Is the channel $H \rightarrow b\bar{b}$ observable at LHC?

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Abstract

A detailed study of associated Standard Model Higgs production (WH and $t\bar{t}H$) at the LHC (or a possible upgraded Tevatron collider), where the Higgs boson decays to $b\bar{b}$ pairs, is reported for $80 < m_H < 120$ GeV. Even for optimistic b -tagging performances of the detector, the signal cannot be cleanly extracted from the background. For an integrated luminosity of 10^4 pb^{-1} and $m_H = 100$ GeV, one can expect at best ~ 110 reconstructed $H \rightarrow b\bar{b}$ decays from WH production, above a resonant background of $\sim 150 \text{ } WZ$ events and a non-resonant background of ~ 4800 events, and ~ 100 reconstructed $b\bar{b}$ pairs (of which ~ 50 from $H \rightarrow b\bar{b}$ decay) from $t\bar{t}H$ production, above a background of ~ 4000 events. The main difficulty in extracting these two channels is in the expected low signal rate after reconstruction, the need for accurate control of all the background sources and for extremely good b -tagging performance. Nevertheless, for a few years of running at a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, the $H \rightarrow b\bar{b}$ channel may be the best way to probe the region $80 < m_H < 100$ GeV.

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1 Introduction

Recent experimental results obtained at the Fermilab Tevatron by the CDF collaboration [1] have shown that high-performance b -tagging is possible at hadron colliders: high- p_T b -jets, such as those expected from top quark decay, can be tagged with an efficiency of ~ 25 -30% using secondary vertices, thereby rejecting light-quark jets by a factor ~ 150 . Similar, but lower efficiency, performance [1, 2] has been also achieved by tagging b -jets using soft leptons (muons and electrons of a few GeV p_T).

These experimental results are highly encouraging for experiments at future hadron colliders, such as the LHC and a possible upgraded Tevatron [3] ($p\bar{p}$ at 3.5 TeV). Several recent theoretical papers [4, 5] have claimed that $H \rightarrow b\bar{b}$ decays may be observed above background at such machines. This is particularly interesting in the Higgs mass range, $80 < m_H < 130$ GeV, where $H \rightarrow b\bar{b}$ is the dominant decay mode and where discovery through other channels, such as $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$ or $H \rightarrow ZZ^* \rightarrow lll$, although experimentally possible over some range of Higgs mass values, may need confirmation from as many observed decay channels as possible. This is true for the search for a Standard Model Higgs boson, but even more so for that for neutral Higgs bosons expected in supersymmetric extensions of the Standard Model such as the MSSM [6].

In the study described here, performed in preparation for the Technical Proposal of the ATLAS collaboration, we concentrate mainly on the search for a Standard Model Higgs boson produced in association with a W boson. In section 2 we present the signal and background channel production cross-sections, and in section 3 we discuss the methodology and cuts used for the experimental simulation, with some emphasis on the differences between parton-level and jet-level simulations for b -jet reconstruction. Section 4 describes the results obtained for the signal and various background processes at the LHC. Section 5 compares our results to those of [4], both for the LHC and a possible upgraded Tevatron. Finally, section 6 discusses the results obtained from a similar analysis for $t\bar{t}H$ production with $H \rightarrow b\bar{b}$.

2 Signal and background channels

2.1 Basic processes

Higgs production in association with a W or Z boson is a priori the most promising signal production process for a search for $H \rightarrow b\bar{b}$ decays. Leptonic decays (electron or muon) of the W or Z provide an isolated lepton for triggering the experiment. We do not seriously consider here the possibility of using $Z \rightarrow \nu\bar{\nu}$ decays, as suggested in [4], because the trigger is much more difficult and the backgrounds are totally different from those considered for the W , Z decays to electron or muon. In the following we therefore limit ourselves to the discussion of WH production with $W \rightarrow l\nu$, since the ZH contribution with $Z \rightarrow ll$ is not more than $\sim 10\%$. The only other visible particles produced in the hard scattering process (HP) are the

two b -quarks from the Higgs boson decay. This allows us to hope that adequate rejection of the very large backgrounds from $t\bar{t}$ production can be obtained by vetoing the presence of any other high- p_T partons/jets or leptons in the final state. To summarise, we study here exclusive $l\bar{b}b$ final states, with the goal of reconstructing a peak in the invariant mass spectrum of the $b\bar{b}$ pairs.

The background channels can be divided into three classes:

- irreducible backgrounds: $WZ \rightarrow l\nu b\bar{b}$ and $Wb\bar{b} \rightarrow l\nu b\bar{b}$. The first one is resonant in terms of $m_{b\bar{b}}$ and is therefore of special concern for m_H close to m_Z . The latter is dominated by $q\bar{q} \rightarrow Wg \rightarrow Wb\bar{b}$, but also has a small contribution from $q\bar{q} \rightarrow W^* \rightarrow t\bar{b} \rightarrow Wb\bar{b}$;
- reducible backgrounds with at least two b -quarks in the final state: these are dominantly from $t\bar{t} \rightarrow l\nu b\bar{b} + W$ and to a lesser extent from single top production through $qg \rightarrow t\bar{b}q \rightarrow l\nu b\bar{b} + q$;
- reducible backgrounds containing jets misidentified as b -jets: these arise mainly from Wjj production and their magnitude obviously depends on the quality of the b -tagging performance.

2.2 Event generators

In this study we have used wherever possible the PYTHIA 5.7 Monte Carlo program [7], as an event generator for the hard scattering process using the appropriate leading order (LO) matrix element (ME) calculations, and as a full event generator with the parton shower approximation, thus including initial state radiation (ISR), final state radiation (FSR) and hadronization/decays (HD).

It is however well known that the parton shower approximation does not always correctly reproduce rates nor relevant kinematical distributions of additional jets in certain physics processes, as in e.g. $gg \rightarrow Zb\bar{b}$ [8] or $W + n - jet$ production [9]. Therefore, in the cases where the LO matrix element calculation is not available in PYTHIA 5.7, we have used separate code to fully simulate the events and/or to cross-check the results obtained with PYTHIA 5.7:

- for the $Wb\bar{b}$ background we have used the ME calculations of [10], interfaced to HERWIG 5.6 [11];
- for $qg \rightarrow t\bar{b}q \rightarrow l\nu b\bar{b} + q$ production we have used PYTHIA 5.7, which has been cross-checked in the past [12] to some extent by comparison to a complete ME calculation;
- for the Wjj channel we have used the full tree-level ME calculations available in the LDW event generator [13] to properly normalise at the parton level the results obtained using PYTHIA 5.7 (where Wj events are produced through the correct ME calculation and the second jet is produced in the parton shower process).

No K-factors were included in the rates presented below since they are not available for all processes considered here. Including them for the signal [14] and those of the background processes where they have been calculated does not change the final results significantly, and would certainly add some confusion when comparing

to other studies of these channels.

We have used the recent CTEQ LO parameterization [15] for the structure functions. The top quark was assumed to have a mass of 170 GeV and to decay to Wb before hadronization. The b -quarks were fragmented using the parameterization of [16] with $\epsilon_b = -0.006$.

