson. Similarly, for channel two we asked that all MC partons can be matched to the corresponding reconstructed object.

²¹In the case of channels 4, 5 we use the mass of the hadronic W boson and top quark. For channel 2 we use the masses of both W -bosons and t -quarks.

²²Also for events with no matching at all.

Fig. 4.7 The input variables for the $t\bar{t}$ system reconstruction likelihood L_W : (a) the mass of the W -boson from the hadronically decayed t -quark, (b) the distance ΔR between jets from the W -boson from the hadronically decayed t -quark, (c) the mass of the hadronically decayed t -quark, (d) the distance ΔR between the b -jet and the W -boson from the hadronically decayed t -quark, and (e) the distance ΔR between the b -jet and the lepton from the semileptonically decayed t -quark. The final likelihood $\ln(L_W)$ is given in (f). The matched combination is shown with a blue solid line, the non-matched with a red dashed, and the combination that gives the maximal likelihood L_W with a brown dash-dotted line. All distributions are normalized to unity

matched. Figure 4.7 shows the distribution²³ of the input variables²⁴—(a) the mass of the W -boson from the hadronically decayed t -quark, (b) the distance ΔR between jets from the W -boson from the hadronically decayed t -quark, (c) the mass of the hadronically decayed t -quark, (d) the distance ΔR between the b -jet and the W -boson from the hadronically decayed t -quark, and (e) the distance ΔR between the b -jet and the lepton from the semileptonically decayed t -quark for the matched combinations (blue solid line), non matched ones (red dashed line) and those that give maximal likelihood (brown dash-dotted line) for $t\bar{t}H^0 \rightarrow b\bar{\nu}_\ell\bar{b}jj\tau^+\tau^-$. The final $t\bar{t}$ system likelihood $\ln(L_W)$ is shown in Fig. 4.7(f).

²³Distributions are normalized to unity.

²⁴For channels 4 and 5.

Table 4.4 The High Level Trigger (HLT) menu for the low and high luminosity conditions. “Electron (1) or (2)” (for instance) means that the trigger condition is either one electron with the $p_T > 25$ GeV (for low luminosity), or two electrons both having $p_T > 15$ GeV. “Electron + muon” means that the trigger condition is one electron with the $p_T > 15$ GeV and one muon with the $p_T > 10$ GeV (low luminosity)

Selection	Low luminosity	High luminosity
Electron (1) or (2)	$p_T(e_1) > 25$ GeV, $p_T(e_2) > 15$ GeV	$p_T(e_1) > 30$ GeV $p_T(e_2) > 20$ GeV
Muon (1) or (2)	$p_T(\mu_1) > 20$ GeV, $p_T(\mu_2) > 10$ GeV	$p_T(\mu_1) > 20$ GeV, $p_T(\mu_2) > 10$ GeV
Electron + Muon	$p_T(e_1) > 15$ GeV and $p_T(\mu_1) > 10$ GeV	$p_T(e_1) > 15$ GeV and $p_T(\mu_1) > 10$ GeV
Jets (1) or (3) or (4)	$p_T(j_1) > 400$ GeV, $p_T(j_3) > 165$ GeV, $p_T(j_4) > 110$ GeV	$p_T(j_1) > 590$ GeV, $p_T(j_3) > 260$ GeV, $p_T(j_4) > 150$ GeV
Jet + $\cancel{p}_T$	$p_T(j_1) > 70$ GeV and $\cancel{p}_T > 70$ GeV	$p_T(j_1) > 100$ GeV and $\cancel{p}_T > 100$ GeV
τ_j + $\cancel{p}_T$	$p_T(\tau_j) > 35$ GeV and $\cancel{p}_T > 45$ GeV	$p_T(j_1) > 60$ GeV and $\cancel{p}_T > 60$ GeV

4.6 Final reconstruction and comparison between full and fast simulation

As an example we describe here the final reconstruction of channel 5, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\ell\bar{\nu}_\ell\nu_\tau$. A comparison of the full and the fast simulation is presented, for a data set corresponding to an integrated luminosity of 30 fb^{-1} . The detailed analyses of all channels, including channel 5, are given in Sects. 5.1, 5.2 and 5.3.

Events are preselected if they fulfill the topology requirement: 2 b -tagged jets, one τ -tagged jet, two light jets and two leptons (the default cuts are $p_T > 5$ GeV and $|\eta| < 2.5$ except for jets, where the requirements are $p_T > 15$ GeV, and $|\eta| < 5$ for light and $|\eta| < 2.5$ for τ and b jets). Every event is required to satisfy at least one High Level Trigger (HLT) condition. These conditions are shown in Table 4.4 for low and high luminosity. We also require that the hadronic W -boson and t -quark are successfully reconstructed.²⁵ We compare several properties of the reconstructed objects in the full and fast simulation. This is shown in Fig. 4.8 for p_T of the first lepton (a), p_T of the τ_j (b), p_T of the first b -jet (c), and p_T of the first jet from W (d). The comparisons of the masses of the reconstructed W -boson and t -quark are shown in Fig. 4.8(e) and (f). Finally, Figure 4.9 shows the invariant mass of the τ -jet and lower-energy lepton (that is the lepton originating from τ in 70% of the cases). One can see a fair agreement between the var-

Fig. 4.8 The distributions of the: (a) transverse momentum of the higher energy lepton, (b) transverse momentum of the τ -jet, (c) transverse momentum of the higher energy b -jet, (d) transverse momentum of the higher energy jet from W -boson, (e) mass of the W -boson from the hadronically decayed t -quark, and (f) mass of the hadronically decayed t -quark, for events simulated with the fast simulation (red dashed line) and the full simulation (blue solid line) in the $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\ell\bar{\nu}_\ell\nu_\tau$ channel. All distributions are normalized to 30 fb^{-1} . For parts (c)–(f) we required only reconstruction of light and b -jets, W -boson and top quark, for part (b) we required also τ -jet, and for part (a) also a lepton

Fig. 4.9 The distribution of the invariant mass of the τ -jet and the lower energy lepton in the fast (red dashed line) and the full simulation (blue solid line) in the $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\ell\bar{\nu}_\ell\nu_\tau$ channel. All distributions are normalized to 30 fb^{-1}

ious reconstructions in the full (blue solid line) and the fast (red dashed line) simulation.

This agreement exists also quantitatively. To demonstrate it, we performed a simple cuts based analysis on channel 5 using $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$ as the dominant background. The cut

²⁵We use a constrained fit method for the W reconstruction, and minimization of the $|m_{\text{top}} - m_{bW}|$ for the top reconstruction at this point.

Table 4.5 The number of expected events for 30 fb^{-1} after simple cuts for $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\ell\bar{\nu}_\ell\nu_\tau$ ($m_H = 120 \text{ GeV}$) simulated with the full and the fast simulation, and for the $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$ simulated with the fast simulation. Reconstruction in the second row means that the event is fully reconstructed, i.e. it contains 2 leptons, 2 b jets, one τ jet and missing energy. The $q_{\text{lep}(\tau)}$ is charge of the lepton (τ jet)

Cut flow	Signal fast	Signal full	Background ($t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$)
Reconstruction	14.1	17.3	341
Trigger	13.9	17.1	330
W reconstruction	11.3	10.4	270
Top reconstruction	7.0	6.7	134
$\Sigma p_T(t\bar{t}) > 300 \text{ GeV}$	6.3	6.0	88
$p_T(\text{lep}) > 18 \text{ GeV}$	3.6	3.6	6
$q_{\text{lep}} \cdot q_\tau < 0$	2.8	2.7	3.1
$q_{\text{lep}} \cdot q_{\text{lep}} > 0$	1.4	1.2	1.5
$m_H > 40 \text{ GeV}$	1.3	1.1	0.7

flow is given in Table 4.5 where a good agreement is seen at each stage.

Although the fast simulation suffers from various issues mainly concerning isolation and object tagging it is shown that, after the same cuts, both the distributions and the number of expected events agree. We therefore conclude that the fast simulation can be used for the purpose of this analysis, namely, checking the feasibility of the concerned channels.

5 Analysis

In this section channels 2, 4, and 5 are described in detail. Every event is required to pass corresponding topology and trigger conditions. We further require that the $t\bar{t}$ system is successfully reconstructed²⁶ and that some preselection requirements are fulfilled.

For the analysis we use a multivariate technique. For all events that pass the topology, trigger and some preselection requirements, we use a discriminant $\ln(L_H)$, where L_H is defined as:

$$L_H = \frac{\prod \text{pdf}(V_{\text{Sig}})}{\prod \text{pdf}(V_{\text{Bkg}})} \quad (5.1)$$

where V_{Sig} and V_{Bkg} stand for the variables that enter the likelihood calculation, for signal and background respectively. For the background we use the dominant source, which is $t\bar{t}$ production.

²⁶We use a multivariate technique in this part (see Sect. 4.5).

Fig. 5.1 The transverse momenta of the lepton (a) and τ_j (b), the missing momentum (c), and the $\ln(L_W)$ (d) for the signal events (blue solid line), and for the $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$ (red dotted line) and the $t\bar{t} \rightarrow bjj\bar{b}jj$ (magenta dashed line) background processes. Only the backgrounds affected with the cut are shown in the corresponding part of the figures. All distributions are normalized to unity

5.1 Channel 2

Channel 2, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow bjj\bar{b}jj\tau_j\bar{\nu}_\tau\ell\bar{\nu}_\ell\nu_\tau$, contains one τ -jet, two b -jets, four light jets, one energetic lepton and missing energy. The fact that both t -quarks in the signal decay hadronically has two important consequences:

1. Both t -quarks can be fully reconstructed.
2. The total physical²⁷ missing energy originates in the Higgs boson. That enables to reconstruct the real mass of the Higgs boson using a collinear approximation (see Appendix C).

The dominant backgrounds are $t\bar{t}$ with both t -quarks decaying hadronically, $t\bar{t} \rightarrow bjj\bar{b}jj$, or one decays semileptonically and the other hadronically, $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$. To suppress background, we applied the following preselection cuts:

- The reconstructed Higgs mass²⁸ is in a window between 0 and 250 GeV. This variable is also an input variable to the Likelihood and it is shown in Fig. 5.3(b).
- The charges of the τ -jet and the lepton must be opposite.
- The transverse momentum of the lepton is larger than 10 GeV (Fig. 5.1(a)). This cut is introduced to suppress background events with no isolated leptons.
- The transverse momentum of the τ -jet is larger than 35 GeV (Fig. 5.1(b)). The real τ -jets tend to have higher transverse momenta than the fake ones.

²⁷The physical missing energy originates in neutrinos. The non-physical can be detector related.

²⁸Where we use a collinear approximation to reconstruct the Higgs mass.

Fig. 5.2 The reconstructed masses of the first W -boson (a), the first t -quark (b), the second W -boson (c), and the second t -quark (d) for the signal events (blue solid line), and the $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$ (red dotted line) background process. All distributions are normalized to unity

- The missing p_T is larger than 20 GeV (Fig. 5.1(c)). This cut should reject events without any real missing energy.
- $\ln(L_W) > 0.75$ (defined in 4.5) (Fig. 5.1(d)).
- The mass of the first reconstructed W -boson²⁹ is between 60 and 110 GeV (Fig. 5.2(a)).
- The mass of the second reconstructed W -boson³⁰ is between 40 and 110 GeV (Fig. 5.2(c)).
- The masses of both t -quarks are between 140 and 210 GeV (Fig. 5.2(b) and (d)).

The $t\bar{t} \rightarrow bjj\bar{b}jj$ system is fully reconstructed in $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow bjj\bar{b}jj\tau_j\bar{\nu}_\tau\bar{\ell}\bar{\nu}_\ell\nu_\tau$ (signal) events. Cuts on the W and top variables are introduced to suppress events without two top quarks that decayed hadronically like $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$ as well as $t\bar{t} \rightarrow bjj\bar{b}jj$ events without Higgs boson.

For the determination of the likelihood the $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$ events serve as a background. The input variables for the discriminant likelihood are:

- The transverse mass of the lepton³¹ and missing p_T , defined as

$$m_T(l\cancel{p}_T) \equiv \sqrt{(|p_T(l)| + |\cancel{p}_T|)^2 - |\vec{p}_l + \vec{\cancel{p}_T}|^2}. \quad (5.2)$$

In the $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$ events, most of the missing energy originates in $W \rightarrow \bar{\ell}\bar{\nu}_\ell$ decay, while in the signal events the biggest part of the missing energy originates in τ_l decays. It is expected that $m_T(l\cancel{p}_T)$ would have an edge at m_W for the $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$ events, and would peak toward zero for the signal events. This is shown in Fig. 5.3(a).

²⁹The first reconstructed t -quark is the one with the more energetic b -jet. The corresponding W -boson is called the first.

³⁰The second reconstructed t -quark is the one with the less energetic b -jet. The corresponding W -boson is called the second.

³¹The mass of the lepton is neglected.

Fig. 5.3 The input variables for the L_H : (a) the transverse mass of the lepton and neutrino, (b) the reconstructed Higgs mass, (c) x_l , (d) the distance between lepton and τ_j , (e) maximal $\Delta\phi$ between lepton or τ_j , and missing p_T , and (f) $\Delta\phi$ between reconstructed Higgs boson and missing p_T . The distributions are shown for the signal events (blue solid line), and the $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$ (red dotted line) background process. All distributions are normalized to unity

- The reconstructed Higgs mass shown in Fig. 5.3(b) (see Appendix C). In order to further suppress backgrounds, especially the irreducible $Zt\bar{t} \rightarrow \tau^+\tau^-t\bar{t}$, the likelihood is set to zero if the reconstructed Higgs mass is smaller³² than 100 GeV or larger than 170 GeV.
- x_l , i.e. the fraction of the energy of the leptonically decayed τ_l carried by neutrinos from that decay shown in Fig. 5.3(c) (see Appendix C). The likelihood is set to zero if either x_l or x_h , i.e. the fraction of the energy of the hadronically decayed τ_l carried by ν_τ , are larger than 1.
- The following distances:
 - $\Delta R_{\tau_j l}$ between the τ -jet and the lepton. In the signal events, the τ -jet and the lepton originate from the same particle, the Higgs boson and it is expected that their distance is smaller in the signal than in the $t\bar{t}$ events (Fig. 5.3(d)).
 - ΔR_{jj2} between the light jets from the W -boson. It is assumed that the jet matching is better in the signal events than in the $t\bar{t}$.³³ Also, there is less phase space in

³²For a Higgs mass of 110 GeV, the lower limit was set to 92 GeV, and for a Higgs mass of 130 GeV to 105 GeV.

³³ $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$ is the biggest background for this channel. The assumption is that the signal is fully reconstructed, while in the background, some of the objects are randomly assigned to the top quark

Table 5.1 Signal efficiencies for channel 2, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow bjj\bar{b}jj\tau_j\bar{\nu}_\tau\ell\bar{\nu}_\ell\nu_\tau$. The second line shows efficiency for the events that are reconstructed, triggered and pass the topology requirement

m_H (GeV)	110	120	130
Initial number of events (%)	100	100	100
Reconstructed events (%)	7.0	10.9	19.7
Final number of events (%)	0.19	0.32	0.26

the signal than in the $t\bar{t}$ events. Thus, we expect that this distance is smaller in the signal than in the $t\bar{t}$ events. We use the distance between the jets that correspond to the second W -boson.