2.3 Expected production rates

Table 1: *Production cross-sections for WH signal and background processes.*

Final state : $lb\bar{b}$	Event generator	$p\bar{p}$ at $\sqrt{s} = 3.5$ TeV $\sigma[pb]$	pp at $\sqrt{s} = 14$ TeV $\sigma[pb]$
WH	PYTHIA 5.7		
$m_H = 80$ GeV		0.173	0.769
$m_H = 100$ GeV		0.091	0.405
$m_H = 120$ GeV		0.045	0.209
WZ	PYTHIA 5.7	0.19	0.86
$Wb\bar{b}$	ME + HERWIG 5.6	19.9	69.3
$q\bar{q} \rightarrow W \rightarrow t\bar{b}$	HERWIG 5.6	0.28	1.42
$t\bar{t}$	PYTHIA 5.7	12.1	266.1
$qg \rightarrow Wg \rightarrow t\bar{b}q$	PYTHIA 5.7	2.86	45.6
Wjj (see text)	LDW	620.0	5480.0

Table 1 shows the production cross-sections of the signal and various backgrounds for $p\bar{p}$ collisions at $\sqrt{s} = 3.5$ TeV and pp collisions at $\sqrt{s} = 14$ TeV. The $H, Z \rightarrow b\bar{b}$ and $W \rightarrow l\nu$ branching ratios are included. The Wjj cross-sections are quoted for parton transverse momenta above 15 GeV and angular separation above 30° .

The dominant uncertainties on these expected rates arise from higher order corrections and the structure function parameterization. A larger uncertainty is expected for Wjj production, due to known limitations in the perturbative QCD calculations for p_T^j as low as 15 GeV. In all cases the Monte-Carlo statistics used in this study were such that the statistical uncertainty was much smaller than the above theoretical uncertainties, which in the worst cases are as large as a factor ~ 2 .

The signal cross-section is ~ 4.5 times larger at the LHC, independently of m_H , whereas the background cross-sections are between 3.5 ($Wb\bar{b}$) and 22 ($t\bar{t}$) times larger. If $t\bar{t}$ were the only background and if these ratios were preserved after selection cuts and event reconstruction, one would therefore expect similar significances for a potential signal at both machines for the same integrated luminosity. The signal rates before cuts and reconstruction appear quite comfortable for an integrated luminosity of 10^4 pb^{-1} , even at the upgraded Tevatron machine.

3 Simulation of experimental cuts

3.1 Simulation procedures

Most studies performed until now used parton-level simulations, which often lead to too optimistic results. In order, therefore, not only to present the results of our study for ATLAS, but also to compare them to those of [4], two simulation procedures were applied:

- a) parton-level procedure: this simulation generates the hard scattering process (e.g. WH , $Wb\bar{b}$, $t\bar{t}$...), then simulates the appropriate decays (e.g. $W \rightarrow l\nu$, $H \rightarrow b\bar{b}$, $t \rightarrow Wb$ with $W \rightarrow q\bar{q}$...). The final state products thus consist of charged leptons, neutrinos and partons to which the selection criteria described below are applied;
- b) jet-level procedure: this simulation generates the full event, including QCD or QED initial and final state radiation, fragmentation, hadronization and decays of unstable particles. The final state particles are then submitted to a jet-clustering algorithm, after which isolated leptons, b -jets and non b -jets can be selected.

The comparison of these two procedures for the same generated hard scattering events explains the large differences observed between the parton-level and the more realistic jet-level simulations in some cases, such as reconstruction of b -jets (section 3.2.3) and of $b\bar{b}$ invariant masses (section 3.2.4)

3.2 Selection criteria

We describe here the selection criteria used to study in some detail the differences between parton-level and jet-level simulations, for the signal and the dominant background processes (see section 4), and to evaluate the expected performance at the LHC. These selection criteria were chosen optimistically in terms of p_T -thresholds and pseudorapidity coverages for ATLAS, mainly so as to estimate whether there is any hope to see this difficult channel at the LHC. We restrict ourselves for the moment to selection criteria, which can be achieved at the initial luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

Table 2: *Selection criteria for $l\bar{b}\bar{b}$ events.*

Particle type	Cut
Leptons	Trigger lepton with: $p_T^l > 6$ GeV (muons) or 30 GeV (electrons), $ \eta^l < 2.5$ and isolation
b -jets	Two b -jets with: $p_T^{b-jet} > 15$ GeV and $ \eta^{b-jet} < 2.5$ $\Delta R_{b-jet,b-jet} > 0.7$ and $\Delta R_{b-jet,l} > 0.7$
Lepton veto	No other isolated lepton with: $p_T^l > 6$ GeV and $ \eta^l < 2.5$
Jet veto	No other jet with: $p_T^{jet} > 15$ GeV and $ \eta^{jet} < 5.0$

3.2.1 Trigger lepton

The trigger lepton is required to have pseudorapidity $|\eta^l| < 2.5$ and transverse momentum $p_T^l > 6$ GeV for muons and 30 GeV for electrons. In addition this trigger lepton is required to be isolated:

- it is required to be at a distance $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.7$ from any parton/jet which passes the selection criteria;
- at the jet-level, the total hadronic transverse energy in a cone, $\Delta R < 0.3$, around the lepton is required to be below 10 GeV. Non-isolated muons with $|\eta^l| < 2.5$ and electrons with $|\eta^l| < 5.0$ are considered as jets for $p_T^l > 15$ GeV.

3.2.2 Jet reconstruction

In the jet-level procedure jets are formed from calorimeter cells of granularity $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, where particle energies are stored with an energy smearing of $\sigma_E = 0.5 \times \sqrt{E} \oplus 0.03 \times E$. Only cells with total transverse energy above a threshold of 1 GeV were used to collect the jet energy in a cone of $\Delta R = 0.4$.

A parton or jet was accepted by the selection criteria if it had a transverse energy $p_T > 15$ GeV and $|\eta^{jet}| < 5.0$ (overall acceptance of ATLAS hadron calorimetry). It was called a b -jet at parton-level if it was within $|\eta^{b-jet}| < 2.5$ (overall acceptance of ATLAS inner tracker). At the jet-level, the b -jet was required in addition to be

within $\Delta R < 0.2$ from a b -quark with $p_T > 5$ GeV (after ISR and FSR). A b -jet pair is accepted if the b -jets are separated by $\Delta R > 0.7$. The event was accepted if it contained two (and only two) b -jets.

In order to reduce backgrounds from $t\bar{t}$ production, a lepton veto and a jet veto were applied. Events with a second isolated charged lepton with $p_T^l > 6$ GeV and $|\eta^l| < 2.5$ were rejected, as well as events with any additional jet with $p_T > 15$ GeV within $|\eta^{jet}| < 5.0$.

3.2.3 Comparison of parton-level and jet-level procedures

For WH production at the LHC, table 3 shows the probability that a lepton or quark, accepted by the parton-level procedure, passes the jet-level selection criteria, as a function of the ingredients used in the jet-level event generation. If only the hard scattering process (HP) is generated, both procedures agree to better than 1%, as expected since the jet-level procedure is then applied to the final state leptons and partons. The agreement remains excellent if initial state radiation (ISR) is included (some leptons are lost because of the isolation cuts). However, if final state radiation (FSR) and hadronization/decays (HD) are included, the efficiency for b -jets drops to 77%. This is due to the fact that the original b -quark from Higgs decay loses a significant fraction of its energy through FSR and HD. This 77% efficiency is probably still optimistic since magnetic field effects, which are expected to be significant for jets with $p_T^{jet} \sim 15$ GeV, were not included in the simulation.