- ΔR_{bW1} between the b -jet and the reconstructed W -boson. This distance is smaller in the signal than in the $t\bar{t}$ events.³⁴ We use the distance between the b -jet and the W that correspond to the first t -quark.
- The following angular distances in the transverse plane:
 - The minimal and maximal $\Delta\Phi$ between τ_j or lepton, and the missing momentum (the maximal one is shown in Fig. 5.3(e)). The missing momentum in the signal events originates in the neutrinos from the τ -leptons from the Higgs boson decays. Thus we expect that the missing momentum is closer to the products of the τ -leptons decays (lepton and τ -jet) in the signal than in the background events.
 - $\Delta\Phi$ between the visible Higgs boson ($l\tau_j$)³⁵ and the missing momentum. In the signal events complete missing energy originates in the Higgs boson. Thus, it is expected that the $\vec{p}_T$ and visible Higgs boson are closer in the signal than in the background (Fig. 5.3(f)).
 - $\Delta\Phi$ between the reconstructed $t\bar{t}$ system and the missing momentum. There is no missing energy originating in the $t\bar{t}$ system in the signal events. Thus, the reconstructed $t\bar{t}$ system and $\vec{p}_T$ are more back-to-back in the signal events.

The resulting discriminant for $m_h = 120$ GeV is shown in Fig. 5.4. For both $m_h = 110$ GeV and $m_h = 130$ GeV, the likelihood was slightly changed.³⁶ The events are accepted if $\ln(L_H) > 2.5$ for $m_h = 110$ GeV and $m_h = 120$ GeV, and if $\ln(L_H) > 2.1$ for $m_h = 130$ GeV. Final signal efficiencies are given in Table 5.1. Results for 30 fb^{-1} are shown in Table 5.2. The $t\bar{t}$ background contributes more than 80% to the total background (Table 5.3).

reconstruction (there is no second true hadronic t -quark in the biggest background).

³⁴With the inclusion of $t\bar{t}$ + jets this might change, and it might be possible that this variable becomes obsolete.

³⁵Sum of the τ -jet and lepton.

³⁶The reconstructed mass of the Higgs boson is changed.

Table 5.2 The number of expected events for the signal and the total background for 30 fb^{-1} for channel 2, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow bjj\bar{b}jj\tau_j\bar{\nu}_\tau\ell\bar{\nu}_\ell\nu_\tau$. S/B and $S/\sqrt{B}$ are also given. Only the statistical errors are shown

m_H (GeV)	Signal	Background	S/B	$S/\sqrt{B}$
110	0.77 ± 0.11	0.72 ± 0.35	1.07	0.91
120	0.93 ± 0.10	0.82 ± 0.41	1.13	1.03
130	0.45 ± 0.06	0.77 ± 0.39	0.58	0.51

Table 5.3 The dominant background sources for channel 2, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow bjj\bar{b}jj\tau_j\bar{\nu}_\tau\ell\bar{\nu}_\ell\nu_\tau$, (in %)

m_H (GeV)	$t\bar{t}$ (%)	$Zt\bar{t}$ (%) $Z \rightarrow \tau^+\tau^-$ $t\bar{t} \rightarrow b\bar{\nu}_\ell\bar{b}jj$	$Zt\bar{t}$ (%) $Z \rightarrow \tau^+\tau^-$ $t\bar{t} \rightarrow bjj\bar{b}jj$
110	79	3	18
120	84	3	13
130	89	3	8

Fig. 5.4 The resulting likelihood L_H for the signal with $m_h = 120$ GeV (blue solid line), and the $t\bar{t} \rightarrow b\bar{\nu}_\ell\bar{b}jj$ (red dotted line) and the $t\bar{t} \rightarrow bjj\bar{b}jj$ (magenta dashed line) background processes. All distributions are normalized to 30 fb^{-1}

5.2 Channel 4

Channel 4, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\tau_j\nu_\tau$, contains two τ -jets, two b -jets, two light jets, one energetic lepton and missing energy. The dominant background is $t\bar{t} \rightarrow b\bar{\nu}_\ell\bar{b}jj$. In order to suppress the background we applied the following preselection cuts:

- The charges of the two τ -jets must be opposite to remove fake τ -jets.
- The transverse momenta of the τ -jets should fulfill $p_T(\tau_{j1}) > 50 \text{ GeV}$ and $p_T(\tau_{j2}) > 30 \text{ GeV}$ (Fig. 5.5(a) and (b)). The real τ -jets tend to have higher transverse momenta than the fake ones.
- The transverse momentum of the lepton is larger than 10 GeV (Fig. 5.5(c)). This cut is introduced to suppress events with no real leptons.

Fig. 5.5 The transverse momenta of the first τ -jet (a), the second τ -jet (b), the lepton (c), and the missing transverse momentum (d) for the signal events (blue solid line), and for the $t\bar{t} \rightarrow b\bar{\nu}_\ell \bar{b}jj$ (red dotted line), the $t\bar{t} \rightarrow b\bar{\nu}_\ell b\bar{\nu}_\ell$ (magenta dashed line) and the $t\bar{t} \rightarrow bjbjbj$ (black dash-dotted line) background processes. All distributions are normalized to unity

- The missing p_T must be larger than 30 GeV (Fig. 5.5(d)). This cut is introduced to reject events without real missing momentum.
- $\ln(L_W) > 0$ (Fig. 5.6(a)).
- The invariant mass of the lepton and b -jet from the semileptonic t -quark decay $m_{t_l} > 30$ GeV (Fig. 5.6(b)).
- The mass of the reconstructed W -boson from the hadronically decayed t -quark is between 40 and 110 GeV (Fig. 5.6(c)).
- The mass of the reconstructed hadronically decayed t -quark is between 135 and 210 GeV (Fig. 5.6(d)).

The $t\bar{t} \rightarrow b\bar{\nu}_\ell \bar{b}jj$ system is fully reconstructed in $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\bar{\nu}_\ell \bar{b}jj\tau_j\bar{\nu}_\tau\tau_j\nu_\tau$ (signal) events. Cuts on the W and top variables are introduced to suppress events without two top quarks out of which one decayed hadronically and the other semileptonically as well as $t\bar{t} \rightarrow b\bar{\nu}_\ell \bar{b}jj$ events without Higgs boson.

The input variables for the discriminant likelihood are:

- The transverse mass of the lepton and missing transverse momentum (5.2). In the $t\bar{t} \rightarrow b\bar{\nu}_\ell \bar{b}jj$ events most of the missing transverse momentum is coming from $W \rightarrow \bar{\nu}_\ell \nu_\tau$ decay, while in the signal events a significant part of the missing transverse momentum originates in $\tau_l \rightarrow \tau_j \nu_\tau$. This is shown in Fig. 5.7(a).
- The transverse momentum of the hadronically decayed t -quark (Fig. 5.7(b)).

Fig. 5.6 The $\ln(L_W)$ (a), the invariant mass of the lepton and b -jet from the semileptonically decayed t -quark (b), the mass of the reconstructed W -boson from the hadronically decayed t -quark (c), and the mass of the reconstructed hadronically decayed t -quark (d) for the signal events (blue solid line), and for the $t\bar{t} \rightarrow b\bar{\nu}_\ell \bar{b}jj$ (red dotted line), the $t\bar{t} \rightarrow b\bar{\nu}_\ell b\bar{\nu}_\ell$ (magenta dashed line) and the $t\bar{t} \rightarrow bjbjbj$ (black dash-dotted line) background processes. All distributions are normalized to unity

- The following distances:
 - $\Delta R_{\tau_j \tau_j}$ between the two τ -jets. This distance is smaller in the signal than in the $t\bar{t}$ events (Fig. 5.7(c)).
 - ΔR_{bW} between the b -jet and the reconstructed W -boson from the hadronically decayed t -quark. This distance is smaller in the signal than in the $t\bar{t}$ events³⁷ (Fig. 5.7(d)).
- The following angular distances in transverse plane:
 - The minimal $\Delta\Phi$ between the τ_j and the missing momentum (Fig. 5.8(a)).³⁸
 - $\Delta\Phi$ between the lepton and the missing momentum (Fig. 5.8(b)).
 - $\Delta\Phi$ between the reconstructed visible Higgs boson³⁹ and the missing momentum (Fig. 5.8(c)).
 - $\Delta\Phi$ between the reconstructed visible Higgs boson and the b -jet from the hadronically decayed t -quark⁴⁰ (Fig. 5.8(d)).
 - $\Delta\Phi$ between the reconstructed hadronically decayed t -quark and the missing momentum (Fig. 5.8(e)).