Table 3: *Probability to accept a lepton or b -jet at the jet-level if it was accepted by the parton-level cuts as a function of the ingredients used in the event generation for the WH signal at the LHC.*

Event generation	Lepton	b-jet
HP	99%	99%
HP+ ISR	97%	99%
HP+ ISR + FSR	96%	86%
HP+ ISR + FSR + HD	96%	77%

Table 4: *Probability to accept a lepton or b-jet at the jet-level after full event generation, if it was accepted by the parton-level cuts for the WH signal and for various backgrounds at the LHC.*

Process	Event generator	Lepton	b-jet
WH	PYTHIA 5.7	96%	77%
$Wb\bar{b}$	HERWIG 5.6	98%	76%
$t\bar{b}$	HERWIG 5.6	97%	85%
$t\bar{t}$	PYTHIA 5.7	94%	81%

In conclusion, table 3 shows that less than 60% of the $H \rightarrow b\bar{b}$ decays with $p_T^{b,\bar{b}} > 15$ GeV are reconstructed as events containing two b -jets with $p_T^{jet} > 15$ GeV. These losses depend of course on the b -quark p_T -distribution and therefore on the process considered. Table 4 shows for example that the lepton efficiency for $t\bar{t}$ events is lower than for the WH signal (less isolated leptons) and that the b -jet reconstruction efficiency is higher (higher-energy b -quarks are produced in top decay).

3.2.4 Reconstruction of the Higgs mass peak

The last step in the event analysis is the reconstruction of the invariant mass of the two b -jets. Table 5 shows that a significant additional loss of signal events also occurs in this step, when going from the parton-level simulation (HP) to the more realistic jet-level simulation. This is again due to final state radiation and hadronization/decays. The first effect seen in the jet-level simulation is a large shift in the mass peak from 100 GeV to ~ 80 GeV for $m_H = 100$ GeV. This can of course be calibrated away (by using for example WZ background events), but the background contributions have to be estimated in the appropriate mass region. The second effect is a degradation of the mass resolution from 7 GeV at the parton-level to 11 GeV at the jet-level. Finally the last effect is that the fraction of events lost outside a 4σ mass-bin is much smaller at the parton-level, $\sim 4\%$ loss outside (100 ± 15) GeV, than at the jet-level, $\sim 20\%$ loss outside (80 ± 20) GeV, due to the asymmetric tail observed in the mass distribution reconstructed at the jet-level, as illustrated in fig. 1 for $m_H = 100$ GeV.

Figure 1: *Reconstruction of the invariant mass distribution of the two b -jets from Higgs boson decay for $m_H = 100$ GeV and WH production at the LHC, as a function of the ingredients used in the event generation: (a) hard scattering process, (b) initial state radiation, (c) final state radiation and (d) hadronization/decays.*

Table 5: *Main characteristics of reconstruction of $H \rightarrow b\bar{b}$ mass peak at the jet-level, as a function of the ingredients used in the event generation, for the WH signal at the LHC and for $m_H = 100$ GeV.*

Event generation	Peak position $\langle m \rangle$ in GeV	Resolution σ_m in GeV	Efficiency for $m_{b,\bar{b}}$ within $\langle m \rangle \pm 2\sigma_m$
HP	99.2	7.1	96%
HP+ ISR	100.8	7.6	94%
HP+ ISR+ FSR	93.9	10.1	82%
HP+ ISR+ FSR+ HD	80.9	11.0	81%

The effects observed in the jet-level simulation discussed above depend only weakly on the parameters used in the jet-finding algorithm. For example, as shown in fig. 2, increasing the jet cone size to $\Delta R = 0.7$ and relaxing the b -quark matching criterion to $\Delta R < 0.3$, decreases the mass shift from 19 GeV to 16 GeV and increases the mass resolution from 11.0 GeV to 12.3 GeV. In addition the reconstruction efficiency per b -jet increases from 77% to 79% and the efficiency of the mass cut increases only from 81% to 87%.

Figure 2: *Reconstruction of the invariant mass distribution of the two b -jets from Higgs boson decay for $m_H = 100$ GeV and WH production at the LHC, for two options of b -jet definition: (a) a cone size $\Delta R = 0.4$ and a match to a b -quark within $\Delta R < 0.2$ and (b) a cone size $\Delta R = 0.7$ and a match to a b -quark within $\Delta R < 0.3$.*

3.2.5 Tagging of reconstructed b -jets

For WH signal events passing the selection criteria discussed above, fig. 3a shows the fraction of the reconstructed b -jet p_T carried by the B -hadron. For the chosen cone size of $\Delta R = 0.4$, this fraction is on average $\sim 95\%$. However, as shown in fig. 3b, the b -jet itself carries only on average $\sim 80\%$ of the p_T of the b -quark produced in the $H \rightarrow b\bar{b}$ decays. These plots illustrate well some of the large differences between the parton-level simulation of b -quark reconstruction and the simulation of b -tagging in a real experiment.

Figure 3: *The ratio of the transverse momenta of: (a) B -hadron to reconstructed b -jet and (b) reconstructed b -jet to b -quark from $H \rightarrow b\bar{b}$ decays for WH signal events.*

In order to explore the expected inner tracker environment, when attempting to tag b -jets in this search, fig. 4 shows, for three choices of charged particle p_T -thresholds, the expected numbers of charged particles found within the b -jet cone for $\Delta R = 0.4$. These distributions are shown for all charged particles in the cone in fig. 4a, and only for those originating from the decay of the B -hadron in fig. 4b.

Figure 4: For reconstructed b -jets within a cone of $\Delta R = 0.4$, distributions of the numbers of: (a) all charged particles and (b) charged particles from B -hadron decay. Distributions are for all p_T (top), $p_T > 1$ GeV (middle) and $p_T > 5$ GeV (bottom).

The average numbers of charged particles expected, for all p_T , for $p_T > 1$ GeV, and for $p_T > 5$ GeV, are displayed in table 6, for b -jet cone sizes of $\Delta R = 0.4$ and 0.7 . Clearly a cone size of $\Delta R = 0.4$ is sufficient to measure more than 90% of the charged particles from the B -hadron decay. For a realistic threshold of $p_T > 1$ GeV, this cone size englobes on average ~ 4.8 charged tracks from B -hadron decay, ~ 2.4 charged tracks from the b -quark fragmentation and from the underlying event, and a negligible number (< 0.2) from minimum bias pile-up at a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

Table 6: *For b -jets from $H \rightarrow b\bar{b}$ decays, reconstructed within cone sizes of $\Delta R = 0.4$ and $\Delta R = 0.7$, expected average multiplicities of all stable charged particles within the b -jet cone and of those originating from B -hadron decay. These multiplicities are given for all p_T , for $p_T > 1$ GeV and for $p_T > 5$ GeV.*

	Average number	$\Delta R = 0.4$	$\Delta R = 0.7$
All p_T	In b -jet	9.2	11.8
	In B -hadron	5.4	5.6
$p_T > 1$ GeV	In b -jet	7.2	8.0
	In B -hadron	4.8	4.9
$p_T > 5$ GeV	In b -jet	2.8	2.8
	In B -hadron	2.2	2.2

Obviously a detailed study of these b -jets, using the full simulation of the ATLAS inner tracker, is needed to evaluate how the b -jet tagging efficiency ϵ_b varies as a function of the rejection R of the non- b jets. In the next sections, we will compare the expected WH signal rates to the various backgrounds, assuming a range of plausible to optimistic values for ϵ_b and R .

4 Expected signal and background rates

4.1 WH signal rate and acceptance

Table 7 compares the expected signal event rates and acceptances at parton-level and at jet-level, for an integrated luminosity of 10^4 pb^{-1} and for $m_H = 100 \text{ GeV}$. The selection criteria are those described above; we recall in particular that the chosen mass windows are different at parton-level ($85 < m_{b\bar{b}} < 115 \text{ GeV}$) and at jet-level ($60 < m_{b\bar{b}} < 100 \text{ GeV}$). It is also important to note that the b -tagging efficiency ϵ_b is not included in the overall acceptance.