³⁷With the inclusion of $t\bar{t} + \text{jets}$ this might change, and it might be possible that this variable becomes obsolete.

³⁸There are two τ_j in events, so we chose the smaller $\Delta\Phi$.

³⁹The sum of the two τ -jets.

⁴⁰In the $t\bar{t} \rightarrow b\bar{\nu}_\ell \bar{b}jj$ events both jets from W -boson are often tagged as τ -jets.

Fig. 5.7 The input variables for the L_H : (a) the transverse mass of the lepton and neutrino, (b) the transverse momentum of the reconstructed hadronically decayed t -quark, $p_T(t_H)$, (c) the ΔR between two τ -jets, and (d) the ΔR between the b -jet and the W -boson from the hadronically decayed t -quark, for the signal events (blue solid line), and for the $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$ (red dotted line) background process

– Finally, we have used the maximal $\Delta\eta$ between the visible Higgs boson and the reconstructed t -quark⁴¹ (Fig. 5.8(f)).

The resulting discriminant is shown in Fig. 5.9. For all masses we accepted events if $\ln(L_H) > 1.3$. For the $m_H = 110$ GeV and $m_H = 120$ GeV we required that the invariant mass of the two τ_j , i.e. the visible Higgs mass, is between 50 and 140 GeV, while for $m_H = 130$ GeV we set the mass window to (55, 140) GeV. The distribution of the visible Higgs mass for $m_H = 120$ GeV is shown in Fig. 5.10 before (a) and after (b) the aforementioned cut on the likelihood. It can be seen clearly that $t\bar{t}$ events, where both jets from the W -boson decay are tagged as τ -jets, have smaller values of the likelihood, and, therefore, are cut off.

Final signal efficiencies are given in Table 5.4. The final results for this channel for 30 fb^{-1} are shown in Table 5.5. About 50% of the total background originates from $t\bar{t}$ events, and $\sim 40\%$ is from the irreducible $Zt\bar{t} \rightarrow \tau^+\tau^-t\bar{t}$ (Table 5.6).

5.3 Channel 5

Channel 5, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\bar{\ell}\bar{\nu}_\tau\nu_\tau$, contains one τ -jet, two b -jets, two light jets, two energetic leptons and missing energy. The dominant backgrounds are $t\bar{t}$ where both top-quarks decay semi-leptonically, or one

Fig. 5.8 The input variables for the L_H : (a) the minimal $\Delta\phi$ between the τ -jet and the missing momentum, (b) $\Delta\phi$ between the lepton and the missing momentum, (c) $\Delta\phi$ between the visible Higgs boson and the missing momentum, (d) $\Delta\phi$ between the visible Higgs boson and the b -jet from the hadronically decayed t -quark, (e) $\Delta\phi$ between the hadronically decayed t -quark and the missing momentum, and (f) the maximal $\Delta\eta$ between the reconstructed visible Higgs boson and the t -quark. The distributions are shown for the signal events (blue solid line), and for the $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$ (red dotted line) background process. All distributions are normalized to unity

Table 5.4 Signal efficiencies for channel 4, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\bar{\ell}\bar{\nu}_\tau\nu_\tau$. The second line shows efficiency for the events that are reconstructed, triggered and pass the topology requirement

m_H (GeV)	110	120	130
Initial number of events (%)	100	100	100
Reconstructed events (%)	5.0	5.2	6.5
Final number of events (%)	0.23	0.42	0.33

⁴¹We consider the fully reconstructed hadronically decayed t -quark, while for the semileptonically decayed t -quark, we encountered just its visible part, i.e. $t_l = b + l$.

decays semi-leptonically and the other hadronically, $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}\ell\nu_\ell$ and $t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$, respectively. In order to reduce the background, we applied the following preselection cuts:

Table 5.5 The number of expected events for the signal and the total background for 30 fb^{-1} for channel 4, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\tau_j\nu_\tau$. S/B and $S/\sqrt{B}$ are also given

m_H (GeV)	Signal	Background	S/B	$S/\sqrt{B}$
110	0.56 ± 0.10	0.7 ± 0.26	0.8	0.67
120	0.71 ± 0.09	0.7 ± 0.26	1.01	0.85
130	0.35 ± 0.05	0.65 ± 0.25	0.54	0.43

Table 5.6 The dominant background sources for channel 4, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\tau_j\nu_\tau$ (in %)

m_H (GeV)	$t\bar{t}$ (%)	$Zt\bar{t}$ (%)	$Zt\bar{t}$ (%)
		$Z \rightarrow \tau^+\tau^-$	$Z \rightarrow \tau^+\tau^-$
		$t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$	$t\bar{t} \rightarrow b\tau\bar{\nu}_\tau\bar{b}jj$
110	49	41	10
120	49	41	10
130	52	37	11

Fig. 5.9 The resulting likelihood L_H for the signal with $m_H = 120 \text{ GeV}$ (blue solid line), and for the $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$ (red dotted line) and the $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}\ell\nu_\ell$ (magenta dashed line) background processes. All distributions are normalized to 30 fb^{-1}

- The charges of the τ -jet and the lepton⁴² coming from the other τ must be opposite.
- $\ln(L_W) > 0.5$ (Fig. 5.11(a)).
- The missing p_T is larger than 30 GeV (Fig. 5.11(b)). This cut is introduced to suppress events without real missing momentum.
- The transverse momenta of each of the leptons is larger than 15 GeV (Fig. 5.11(c) and (d)).
- The mass of the reconstructed W -boson from the hadronically decayed t -quark is between 40 and 110 GeV (Fig. 5.11(e)).

⁴²Since we reconstruct the complete $t\bar{t}$ system, the lepton that is not associated with the semileptonically decayed top quark, is assumed to originate in the τ (see Sect. 4.5).

Fig. 5.10 The invariant mass of the two τ -jets (visible Higgs boson) before (a) and after (b) cut on the likelihood (see text) for $m_H = 120 \text{ GeV}$, shown for the signal on top of the backgrounds. All distributions are normalized to 30 fb^{-1} **Fig. 5.11** The distributions of the: (a) $\ln(L_W)$, (b) missing transverse momentum, (c) transverse momentum of the lepton from the semileptonically decayed t -quark, (d) transverse momentum of the lepton from τ , (e) mass of the W -boson from the hadronically decayed t -quark, and (f) mass of the hadronically decayed t -quark, for the signal events (blue solid line), and for the $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$ (red dotted line) and the $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}\ell\nu_\ell$ (magenta dashed line) background processes. All distributions are normalized to unity

Table 5.10 The dominant background sources for channel $5\ t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\bar{b}\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\bar{\nu}_\ell\nu_\tau$ (in %)

m_H (GeV)	$t\bar{t}$ (%)	$Zt\bar{t}$ (%)	$Zt\bar{t}$ (%)	$Zt\bar{t}$ (%)	$Zt\bar{t}$ (%)
		$Z \rightarrow \tau^+\tau^-$	$Z \rightarrow e^+e^-, \mu\mu$	$Z \rightarrow \tau^+\tau^-$	$Z \rightarrow e^+e^-, \mu\mu$
		$t\bar{t} \rightarrow b\bar{b}\bar{\nu}_\ell\bar{b}jj$	$t\bar{t} \rightarrow b\bar{b}\bar{\nu}_\ell\bar{b}jj$	$t\bar{t} \rightarrow b\tau\bar{\nu}_\tau\bar{b}jj$	$t\bar{t} \rightarrow b\tau\bar{\nu}_\tau\bar{b}jj$
110	26	40	10	15	9
120	26	40	10	15	9
130	30	35	13	13	9

Table 5.11 The number of expected events for the signal and the total background for 30 fb^{-1} for the combined three channels under consideration. S/B and $S/\sqrt{B}$ are also given

m_H (GeV)	Signal	Background	S/B	$S/\sqrt{B}$
110	2.33 ± 0.19	2.42 ± 0.48	0.96	1.50
120	2.61 ± 0.17	2.61 ± 0.53	1.0	1.62
130	1.23 ± 0.09	2.53 ± 0.52	0.46	0.77

Fig. 5.14 The invariant mass $m_{\ell\tau_j}$ of the signal on top of the backgrounds for 30 fb^{-1} and $m_H = 120\text{ GeV}$

(Fig. 5.12(b)):

$$p_T(t\bar{t} + \cancel{p}_T) \equiv p_T(l_1) + p_T(b_1) + p_T(b_2) + p_T(j_1) + p_T(j_2) + \cancel{p}_T \quad (5.3)$$

Even though this paper is a feasibility study for the low luminosity benchmark case (30 fb^{-1}), a preliminary fast simulation study of the high luminosity is performed. Though, one is tempted to believe that increasing the luminosity by a factor x would result in an increase of a $S/\sqrt{B}$ by a factor of $\sqrt{x}$, this is not the case. When the luminosity is increased the pile up becomes a major issue. At the design luminosity of $10^{34}\text{ cm}^2\text{ s}^{-1}$, an average 23 minimum bias events are expected per bunch-crossing. The minimum bias events with small transverse momenta arise from long-range p - p interactions. They can be viewed as a bath of energy superposed on the hard scattering of interest, a phenomenon known as *pile-up*.