Table 7: *For an integrated luminosity of 10^4 pb^{-1} and for $m_H = 100 \text{ GeV}$, expected rates and acceptances for WH signal events, as a function of the selection criteria used both at parton-level and at jet-level. The lepton identification and b -tagging efficiencies are not included.*

Cuts	Parton-level	Parton-level	Jet-level	Jet-level
	Events	Acceptance	Events	Acceptance
Trigger lepton	2626	65%	2618	64%
+ b -jets	1672	41%	1062	26%
+ lepton veto	1672	41%	1056	26%
+ jet veto	1672	41%	606	15%
+ mass window	1576	39%	491	12%

The trigger lepton acceptance is $\sim 65\%$ and does not depend much on the details of the simulation procedure. On the other hand, as discussed above, the acceptance of the b -jet selection criteria is much lower at the jet-level ($\sim 40\%$) than at the parton-level ($\sim 63\%$).

The parton-level procedure uses by definition only the hard scattering process and, therefore, has an acceptance of 100% for the lepton and jet veto cuts. For the jet-level simulation, the acceptance of the lepton veto cut remains close to 100%, because high- p_T isolated leptons are seldom produced through initial or final state radiation and in the underlying event. In contrast however, additional jets are often

expected through initial/final state radiation, and this accounts for the low acceptance ($\sim 57\%$) of the jet-veto cut. Relaxing the jet-veto threshold from 15 to 30 GeV would result in an increase of the total signal acceptance from 15% to 19%, but of course at the expense of a much larger increase of e.g. the $t\bar{t}$ background (see section 4.3).

4.2 Background rates and acceptances

We restrict ourselves here to the more realistic jet-level simulation and describe the acceptances of the selection cuts for the various background processes presented in section 2. Table 8 gives, for the various background processes, the acceptances of the jet-level selection criteria, and also the expected event rates after all cuts with $60 < m_{b\bar{b}} < 100$ GeV and for an integrated luminosity of 10^4 pb^{-1} . The efficiency of the lepton identification and b -tagging and the rejection of non- b jets are not included in these numbers.

Table 8: *Acceptances of selection criteria at jet-level and expected event rates after cuts for the various background channels and for an integrated luminosity of 10^4 pb^{-1} at the LH. The lepton identification and b -tagging efficiencies, as well as the rejection of non- b jets, are not included.*

Background channel	Trigger lepton	+ b-jets	+ lepton veto	+ jet veto	+ mass window	Event rate
WZ	59%	19%	19%	10%	7.7%	670
$Wb\bar{b}$	53%	3.5%	3.5%	2.6%	0.6%	4070
$q\bar{q} \rightarrow W \rightarrow t\bar{b}$	61%	35%	35%	15%	4.4%	640
$t\bar{t}$	73%	40%	31%	1.0%	0.2%	5750
$qg \rightarrow Wg \rightarrow t\bar{b}q$	70%	3.5%	3.5%	0.1%	0.05%	230
Wjj	51%	6.2%	6.2%	5%	1.4%	$5.9 \cdot 10^6$

4.2.1 WZ channel

The acceptances for the resonant WZ channel are somewhat lower than for the WH signal with $m_H = 100$ GeV, mainly because m_Z is less than m_H and therefore

the b -jets are less energetic. In the mass window, however, more events from WZ are expected than from WH because of the larger WZ production cross-section (see also fig. 5a).

4.2.2 $Wb\bar{b}$ channel

The acceptance of the b -jet selection cuts is much lower in this channel, because the $b\bar{b}$ pair is produced through gluon splitting. This results in a much softer b -quark p_T -spectrum and therefore a much lower probability of reconstructing two b -jets which pass the kinematical cuts (even at parton-level this probability is only 12%). The gluon splitting mechanism also induces a distribution of $m_{b\bar{b}}$ peaked at small values of $m_{b\bar{b}}$, typically around 40 GeV for $p_T^b > 15$ GeV, as shown in fig. 5b. The shape of this mass distribution is not affected much when going from the parton-level to the jet-level simulation, but the contribution from this channel is sensitive to the exact choice of the mass window.

The parton shower approximation was also used to generate $Wb\bar{b}$ events in the framework of PYTHIA 5.7. It was found that PYTHIA 5.7 overestimates the $Wb\bar{b}$ event rates by $\sim 40\%$ after cuts and by $\sim 60\%$ in the mass window. On the other hand, this procedure gave an estimate of the ratio of $Wc\bar{c}/Wb\bar{b}$, which was found to decrease from ~ 3 at production (no selection cuts) to ~ 1.4 after all the selection cuts. Although charm jets contain long-lived hadrons, they are expected to be tagged with much lower efficiency than b -jets, and we therefore conclude that the $Wb\bar{b}$ background is much larger than the $Wc\bar{c}$ background after all cuts.

4.2.3 $q\bar{q} \rightarrow W \rightarrow t\bar{b} \rightarrow Wb\bar{b}$ channel

This channel has a production cross-section almost two orders of magnitude smaller than that of the $Wb\bar{b}$ background. Therefore, as shown in table 8, although its acceptance is almost ten times larger than that of $Wb\bar{b}$, it only increases the $Wb\bar{b}$ background by $\sim 20\%$.

4.2.4 $t\bar{t}$ channel

This channel results in a $WWb\bar{b}$ final state, where the extra W may decay into leptons or jets. This leads to large differences between parton-level and jet-level simulations because of the complexity and variety of final state topologies. The lepton and jet vetoes provide a large overall rejection of ~ 40 against this channel, as shown in table 8. The $t\bar{t}$ events remaining after the veto cuts can be split in terms of the decay of the extra W : 40% $W \rightarrow \tau\nu$, 27% $W \rightarrow \mu\nu$, 21% $W \rightarrow e\nu$ and only 12% $W \rightarrow q\bar{q}$. For these events, the distribution of $m_{b\bar{b}}$ is almost flat in the region $50 < m_{b\bar{b}} < 150$ GeV (see also fig. 5c).

4.2.5 $qg \rightarrow Wg \rightarrow t\bar{b}q$ channel

As for the $Wb\bar{b}$ channel, the acceptance of the b -jet selection cuts for this channel is quite low. In addition the extra quark-jet in the final state can be efficiently tagged at large pseudorapidity, leading to a large rejection of the jet-veto cut. Background from single top production therefore turns out to be significantly smaller than that from $t\bar{t}$ production even after the jet-veto cuts.

4.2.6 Wjj channel

As described in section 2, this background was simulated at the jet-level using PYTHIA 5.7, but the more reliable LDW Monte-Carlo program was used to define the cross-section after selection cuts at parton-level. This procedure showed that PYTHIA 5.7 underestimates the cross-section at parton level by a factor ~ 2.5 , which is included in the rates of table 8, but reproduces well the shape of the m_{jj} distribution. In addition this shape does not change much when going from the parton-level to the jet-level simulation. Figure 5d shows the $m_{b\bar{b}}$ distribution for the jet-level simulation using PYTHIA 5.7 after all cuts. A small fraction of $\sim 0.6\%$ of these Wjj events contain one b -jet and will therefore be labelled as Wjb events in the following. This fraction is found to be in fact $\sim 2\%$ in PYTHIA 5.7, but the Wjb background cross-section was not rescaled by a factor 2.5 as was the Wjj background cross-section, since PYTHIA 5.7 has been shown to overestimate the rate of $b\bar{b}$ pairs from gluon splitting for the $Wb\bar{b}$ background, as discussed above.