- The distance, ΔR , between the light jets that originate in the W -boson (Fig. 5.12(c)). The light jets are closer in the signal than in the $t\bar{t}$ events.

- The following angular distances in the transverse plane:
 - $\Delta\Phi$ between the Higgs boson⁴³ and the missing momentum (Fig. 5.12(d)).
 - $\Delta\Phi$ between the reconstructed hadronically decayed t -quark and the missing momentum.
- Finally, we use $\Delta\eta$ between the following reconstructed objects:
 - The τ -jet and the lepton coming from the other τ (Fig. 5.12(e)).
 - The b -jet and the reconstructed W coming from the hadronically decayed t -quark (Fig. 5.12(f)).

The resulting discriminant is shown in Fig. 5.13(a). Note that the distributions are normalized to 1. When normalized to the corresponding cross-sections (Fig. 5.13(b)), it appears that $t\bar{t} \rightarrow b\bar{b}\bar{\nu}_\ell\bar{b}jj$ (magenta dashed line) is by two orders of magnitude larger than the signal (blue solid line) and $t\bar{t} \rightarrow b\bar{b}\bar{\nu}_\ell\bar{b}jj$ (red dotted line). To suppress this background, and also $Z + X \rightarrow \ell^+\ell^- + X$, we require that both leptons have the same charge (Fig. 5.13(c)). The efficiency of this cut for the signal, and the $t\bar{t} \rightarrow b\bar{b}\bar{\nu}_\ell\bar{b}jj$ and $t\bar{t} \rightarrow b\bar{b}\bar{\nu}_\ell\bar{b}jj$ backgrounds is given in Table 5.7. The final discriminant after this cut is shown in Fig. 5.13(d). We require that $\ln(L_H) > 2.6$. Figure 5.14 shows the “Higgs mass”, i.e. invariant mass of the τ -jet and lepton coming from τ . We count events if the Higgs mass is between 40 and 120 GeV. Final signal efficiencies are given in Table 5.8. Results for three Higgs masses are shown in a Table 5.9. About 40% of the total background is irreducible $Zt\bar{t} \rightarrow \tau^+\tau^-t\bar{t}$, and $\sim 26\%$ originates in $t\bar{t}$ events (Table 5.10).

5.4 Combined results for the low luminosity (30 fb^{-1})

The combined results for all three channels under consideration are given in Table 5.11.

6 High luminosity

It is found that the performance of the tau-algorithm worsened. Figure 6.1 shows the characteristic variables for the

⁴³Here, the Higgs boson is the pseudo particle defined by the sum of the τ -jet and lepton originating from the other τ .

Fig. 6.1 The characteristic variables for the fast τ -tagging: (a) the electromagnetic radius R_{EM} for $30 < p_T < 45$ GeV, (b) the electromagnetic radius for $80 < p_T < 120$ GeV, (c) the transverse momentum, p_T , of the candidate τ -jet, and (d) the number of charged tracks, shown for the low luminosity matched (blue solid line) and non-matched (red dotted line) jets, and the high luminosity matched (green dash-dotted line) and non-matched (magenta dashed line) jets. All distributions are normalized to unity

fast τ -tagging. It can be seen that the electromagnetic radius shown in Fig. 6.1(a) and (b) becomes smaller when the high luminosity condition is applied. The effect is more dramatic for non-matched jets. Also, the p_T spectrum of non-matched jets is harder (Fig. 6.1(c)). One can either keep the same efficiency of the τ -tagging, or the same rejection against light jets (Fig. 6.2). Analysis is performed in both cases and it is found that keeping the same rejection gives slightly better overall results (Table 6.1).

Moreover, the trigger conditions are tighter (see Table 4.4). The performance of channel 4, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow$

Fig. 6.2 The efficiency and rejection of the tau-algorithm for the low luminosity (blue solid line), and for the high luminosity when cuts for the tagging of the τ -jet are not changed (magenta dashed line), and when they are changed in order to preserve the rejection (red dotted line)

Table 6.1 The expected number of events at several stages of the analysis, for the low and high luminosity when two different criteria for the τ -tagging are adopted. “rec pass” means that topology requirement, i.e. 2 b -jets, 1 τ -jet, 1 lepton and 2 light jets, is fulfilled. In columns 3, 5 and 7 percentage is given with respect to the previous row

Signal	High (300 fb ⁻¹)				Low (30 fb ⁻¹)	
	Same τ efficiency		Same rejection			
	Events	%	Events	%	Events	%
N^0	1.422×10^4	100	1.422×10^4	100	1.422×10^3	100
1 τ -jet	3192.99	22.45	2783.96	19.58	351.12	24.69
rec pass	124.51	3.9	109.07	3.9	19.58	5.6
Final	4.03	3.2	3.66	3.4	1.01	5.1
$t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}jj$						
N^0	6.45×10^7	100	6.45×10^7	100	6.45×10^6	100
1 τ -jet	4.648×10^6	7.21	3.745×10^6	5.81	4.937×10^5	7.5
rec pass	8127	0.18	6192	0.17	1115.85	0.22
Final	1.86	2.3×10^{-2}	1.24	2×10^{-2}	0.19	1.7×10^{-2}
$t\bar{t} \rightarrow b\bar{\ell}\bar{\nu}_\ell\bar{b}\bar{\ell}\nu_\ell$						
N^0	1.56×10^7	100	1.56×10^7	100	1.56×10^6	100
1 τ -jet	1.381×10^6	8.85	1.208×10^6	7.75	1.456×10^5	9.33
rec pass	1.853×10^4	1.4	1.538×10^4	1.3	2349.36	1.6
Final	1.35	1.7×10^{-3}	0.9	6×10^{-3}	0.09	4×10^{-3}
Overall results						
S/B		0.56		0.65		0.94
$S/\sqrt{B}$		1.5		1.54		0.98

Fig. 6.3 The resulting likelihood L_H for the signal with $m_H = 120$ GeV (blue solid line), and the $t\bar{t} \rightarrow b\bar{\nu}_\ell \bar{b}jj$ (red dashed line) background process for high luminosity, i.e. 300 fb^{-1}

Fig. 6.4 The resulting likelihood L_H for the signal with $m_H = 120$ GeV (blue solid line), and for the $t\bar{t} \rightarrow b\bar{\nu}_\ell \bar{b}jj$ (red dotted line) and the $t\bar{t} \rightarrow b\bar{\nu}_\ell \bar{b}lv_\ell$ (magenta dashed line) background processes for high luminosity, i.e. 300 fb^{-1}

Table 6.2 The number of expected events for the signal and the background for 300 fb^{-1} for channel 2, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow bjj\bar{b}jj\tau_j\bar{\nu}_\ell\bar{\nu}_\ell\nu_\tau$. S/B and $S/\sqrt{B}$ are also given

m_H (GeV)	Signal	Background	S/B	$S/\sqrt{B}$
110	1.92	1.73	1.11	1.46
120	1.60	1.54	1.05	1.30
130	0.71	1.22	0.58	0.64

$b\bar{\nu}_\ell \bar{b}jj\tau_j\bar{\nu}_\ell\bar{\nu}_\ell\nu_\tau$ worsened too much and we dropped it from the calculation of the final result.