4.3 Sensitivity to veto cuts

As is apparent from the background study described above, the jet veto (and to a lesser extent the lepton veto) is very important to reject backgrounds consisting of more complex final state topologies than the WH signal. Whereas the final background rates depend only very weakly on the lepton-veto p_T -threshold, they depend much more strongly on the jet-veto p_T -threshold. Table 9 shows for the various background processes the variation of the rejection of the jet-veto cut when the jet p_T -threshold increases from 15 GeV to 30 GeV. For a threshold of 30 GeV, which may even be optimistic at the highest LHC luminosities, the $t\bar{t}$ and $t\bar{b}q$ backgrounds increase by a factor 4 with respect to the chosen low luminosity threshold of 15 GeV. This shows that, even if the b -tagging performance is preserved at the highest LHC luminosities, it will be very difficult to improve the sensitivity of the experiment to a possible WH signal, since the p_T -threshold of the jet veto may well need to be increased beyond 30 GeV in order to preserve a reasonable signal efficiency in the presence of pile-up.

Table 9: *Rejection of jet-veto cut against background processes as a function of the jet p_T -threshold.*

Channel	$p_T^{jet} > 15$ GeV	$p_T^{jet} > 20$ GeV	$p_T^{jet} > 30$ GeV
WZ	1.9	1.6	1.3
$Wb\bar{b}$	1.3	1.2	1.1
$q\bar{q} \rightarrow W \rightarrow t\bar{b}$	2.4	2.0	1.5
$t\bar{t}$	32	19	8
$qg \rightarrow Wg \rightarrow t\bar{b}q$	35	18	8
Wjj	1.3	1.2	1.1

4.4 Significance of WH signal

Table 10 presents the expected rates for the WH signal with $m_H = 100$ GeV and for the background processes with $60 < m_{b\bar{b}} < 100$ GeV, for an integrated luminosity of 10^4 pb^{-1} . A trigger lepton efficiency of 90% has been included in all rates. The second column gives these rates as a function of the b -tagging efficiency ϵ_b and the rejection R of non- b jets. For $\epsilon_b = 100\%$ and an infinite rejection R , the significance of the Higgs signal would be 4.4 for a total of 442 observed signal events. Even this ideal number is over-optimistic, since the resonant WZ background is naively treated in the same way as the non-resonant backgrounds and since additional likely signal losses, due to magnetic field effects and lower b -tagging acceptance in pseudorapidity, have not been included.

The last two columns of table 10 show that for realistic ($\epsilon_b = 30\%$ and $R = 100$) and even for optimistic ($\epsilon_b = 50\%$ and $R = 50$) b -tagging performance values, the signal will be very difficult to extract from the background. Table 11 ($\epsilon_b = 30\%$ and $R = 100$) and table 12 ($\epsilon_b = 50\%$ and $R = 50$) demonstrate that the expected significance improves with decreasing m_H . This is mostly due to the larger production rates at smaller values of m_H . As shown in fig. 5, the backgrounds from $Wb\bar{b}$, Wjj and Wjb are about a factor of 2 larger for $m_H = 80$ GeV than for $m_H = 120$ GeV, but vary fairly smoothly as a function of $m_{b\bar{b}}$ as does the $t\bar{t}$ background. The notable exception to this last feature is of course the WZ background, which hopefully

can be calibrated accurately using WZ events with purely leptonic decays of the vector bosons. For $R = 50$, the backgrounds from non- b jets are slightly larger than those from real b -jets; this indicates that the b -tagging performance of the ATLAS inner tracker should provide a rejection R of at least ~ 100 against light quark jets and ~ 20 against charm jets.

Table 10: *For an integrated luminosity of 10^4 pb^{-1} at the LHC and for $m_H = 100 \text{ GeV}$, expected rates for the WH signal and for the various background processes after all cuts, for events with $60 < m_{b\bar{b}} < 100 \text{ GeV}$. A lepton identification efficiency of 90% is included. The second column gives the rates as a function of the b -tagging efficiency ϵ_b and the rejection R of non- b jets. The last two columns give the results for $\epsilon_b = 30\%$, $R = 100$ and for $\epsilon_b = 50\%$, $R = 50$ respectively.*

$\sqrt{s} = 14 \text{ TeV } pp$		$\epsilon_b = 30\%$	$\epsilon_b = 50\%$
Process	Rates	$R = 100$	$R = 50$
WH	$440 \times \epsilon_b^2$	40	110
WZ	$600 \times \epsilon_b^2$	54	150
$Wb\bar{b}$	$3660 \times \epsilon_b^2$	330	910
$q\bar{q} \rightarrow t\bar{b}$	$570 \times \epsilon_b^2$	50	140
$t\bar{t}$	$5170 \times \epsilon_b^2$	470	1290
$qg \rightarrow t\bar{b}q$	$210 \times \epsilon_b^2$	20	50
Wjj	$5.3 \cdot 10^6 \times 1/R^2$	530	2130
Wjb	$4.1 \cdot 10^4 \times \epsilon_b/R$	120	410
$S/\sqrt{B}$	Ideal $\rightarrow 4.4 \times \epsilon_b$	1.0	1.5

Table 11: *For an integrated luminosity of 10^4 pb^{-1} at the LHC, expected rates for the WH signal and for the various background processes after all cuts as a function of m_H , for a lepton identification efficiency of 90% and for $\epsilon_b = 30\%$ and $R = 100$.*

$\epsilon_b = 30\%, R=100$	WH	WZ	$Wb\bar{b}$	Wjj, Wjb	$S/\sqrt{B}$
$m_H = 80 \text{ GeV}$	63	56	1130	900	1.4
$m_H = 100 \text{ GeV}$	40	54	870	660	1.0
$m_H = 120 \text{ GeV}$	17	14	680	440	0.5

Table 12: *For an integrated luminosity of 10^4 pb^{-1} at the LHC, expected rates and significances for the WH signal after all cuts as a function of m_H , for a lepton identification efficiency of 90% and for $\epsilon_b = 50\%$ and $R = 50$.*

$\epsilon_b = 50\%, R=50$	WH	WZ	$Wb\bar{b}$	Wjj, Wjb	$S/\sqrt{B}$
$m_H = 80 \text{ GeV}$	175	155	3130	3600	2.1
$m_H = 100 \text{ GeV}$	110	150	2400	3130	1.5
$m_H = 120 \text{ GeV}$	47	39	1880	1720	0.8

Figure 5: For an integrated luminosity of 10^4 pb^{-1} at the LHC, for a lepton identification efficiency of 90% and for $\epsilon_b = 30\%$ and $R = 100$, expected $m_{b\bar{b}}$ spectra after all cuts for: (a) the WH signal with $m_H = 100 \text{ GeV}$ (solid line) and the resonant WZ background (dashed line), (b) the $Wb\bar{b}$ background, (c) the $t\bar{t}$ background and (d) the Wjj background.

5 The LHC versus the upgraded Tevatron

We now briefly compare our results with those of [4], both for the LHC and for a possible upgraded Tevatron ($p\bar{p}$ at $\sqrt{s} = 3.5 \text{ TeV}$). We therefore adopt here the selection cuts used in [4]:

- The trigger lepton is required to have $p_T^l > 20$ GeV, pseudorapidity $|\eta^l| < 2.5$ and to be isolated from the b -jets (or partons), i.e. $\Delta R_{b-jet,l} > 0.7$. Events with an additional lepton with $p_T^l > 10$ GeV are rejected. Cuts are also applied on the missing transverse energy, $E_T^{miss} > 20$ GeV and on the transverse mass, $m_T^{l,miss} = \sqrt{2p_T^l E_T^{miss}(1 - \cos\Delta\phi_{l,miss})} < 85$ GeV;
- Events are accepted if they contain exactly two b -jets (or partons) with $p_T^{b-jet} > 15$ GeV, pseudorapidity $|\eta^{b-jet}| < 2.0$ and $\Delta R_{b-jet,b-jet} > 0.7$;
- Events are accepted if they contain no additional jet with $p_T^{jet} > 30$ GeV and $|\eta^{jet}| < 4.0$ and not more than one additional jet with $p_T^{jet} > 15$ GeV and $|\eta^{jet}| < 4.0$;
- The b -tagging efficiency is assumed to be $\epsilon_b = 30\%$ and the rejection of non- b jets is taken to be $R = 100$;
- To define the final signal and background rates, a mass window of 100 ± 17 GeV at the parton-level and 80 ± 17 GeV at the jet-level was used.

Table 13: For an integrated luminosity of 10^4 pb^{-1} at the LHC, expected rates and significances, for the WH signal with $m_H = 100$ GeV, after all cuts and for $\epsilon_b = 30\%$ and $R = 100$. No lepton identification efficiency is included. Shown are the parton-level results of [4] (second column) and the parton-level (third column) and jet-level (last column) results of our analysis.

$\sqrt{s} = 14 \text{ TeV } pp$	Parton-level ([4])	Parton-level	Jet-level
WH	104	102	27
WZ	146	167	36
$Wb\bar{b}$	199	240	200
$q\bar{q} \rightarrow t\bar{b}$	77	70	50
$t\bar{t}$	481	790	440
$qg \rightarrow t\bar{b}q$	364	30	40
Wjj	142	220	320
$S\sqrt{B}$	2.8	2.6	0.8

For the WH signal, these cuts lead, at the jet-level, to a lower acceptance of 8.4% as compared to 12% for the optimal ATLAS cuts defined in section 3. This is mainly due to the much lower p_T -threshold of 6 GeV chosen for the muons and to the larger η -coverage for tagging b -jets in the latter case. The use of the transverse mass cut also reduces the acceptance by $\sim 30\%$ for the signal without much gain on the signal to background ratio if a realistic experimental resolution is included for the missing transverse momentum measurement. Some of this loss of acceptance is recovered however by the looser jet veto cuts used in [4].

Table 14: *For an integrated luminosity of 10^4 pb^{-1} at an upgraded Tevatron machine, expected rates and significances, for the WH signal with $m_H = 100 \text{ GeV}$, after all cuts and for $\epsilon_b = 30\%$ and $R = 100$. No lepton identification efficiency is included. Shown are the parton-level results of [4] (second column) and the parton-level (third column) and jet-level (last column) results of our analysis.*

$\sqrt{s} = 3.5 \text{ TeV } p\bar{p}$	Parton-level ([4])	Parton-level	Jet-level
WH	47	41	13
WZ	73	62	19
$Wb\bar{b}$	82	80	100
$q\bar{q} \rightarrow t\bar{b}$	36	20	15
$t\bar{t}$	19	50	50
$qg \rightarrow t\bar{b}q$	25	3	4
Wjj	26	35	50
$S/\sqrt{B}$	2.9	2.6	0.8

Table 13 shows, for an integrated luminosity of 10^4 pb^{-1} at the LHC, the expected signal and background rates after applying the cuts defined above. In the second column we quote the results of [4], which can be compared to our parton-level (third column) and jet-level (last column) results. Although the expected significances agree to better than 10% at the parton-level, the backgrounds with complex final state topologies, such as $t\bar{t}$ and $t\bar{b}q$, differ by large factors between the two analyses. As discussed in detail in section 3.2.3, the most striking result is however the

very large difference in significance observed between the parton-level and jet-level simulations, which is mainly due to the much smaller signal acceptance obtained at the more realistic jet-level. This reduces greatly the hopes one may have had from the optimistic conclusions of [4], that such a channel may be observed above background at the LHC.

This conclusion applies even more to a possible upgraded Tevatron machine, as shown in table 14 for $\sqrt{s} = 3.5$ TeV $p\bar{p}$ collisions and for an integrated luminosity of 10^4 pb^{-1} (!!). The expected significances are almost identical to those predicted for the LHC; this is essentially due to the fact that the $t\bar{t}$ background is much smaller at the lower energy. The WH signal itself is however smaller by a factor ~ 2 at the lower energy. For signal rates as low as ~ 10 events per year and sizeable residual backgrounds, the real experimental significance will be obviously even smaller than the naive computation of $S/\sqrt{B}$.

In conclusion to this section, our results agree qualitatively with those of [4] at the parton-level, but the more realistic jet-level results demonstrate that large signal losses, which cannot be predicted at the parton-level, will occur in the experiment, and that discovery of the Higgs boson in its dominant $H \rightarrow b\bar{b}$ decay mode, for $m_H \sim 100$ GeV, will be extremely difficult even with high-performance b -tagging. Although the background situation is more favourable at lower energy, the overall prospects are worse because the signal rates are too low.

6 Search for a signal in the $t\bar{t}H$ channel

This channel has also been proposed as a viable channel to search for $H \rightarrow b\bar{b}$ decays [17]. It has a production cross-section very close to that of the WH channel for $m_{top} = 170$ GeV. The final state is however much more complex, consisting of $WWb\bar{b}b\bar{b}$ instead of $Wb\bar{b}$. In this study, we will therefore replace the jet veto cuts, which provided a large rejection against the dominant $t\bar{t}$ background in the WH signal search, by the requirement of three or even four tagged b -jets in the final state in addition to the trigger lepton. The Higgs signal would thus appear as a peak in the invariant $b\bar{b}$ mass distribution, above the combinatorial background from the signal itself and from the various background processes. These can be divided into two classes:

- Irreducible backgrounds, such as the resonant $t\bar{t}Z$ channel and $t\bar{t}b\bar{b}$ production;
- Reducible backgrounds containing jets misidentified as b -jets, such as $t\bar{t}j$, $Wjjj$, $Wb\bar{b}j$ etc. Their magnitude obviously will depend even more than for the WH channel on the quality of the b -tagging performance.

Table 15 shows the production cross-sections at the LHC for the $t\bar{t}H$ signal, the resonant $t\bar{t}Z$ background and the reducible $Wjjj$ background (the $Wjjj$ cross-section is quoted for parton transverse momenta above 15 GeV and angular separation above 30°). The $H, Z \rightarrow b\bar{b}$ and $W \rightarrow l\nu$ branching ratios are included. The basic cross-sections for other backgrounds can be found in table 1. The irreducible

$t\bar{t}b\bar{b}$ background and the reducible backgrounds from $t\bar{t}j$ and $Wb\bar{b}j$ are generated, using the event generators specified in table 1 and the parton shower approximation to obtain the extra jet or jets from initial/final state radiation.

Table 15: *Production cross-sections for $t\bar{t}H$ signal and background processes.*

Final state : $l\bar{b}b\bar{b}$	Event generator	pp at $\sqrt{s} = 14$ TeV $\sigma[pb]$
$t\bar{t}H$		
$m_H = 80$ GeV	PYTHIA 5.7	0.731
$m_H = 100$ GeV		0.390
$m_H = 120$ GeV		0.203
$t\bar{t}Z$	PYTHIA 5.7	0.033
$Wjjj$ (see text)	LDW	2060

The $t\bar{t}H$ signal production cross-sections are remarkably similar to the WH signal cross-sections quoted in table 1. The resonant $t\bar{t}Z$ background cross-section is however much lower than the WZ background cross-section. The strong Higgs coupling to the top quark is of great help here to enhance the Higgs contribution with respect to the Z one. The uncertainties on the production cross-sections used for the study of this channel are significantly larger than for the WH study, since we rely more heavily on the parton shower approximation and the jet multiplicities in the final state are larger.