6.1 Channel 2, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow bjj\bar{b}jj\tau_j\bar{\nu}_\ell\bar{\nu}_\ell\nu_\tau$

We optimized the analysis for the high luminosity conditions. The following preselection cuts were changed:

- The cut on the transverse momentum of the τ -jet was raised to 50 GeV.
- The cut on the missing p_T was raised to 35 GeV.
- The cut on the $\ln(L_W)$ was raised to 1.5.
- The mass of both reconstructed W -boson was required to be between 40 and 110 GeV.

Fig. 6.5 The invariant mass $m_{\ell\tau_j}$ of the signal on top of the backgrounds for 300 fb^{-1} and $m_H = 120$ GeV

Table 6.3 The number of expected events for the signal and the background for 300 fb^{-1} for channel 5, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\bar{\nu}_\ell \bar{b}jj\tau_j\bar{\nu}_\ell\bar{\nu}_\ell\nu_\tau$. S/B and $S/\sqrt{B}$ are also given

m_H (GeV)	Signal	Background	S/B	$S/\sqrt{B}$
110	4.29	5.67	0.76	1.80
120	3.66	5.67	0.65	1.54
130	2.23	5.67	0.39	0.92

Table 6.4 The number of expected events for the signal and the background for 300 fb^{-1} for the combined two channels under consideration. S/B and $S/\sqrt{B}$ are also given

m_H (GeV)	Signal	Background	S/B	$S/\sqrt{B}$
110	6.21	7.40	0.84	2.28
120	5.26	7.21	0.73	1.96
130	2.94	6.89	0.42	1.12

An additional variable used as an input for the L_H was the total scalar sum of the transverse momenta of the $t\bar{t}$ -system ingredients:

$$p_T(t\bar{t}) \equiv p_T(b_1) + p_T(b_2) + p_T(j_1^{W_1}) + p_T(j_2^{W_1}) + p_T(j_1^{W_2}) + p_T(j_2^{W_2}) \quad (6.1)$$

The final likelihood for the $m_H = 120$ GeV is shown in Fig. 6.3. We count events if $\ln(L_H) > 6.6$ for the Higgs masses of 110 and 120 GeV and if $\ln(L_H) > 6.7$ for the Higgs mass of 130 GeV. The final result is given in Table 6.2.

6.2 Channel 5, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\bar{\nu}_\ell \bar{b}jj\tau_j\bar{\nu}_\ell\bar{\nu}_\ell\nu_\tau$

For channel 5 the following preselection cuts were changed:

- The cut on the $\ln(L_W)$ was raised to 1.
- We cut on the distance between the τ -jet and the lepton from the other τ , $\Delta R_{\tau jl} < 2.5$.

Table 7.1 Systematic uncertainties due to the reconstruction of the fully simulated events, from the sources given in column 1 (see text). The statistical uncertainty is given in the last row. The uncertainties are given after the topology requirement (column 2) and after the cuts given in Table 4.5 except $q_{\text{lep}} \cdot q_{\text{lep}} > 0$ (column 3)

Source	Systematic uncertainty after reconstruction (in %)	Systematic uncertainty after several cuts (in %)
b -tag	2.47	3.83
τ -tag	1.63	0
e -tag	1.31	0
e isolation	0.46	0
μ isolation	0	0
e energy	0	5.75
μ energy	0	5.75
Jet energy	0	10.81
Total systematics	3.27	14.06
Statistical uncertainty	6.7	19.25

Table 7.2 Systematic uncertainties due to the analysis. The statistical uncertainty is given in the last row

	Signal	$t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$	$t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}\ell\nu_\ell$	Total $t\bar{t}$
N of events	1.74	6.60	0.9	7.54
Total systematics (in %)	4.20	2.94	7.08	2.05
Statistical uncertainty (in %)	7.69	17.15	31.62	15.33

The resulting discriminant is shown in Fig. 6.4. We require that $\ln(L_H) > 0.6$. Figure 6.5 shows the “Higgs mass”, i.e. invariant mass of the τ -jet and the lepton coming from τ . We count events if the Higgs mass is between 45 and 120 GeV. The results for the three Higgs masses are shown in a Table 6.3.

Combined results for the high luminosity Combined results for the two channels under consideration are given in Table 6.4.

7 Systematic uncertainties

We consider the following sources of the systematic uncertainties:

– Background uncertainties.

We compared $t\bar{t}$ events generated with two generators, PYTHIA and HERWIG 6.5 [27]. We obtained an uncertainty of $\sim 7\%$ for the events passing topology and trigger requirements, and $\sim 25\%$ for the events passing additional analysis cuts.

We also compared $t\bar{t}$ events generated with PYTHIA with two different masses of the t -quark, $m_{\text{top}} = 175$ GeV (that was the default m_{top} throughout our analysis) and $m_{\text{top}} = 178$ GeV. The obtained uncertainty after topology and trigger requirements was $\sim 5.8\%$, and after additional analysis cuts $\sim 11\%$.

– Reconstruction and simulation uncertainties.

In order to estimate uncertainties due to the reconstruction

of the fully simulated events, we changed the tagging⁴⁴ of b -jets, τ -jets and electrons, and the isolation criteria for the electrons and muons by moving the cut value by $\pm 5\%$. We also rescaled the energies of the electrons, muons and jets by a factor $(100 \pm 5)\%$. The results are given in a Table 7.1 for the events passing the topology requirement, and those passing several other cuts.⁴⁵ Statistical uncertainties are given in the last row of the Table. The overall uncertainty is 3.3% after the topology requirement, and 14.1% after several cuts, and they are within the statistical uncertainties.

– Analysis uncertainties.

In order to determine uncertainties due to the analysis, we rescaled all input variables for the final likelihood L_H .⁴⁶ The results after loose cuts⁴⁷ are shown in a Table 7.2. It can be seen that the systematic uncertainties, 4.2% for the signal and 2.1% for the $t\bar{t}$ background are within statistical uncertainties.

⁴⁴We slightly changed the cut values used for the tagging of different objects as described in Sect. 4.

⁴⁵All cuts given in Table 4.5 except $q_{\text{lep}} \cdot q_{\text{lep}} > 0$ were applied.

⁴⁶For the input variables to the likelihood we use *probability density functions* of the corresponding histograms. In order to estimate the uncertainties we have changed the coefficients of the functions by rescaling such that the pdfs get closer, and then get further away from each other.

⁴⁷Cuts on the missing momentum, masses of the W boson and top quark, and the L_W are released. For the calculation of the systematics we also reduce cut on the L_H to 1.

8 Background normalization

In order to reduce the dependence of the analysis on the theoretical calculations⁴⁸ it is necessary to define *Control samples*, i.e. *Signal free regions*, to estimate the normalization of the most influential backgrounds. The basic procedure is:

1. Extract the ratio of the number of events in the *Signal region* and *Signal free region* from the simulated events (MC data in the following).
2. Measure the number of events in the *Signal free region* from the real data.
3. From the measured number of events in the *Signal free region* (real data), and the obtained ratio (MC data), estimate the number of events in the *Signal region* in the real data.

The detailed description will be given in the following.

8.1 Channel 2

For channel 2, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow bj\bar{j}\bar{b}jj\tau_j\bar{\nu}_\tau\ell\bar{\nu}_\ell\nu_\tau$, the *Signal region* comprises the events that pass the final selection as described in Sect. 5.1. The *Signal free region* is defined with the following changes:

1. In the preselection cuts, the cut on the reconstructed mass⁴⁹ of the Higgs boson is set to $0 < m_H < 350$ GeV.
2. The reconstructed mass of the Higgs boson is removed from the calculation of the final likelihood.
3. Events are counted if the $\ln(L_H) < 0$, and $m_H < 95$ GeV or $m_H > 170$ GeV.