The selection cuts (applied at the jet-level) are quite straightforward:

- The trigger lepton is required to satisfy the same cuts as for the WH search (see section 3.2.1);
- Events are accepted if they contain three or four b -jets with $p_T^{b-jet} > 15$ GeV and $|\eta^{b-jet}| < 2.5$. The b -jets are required to be well separated from each other and from the trigger lepton, i.e. $\Delta R_{b-jet, b-jet} > 0.7$ and $\Delta R_{b-jet, l} > 0.7$.

The reconstruction efficiencies for the $t\bar{t}H$ signal are quite similar to those obtained for the WH signal. For $m_H = 100$ GeV, 20% of the events contain two reconstructed b -jets, 44% contain three b -jets and 32% contain four b -jets. However, only 39% of all reconstructed b -jets come from $H \rightarrow b\bar{b}$ decay, whereas 61% come from top quark

decay. This indicates that the combinatorial background from the signal itself will be quite large when searching for a peak in the invariant mass of two tagged b -jets.

Before searching for the Higgs mass peak, we first present the expected rates of signal and background events for three different b -tagging performances:

- $\epsilon_b = 30\%$ and $R = 100$;
- $\epsilon_b = 50\%$ and $R = 50$;
- $\epsilon_b = 70\%$ and $R = 10$.

We stress again that these values do not yet reflect any expected realistic performance of the ATLAS detector, but are rather used to emphasise the even greater importance of high-efficiency b -tagging (rather than large rejection of non- b jets) in this channel which contains four b -quarks in the final state.

Table 16: *For an integrated luminosity of 10^4 pb^{-1} at the LHC, expected rates for the $t\bar{t}H$ signal and backgrounds, as a function of m_H , for events with three tagged b -jets and for a lepton identification efficiency of 90%. The results are shown for the b -tagging performances described in the text.*

Process	$\epsilon_b = 30\%$ $R = 100$	$\epsilon_b = 50\%$ $R = 50$	$\epsilon_b = 70\%$ $R = 10$
$t\bar{t}H$			
$m_H = 80 \text{ GeV}$	93	360	860
$m_H = 100 \text{ GeV}$	54	210	480
$m_H = 120 \text{ GeV}$	30	115	270
$t\bar{t}Z$	4	14	34
$t\bar{t}j$	1720	8700	70500
$Wjjj$	370	1750	32200
$Wb\bar{b}j$	8	31	260
$t\bar{b}q$	21	140	940

Tables 16 (for three tagged b -jets) and 17 (for four tagged b -jets) show the expected rates after reconstruction, but before selection in the appropriate mass window. The $t\bar{t}H$ signal rates are much larger than the resonant $t\bar{t}Z$ background, in con-

trast to the WH case. The largest of all background sources is that from $t\bar{t} + jet(s)$. Only for the lowest values of the non- b jet rejection, $R = 10$, are the $Wjjj(j)$ backgrounds to be also considered, since they then amount to $\sim 50\%$ (resp. 30%) of the $t\bar{t}$ background for three (resp. four) tagged b -jets. The uncertainties on the expected rates of $Wjjj$ and $Wjjjj$ events are of course very large.

Table 17: *For an integrated luminosity of 10^4 pb^{-1} at the LHC, expected rates for the $t\bar{t}H$ signal and backgrounds, as a function of m_H , for events with four tagged b -jets and for a lepton identification efficiency of 90%. The results are shown for the b -tagging performances described in the text.*

Process	$\epsilon_b = 30\%$ $R = 100$	$\epsilon_b = 50\%$ $R = 50$	$\epsilon_b = 70\%$ $R = 10$
$t\bar{t}H$			
$m_H = 80 \text{ GeV}$	6	50	240
$m_H = 100 \text{ GeV}$	4	30	140
$m_H = 120 \text{ GeV}$	2	20	80
$t\bar{t}Z$	-	2	10
$t\bar{t}jj$	30	280	5850
$Wjjjj$	20	110	1660
$Wb\bar{b}jj$	-	-	10
$t\bar{b}qj$	-	-	30

The signal rates for four tagged b -jets are too low except for values of ϵ_b larger than 50%. In the following we will therefore concentrate on the events with three tagged b -jets. Table 18 shows, for $m_H = 100 \text{ GeV}$ and for the three b -tagging performances considered, the respective true b -jet multiplicities in the accepted $t\bar{t}H$ signal and $t\bar{t}$ background events. Most signal events contain three true b -jets, but for $R = 10$, as many as 22% contain one non- b jet tagged as a b -jet. In contrast the $t\bar{t}$ background events contain in most cases the two true b -jets from top quark decay, but seldom a third true b -jet from initial/final state radiation.

Table 18: *True b -jet multiplicity in events with a trigger lepton and at least three tagged b -jets, for the $t\bar{t}H$ signal with $m_H = 100$ GeV and for the $t\bar{t}$ background.*

	True b-jets	$\epsilon_b = 30\%$ $R = 100$	$\epsilon_b = 50\%$ $R = 50$	$\epsilon_b = 70\%$ $R = 10$
$t\bar{t}H$	1	-	1%	1%
	2	7%	8%	22%
	3	93%	91%	76%
$t\bar{t}$	1	5%	5%	15%
	2	70%	75%	78%
	3	24%	20%	5%

We also studied the influence of the rejection against c -jets on the amount of $t\bar{t}$ and $Wjjj$ background events passing the selection cuts. The fraction of $t\bar{t}$ events containing one c -jet tagged as a b -jet is $\sim 8.5\%$, for $\epsilon_b = 30\%$ and $R = 100$. If the rejection against c -jets were to decrease to 10, the $t\bar{t}$ background would almost double, with a $\sim 50\%$ contribution from events containing two true b -jets and one c -jet tagged as a b -jet. This increase is even more pronounced in the case of the $Wjjj$ background, where fewer b -jets are produced.

The final analysis step in this channel is more complicated than in the WH case, since there is no easy way to identify the b -jets from Higgs decay before reconstructing the mass peak. In the following, we consider three possible procedures to estimate the signal significance above the background:

- (1) The obvious but naive method, which consists in including all three mass combinations in the $m_{b\bar{b}}$ distribution, each one with a weight of $1/3$;
- (2) Since the b -quarks from $H \rightarrow b\bar{b}$ decay tend to have lower p_T than those from top quark decay, we choose always the combination corresponding to the two lowest p_T b -jets. This may increase the fraction of true $H \rightarrow b\bar{b}$ decays in the interesting mass window;
- (3) Each combination in the chosen mass window is weighted with $1/N$, where N is the number of combinations falling in the mass window for the event considered. Figure 6 shows the mass distributions obtained, for $\epsilon_b = 30\%$ and $R = 100$, in the case of procedure (1) applied to the $t\bar{t}H$ signal for $m_H = 100$ GeV (fig. 6a) and to the $t\bar{t}$ background (fig. 6b), and in the case of procedure (2) (figs. 6c and 6d).

Figure 7 shows the same distributions for $\epsilon_b = 50\%$ and $R = 50$. The dashed histograms in the $t\bar{t}H$ signal plots represent the $b\bar{b}$ combinations from Higgs decay, which unfortunately turn out in all cases to be only between 30% and 40% of the total event rate observed in the mass window, $60 < m_{b\bar{b}} < 100$ GeV.