The ratio of the background events in the *Signal free region* and the *Signal region* is

$$r_{t\bar{t}} = \frac{\sigma_{\text{Signal}}}{\sigma_{\text{Signal free}}} \quad (8.1)$$

The expected number of events in the *Signal region* and the *Signal free region* is given in Table 8.1.

8.2 Channel 5

For channel 5, $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^- \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj\tau_j\bar{\nu}_\tau\ell\bar{\nu}_\ell\nu_\tau$, the *Signal region* comprises the events that pass the final selection as described in Sect. 5.3. The control samples are defined as:

- *Signal free region without the same lepton charge cut (Sample 1)*

For this sample we make the following changes:

Table 8.1 The expected number of the signal and $t\bar{t}$ events in the *Signal region* and *Signal free region* (see text). Uncertainties are also given

		Signal	$t\bar{t}$
Signal region	N of events	0.93	0.67
	Statistical uncertainty (in %)	11%	58%
Signal free	N of events	0.04	10.13
	Statistical uncertainty (in %)	58%	14%
	Systematics (in %)	40%	18%

Fig. 8.1 The $\Delta\phi_{\text{HE}^{\text{miss}}}$ distribution for the signal (enhanced by factor 5) on top of the $t\bar{t}$ background for Sample 1 (a) and only the signal distribution (b)

1. In the preselection cuts, the cut on the p_T of the second lepton is lowered from 15 GeV to 10 GeV.
2. The $\Delta\phi_{\text{HE}^{\text{miss}}}$ is removed from the likelihood calculation.
3. The cut on the invariant mass of the τ -jet and the lepton originated from the second τ is dropped.
4. We do not require that both leptons have the same charge.

This control sample is then defined requiring that $\ln(L_H) < 0$ and $\Delta\phi_{\text{HE}^{\text{miss}}} > 2$. Figure 8.1(a) shows $\Delta\phi_{\text{HE}^{\text{miss}}}$ distribution for the signal (enhanced by factor 5) on top of the $t\bar{t}$ background for Sample 1. Only the signal distribution is shown in Fig. 8.1(b).

- *Signal free region with the same lepton charge cut (Sample 2)*

This sample is identical as the previous one, except the requirement 4. In this sample we do require that both leptons have the same charge. Figure 8.2(a) shows $\Delta\phi_{\text{HE}^{\text{miss}}}$ distribution for the signal on top of the $t\bar{t}$ background for Sample 2. Only the signal distribution is shown in Fig. 8.2(b).

As shown in Table 8.2 the first sample contains $t\bar{t}$ events with both t -quarks decaying semileptonically (dominates this sample), and with one t -quark decaying semileptonically and the other one hadronically. The second sample contains only $t\bar{t}$ events with one t -quark decaying semileptonically and the other one hadronically.

In order to determine the total number of the $t\bar{t}$ events in the *Signal region*, we define three quantities:

⁴⁸We have shown that the uncertainties on the $t\bar{t}$ production can be as high as $\sim 25\%$.

⁴⁹Using the collinear approximation.

Table 8.2 The expected number of the signal and $t\bar{t}$ events in the *Signal region* and two *Control Samples* (see text). Uncertainties are also given

		Signal	$t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$	$t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}\ell\nu_\ell$
Signal region	N of events	1.01	0.19	0.09
	Statistical uncertainty (in %)	10%	100%	100%
Signal free w/o the same charge lepton cut	N of events	0.11	5.05	33.81
	Statistical uncertainty (in %)	30%	20%	5.3%
	Systematics (in %)	24%	29.5%	7.6%
Signal free with the same charge lepton cut	N of events	0.04	2.14	0.09
	Statistical uncertainty (in %)	50%	30%	100%
	Systematics (in %)	25%	23%	100%

Fig. 8.2 The $\Delta\phi_{\text{HE}^{\text{miss}}}$ distribution for the signal on top of the $t\bar{t}$ background for Sample 2 (requiring that both leptons have the same charge) (a) and only the signal distribution (b)

1. The ratio of the $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}\ell\nu_\ell$ cross-section in the *Signal region* and *Sample 1*:

$$r_{t\bar{t}sl} = \frac{\sigma_{t\bar{t}sl}^{\text{signal region}}}{\sigma_{t\bar{t}sl}^{\text{Sample 1}}}. \quad (8.2)$$

2. The ratio of the $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$ cross-section in the *Signal region* and *Sample 2*:

$$r_{t\bar{t}sh} = \frac{\sigma_{t\bar{t}sh}^{\text{signal region}}}{\sigma_{t\bar{t}sh}^{\text{Sample 2}}}. \quad (8.3)$$

3. The ratio of the $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$ cross-section in *Sample 1* and *Sample 2*:

$$r_{S2}^{S1} = \frac{\sigma_{t\bar{t}sh}^{\text{Sample 1}}}{\sigma_{t\bar{t}sh}^{\text{Sample 2}}}. \quad (8.4)$$

To determine the number of the $t\bar{t}$ events in the *Signal region*, the number of events in the two control samples should be measured (real data). Let us denote the number of the events in *Sample 1* N_{total}^{S1} , and number of the events in *Sample 2* N_{total}^{S2} . The number of $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$ events in the *Signal region* is then:

$$N_{t\bar{t}sh}^{\text{Signal region}} = N_{\text{total}}^{S2} \cdot r_{t\bar{t}sh}. \quad (8.5)$$

The number of $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}jj$ events in *Sample 1* is:

$$N_{t\bar{t}sh}^{S1} = N_{\text{total}}^{S2} \cdot r_{S2}^{S1}. \quad (8.6)$$

The number of $t\bar{t} \rightarrow b\ell\bar{\nu}_\ell\bar{b}\ell\nu_\ell$ events in the *Signal region*:

$$N_{t\bar{t}sl}^{\text{Signal region}} = r_{t\bar{t}sl} \cdot (N_{\text{total}}^{S1} - N_{t\bar{t}sh}^{S1}) \quad (8.7)$$

For the estimation of the systematic uncertainties given in Table 8.2 we use the analysis uncertainties as described in Sect. 7.

9 Conclusions

We performed a feasibility study of the $t\bar{t}H \rightarrow t\bar{t}\tau^+\tau^-$ channel. The signal events were reconstructed using the full and the fast simulation of the ATLAS detector. It is shown that both the distributions and the number of expected events after the same cuts agree, and that the fast simulation can be used (with care) to further develop the analysis.

We obtained a significance⁵⁰ of 1.6σ for the low luminosity condition (30 fb^{-1}) and $m_H = 120 \text{ GeV}$, and 2.0σ for the high luminosity condition (300 fb^{-1}) and $m_H = 120 \text{ GeV}$.

We conclude that this channel can only be used as a corroborative channel for the determination of the top Yukawa coupling, but not as a main or discovery channel. This conclusion can only be strengthened had we used the full simulation with a more thorough systematics study. A refinement of the analysis would require the inclusion of a dedicated $t\bar{t} + \text{jets}$ Monte Carlo which might be a critical background. However, the inclusion of this background will not change the null conclusion of this analysis.

⁵⁰Significance is defined here as $S/\sqrt{B}$. We are aware that for small S and B this slightly overestimates the statistical significance, but the difference is small and does not change our conclusions

Appendix A: Electron identification likelihood and artificial neural network

To construct Electron Identification using Likelihood and Artificial Neural Network in the full simulation framework, the following variables are used [24]:

1. The fraction of the total energy measured in the presampler, E_0/E .
2. The fraction of the total energy measured in the first sampling of the EM Calorimeter, E_1/E .
3. The fraction of the total energy measured in the second sampling of the EM Calorimeter, E_2/E .
4. The fraction of the total energy measured in the third sampling of the EM Calorimeter, E_3/E .
5. The ratio of the energy leakage into the first sampling of the Hadronic Calorimeter, E_{ha}/E .
6. The ratio of the uncorrected energies in a rectangular shape measuring 3×3 and 3×7 cells in the second sampling of the EM Calorimeter, E_{33}/E_{37} .
7. The ratio of the uncorrected energies in 3×7 and 7×7 cells in the second sampling of the EM Calorimeter, E_{37}/E_{77} .
8. The ratio of the transverse energy measured in the Calorimeter and the momentum measured by the Inner detector (from tracking), E/p_T .

In addition, we use the following track-matching quantities in the analysis described in this paper:

- $|\Delta\eta| = |\eta_{\text{strips}} - \eta_{\text{ID}}|$, where η_{strips} is the position in the first sampling of the EM Calorimeter, i.e. strips, and η_{ID} is the position in the Inner Detector.
- $|\Delta\phi| = |\phi_2 - \phi_{\text{ID}}|$, where ϕ_2 is the position in the second sampling of the EM Calorimeter and ϕ_{ID} is the position in the Inner Detector.

Appendix B: τ identification likelihood

To construct τ Identification Likelihood in the full simulation, the following variables are used [26]:

1. Electromagnetic Radius given by:

$$R_{\text{EM}} = \frac{\sum_{i=1}^n E_{Ti} \Delta R_i}{\sum_{i=1}^n E_{Ti}}, \quad (\text{B.1})$$

where sum runs over all cells in the EM Calorimeter. E_{Ti} is the transverse energy deposited in the i th cell and ΔR_i is the distance between the i th cell and τ -candidate axis.

2. The Isolation Fraction defined as the fraction of transverse momentum within an annulus of $0.1 < \Delta R < 0.2$:

$$F_{\text{Iso}} = \frac{p_T(0.2) - p_T(0.1)}{p_T(0.4)}. \quad (\text{B.2})$$

3. Number of associated tracks.
4. Charge of the τ -candidate.
5. Number of hits in the first sampling of the EM Calorimeter, i.e. η – strips.
6. The weighted strip width:

$$\Delta\eta = \sqrt{\frac{\sum_{i=1}^n E_{Ti} \Delta\eta_i^2}{\sum_{i=1}^n E_{Ti}}}. \quad (\text{B.3})$$

7. Lifetime signed impact parameter significance defined as:

$$\sigma_{\text{IP}} = \frac{d_0}{\sigma_{d_0}} \cdot \text{sign}(\sin(\phi_{\text{cl}} - \phi_{\text{track}})) \quad (\text{B.4})$$

where d_0 is the impact parameter in the transverse plane, σ_{d_0} the corresponding error, and ϕ_{cl} and ϕ_{track} the position of the τ -candidate axis and the highest p_T track at the point of the closest approach of the track.

8. The ratio of the transverse momentum of the τ -candidate and the track with the highest p_T .

Appendix C: The collinear approximation

When the τ -lepton has a high momentum, one can approximate the direction of the neutrinos to be collinear with the visible τ decay products.⁵¹ Then, the conservation of the total transverse momentum leads to:

$$(\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2}) = \frac{\mathbf{p}_T^l}{x_l} + \frac{\mathbf{p}_T^h}{x_h} = \mathbf{p}_T^l + \mathbf{p}_T^h + \mathbf{p}_T, \quad (\text{C.1})$$

where

$$x_l = \frac{p_x^h p_y^l - p_y^h p_x^l}{p_x^h p_y^l - p_y^h p_x^l - p_y^h p_x^l + p_x^h p_y^l}, \quad (\text{C.2})$$

$$x_h = \frac{p_x^h p_y^l - p_y^h p_x^l}{p_x^h p_y^l - p_y^h p_x^l - p_y^h p_x^l + p_x^h p_y^l}$$

are the fractions of the parent τ -momentum carried by the lepton-daughter or τ -jet-daughter. $\mathbf{p}_T^l$ is the transverse momentum of the lepton-daughter, and $\mathbf{p}_T^h$ is the transverse momentum of the τ -jet-daughter, and $\mathbf{p}_T$ is the missing transverse momentum. Both x_l and x_h were required to be positive.⁵² Following these equations, the $\tau\tau$ invariant mass is:

$$m_{\tau\tau}^2 = 2(E_l + E_{\nu_l})(E_h + E_{\nu_h})(1 - \cos\theta) = \frac{m_{lh}^2}{x_l x_h}, \quad (\text{C.3})$$

where m_{lh} is invariant mass of the lepton-daughter and τ -jet-daughter.

⁵¹The case when one τ -lepton decays hadronically (index h), and the other leptonically (index l) is described.

⁵²Negative values are non-physical.

Acknowledgements We would like to thank the members of the Weizmann group: Giora Mikenberg and Ehud Duchovni for their help in discussing the various aspect of the present work. We want to thank members of the ATLAS Higgs group for their support and help. We would also like to thank Paul De Jong for his help in making this paper clearer. We are obliged to the Benoziyo center for High Energy Physics for their support of this work. This work was also supported by the Israeli Science Foundation (ISF). Part of this work was supported by the Federal Ministry of Education, Science, Research and Technology (BMBF) within the framework of the German-Israeli Project Cooperation in Future-Oriented Topics(DIP) and another part within the framework of the Minerva Foundation.

References

1. The LEP Collaborations ALEPH, DELPHI, L3, OPAL, and the LEP Electroweak Working Group, [arXiv:hep-ex/0612034](#)
2. H.E. Haber, R. Hempfling, Phys. Rev. Lett. **66**, 1815 (1991)
3. J. Ellis, G. Ridolfi, F. Zwirner, Phys. Lett. B **257**, 83 (1991)
4. J. Ellis, G. Ridolfi, F. Zwirner, Phys. Lett. B **262**, 477 (1991)
5. Y. Okada, M. Yamaguchi, T. Yanagida, Prog. Theor. Phys. **85**, 1 (1991)
6. M. Carena, J.R. Espinosa, M. Quiros, C.E.M. Wagner, Phys. Lett. B **335**, 209 (1995)
7. S. Heinemeyer, W. Hollik, G. Weiglein, Eur. Phys. J. C **9**, 343 (1999)
8. G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. Weiglein, Eur. Phys. J. C **28**, 133 (2003)
9. The ALEPH, DELPHI, L3, OPAL Collaborations, and the LEP Working Group for Higgs boson searches, Phys. Lett. B **565**, 61 (2003)
10. The ALEPH, DELPHI, L3, OPAL Collaborations, and the LEP Higgs Working Group, Eur. Phys. J. C **47**, 547 (2006)
11. J. Cammin, M. Schumacher, The ATLAS discovery potential for the channel ttH , H to bb
12. D. Benedetti et al., J. Phys. G **34**, N221 (2007)
13. A. Belyaev, L. Reina, J. High Energy Phys. **0208**, 041 (2002)
14. L. Reina, A. Belyaev, private communication
15. A. Djouadi, J. Kalinowski, M. Spira, Comput. Phys. Commun. **108**, 56 (1998)
16. W. Beenakker, S. Dittmaier, M. Kramer, B. Plumper, M. Spira, P.M. Zerwas, Phys. Rev. Lett. **87**, 201805 (2001). [arXiv:hep-ph/0107081](#)
17. Computing Technical Design Report—TDR, p. 64, CERN-LHCC-2005-022 and references therein
18. E. Richter-Was, D. Froidevaux, L. Poggioli, ATLFAS 2.0, ATLAS internal note, 13 Nov. 1998
19. T. Sjostrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna, E. Norrbin, Comput. Phys. Commun. **135**, 238 (2001)
20. Z. Was, P. Golonka, Nucl. Phys. Proc. Suppl. **144**, 88 (2005), and references therein
21. K. Jakobs, K. Mahboubi, A fast parametrization of electromagnetic and hadronic calorimeter showers
22. B.P. Kersevan, E. Richter-Was, Comput. Phys. Commun. **149**, 142 (2003)
23. B.P. Kersevan, E. Richter-Was, The Monte Carlo event generator AcerMC version 2.0 with interfaces to PYTHIA 6.2 and HERWIG 6.5
24. K. Benslama, private communication
25. L. Živković, Higgs boson searches at OPAL (LEP), ATLAS (LHC) and ILC
26. M. Heldmann, D. Cavalli, An improved tau-identification for the ATLAS experiment
27. G. Corcella et al., J. High Energy Phys. **0101**, 010 (2001)