Figure 6: For an integrated luminosity of 10^4 pb^{-1} at the LHC, for a lepton identification efficiency of 90% and for $\epsilon_b = 30\%$ and $R = 100$, expected $m_{b\bar{b}}$ spectra after all cuts for: (a) the $t\bar{t}H$ signal with $m_H = 100$ GeV using procedure (1). The solid histogram corresponds to all mass combinations and the dashed one only to those from $H \rightarrow b\bar{b}$ decay; (b) the $t\bar{t}$ background using procedure (1); (c) the $t\bar{t}H$ signal with $m_H = 100$ GeV using procedure (2). The solid histogram corresponds to all mass combinations and the dashed one only to those from $H \rightarrow b\bar{b}$ decay; (d) the $t\bar{t}$ background using procedure (2).

Figure 7: For an integrated luminosity of 10^4 pb^{-1} at the LHC, for a lepton identification efficiency of 90% and for $\epsilon_b = 50\%$ and $R = 50$, expected $m_{b\bar{b}}$ spectra after all cuts for: (a) the $t\bar{t}H$ signal with $m_H = 100 \text{ GeV}$ using procedure (1). The solid histogram corresponds to all mass combinations and the dashed one only to those from $H \rightarrow b\bar{b}$ decay; (b) the $t\bar{t}$ background using procedure (1); (c) the $t\bar{t}H$ signal with $m_H = 100 \text{ GeV}$ using procedure (2). The solid histogram corresponds to all mass combinations and the dashed one only to those from $H \rightarrow b\bar{b}$ decay; (d) the $t\bar{t}$ background using procedure (2).

Table 19, for three and four tagged b -jets, presents the expected signal and background rates and the naive signal significances, computed as $S/\sqrt{B}$, using procedure (1) and the different b -tagging performances considered above, for $m_H = 100 \text{ GeV}$ and an integrated luminosity of 10^4 pb^{-1} at the LHC. This table clearly demonstrates

that the identification of all four b -jets is too expensive in terms of signal rate, even for a probably much too optimistic b -tagging efficiency of 70%. On the other hand, for the more standard values, $\epsilon_b = 30\%$ and $R = 100$, the expected signal significance of 0.8 for three tagged b -jets is very similar to that of the WH channel. The signal rate is however a factor of ~ 2 smaller, with 21 combinations in the mass window (of which only 7 from $H \rightarrow b\bar{b}$ decay) for $t\bar{t}H$ compared to 40 $b\bar{b}$ pairs for WH .

Table 19: *For an integrated luminosity of 10^4 pb^{-1} at the LHC and for $m_H = 100 \text{ GeV}$, expected rates for the $t\bar{t}H$ signal, $t\bar{t}$ and $Wjjj$ backgrounds and expected signal significance, in a mass window $60 < m_{b\bar{b}} < 100 \text{ GeV}$, for events with three and four tagged b -jets, and for a lepton identification efficiency of 90%. The results are shown for procedure (1) and for the b -tagging performances described in the text.*

Three b -jets	$t\bar{t}H$	$t\bar{t}$	$Wjjj$	$S/\sqrt{B}$
$\epsilon_b = 30\%, R = 100$	19	440	110	0.8
$\epsilon_b = 50\%, R = 50$	74	2490	540	1.3
$\epsilon_b = 70\%, R = 10$	160	20800	10000	0.9

Four b -jets	$t\bar{t}H$	$t\bar{t}$	$Wjjjj$	$S/\sqrt{B}$
$\epsilon_b = 30\%, R = 100$	1	10	5	-
$\epsilon_b = 50\%, R = 50$	10	80	30	1.0
$\epsilon_b = 70\%, R = 10$	49	1760	500	1.0

Table 19 also shows that the rejection of non- b jets should be better than ~ 50 in order not to be swamped by the background. Table 20 further shows that the significance of the $t\bar{t}H$ signal depends also to some extent on the rejection of c -jets. Again a rejection of c -jets of at least ~ 20 is needed in order to keep the background under control.

Table 20: For an integrated luminosity of 10^4 pb^{-1} at the LHC and for $m_H = 100 \text{ GeV}$, expected rates for the $t\bar{t}H$ signal, $t\bar{t}$ and $Wjjj$ backgrounds and expected signal significance, in a mass window $60 < m_{b\bar{b}} < 100 \text{ GeV}$, as a function of the rejection of c -jets ($R_{c\text{-jet}}$), for events with three tagged b -jets and for a lepton identification efficiency of 90%. The results are shown for procedure (1) and for $\epsilon_b = 30\%$ and $R = 100$.

$\epsilon_b = 30\%$ $R = 100$	$R_{c\text{-jet}} = 100$	$R_{c\text{-jet}} = 50$	$R_{c\text{-jet}} = 10$
$t\bar{t}H$	19	20	21
$t\bar{t}$	440	680	1000
$Wjjj$	110	260	380
$S/\sqrt{B}$	0.8	0.7	0.6

For $m_H = 80, 100$ and 120 GeV , tables 21 and 22 display the expected rates and significances for procedures (2) and (3). There is very little improvement in significance over the naive procedure (1), but procedure (3) does yield a larger fraction ($\sim 60\%$) of $b\bar{b}$ pairs from $H \rightarrow b\bar{b}$ decay in the mass window than procedures (1) and (2), for which this fraction is only $\sim 35\%$. This means that procedure (3) will rely less heavily on an accurate Monte-Carlo description of the expected shape of the $b\bar{b}$ mass distribution for both signal and background.

7 Conclusions

We have presented here the results of a detailed study of associated Standard Model Higgs production (WH and $t\bar{t}H$), where the Higgs boson decays to $b\bar{b}$ pairs, which corresponds to the dominant Higgs boson decay mode in the mass range $80 < m_H < 130 \text{ GeV}$.

The final states are quite complex and the reconstruction and tagging of b -jets with high efficiency is obviously a crucial element in the detector performance in the search for such a decay channel. Even for optimistic b -tagging performances, $\epsilon_b = 50\%$ and $R = 50$, the signal cannot be cleanly extracted from the background. This would be even more the case of associated SUSY Higgs production, which in the framework of the MSSM is at best similar in rate to the Standard Model case, but is strongly suppressed for large values of $\tan\beta$.

Table 21: *For an integrated luminosity of 10^4 pb^{-1} at the LHC, expected rates for the $t\bar{t}H$ signal, $t\bar{t}$ and $Wjjj$ backgrounds and expected signal significance, in the appropriate mass window, as a function of m_H , for events with three tagged b -jets and for a lepton identification efficiency of 90%. The results are shown for procedure (2) and for the first two b -tagging performances described in the text.*

$m_H = 80 \text{ GeV}$	$t\bar{t}H$	$t\bar{t}$	$Wjjj$	$S/\sqrt{B}$
$\epsilon_b = 30\% \ R = 100$	47	660	140	1.7
$\epsilon_b = 50\% \ R = 50$	184	3430	630	2.9

$m_H = 100 \text{ GeV}$	$t\bar{t}H$	$t\bar{t}$	$Wjjj$	$S/\sqrt{B}$
$\epsilon_b = 30\% \ R = 100$	22	550	140	0.8
$\epsilon_b = 50\% \ R = 50$	87	2880	630	1.5

$m_H = 120 \text{ GeV}$	$t\bar{t}H$	$t\bar{t}$	$Wjjj$	$S/\sqrt{B}$
$\epsilon_b = 30\% \ R = 100$	11	410	140	0.5
$\epsilon_b = 50\% \ R = 50$	42	2200	630	0.8

For an integrated luminosity of 10^4 pb^{-1} and $m_H = 100 \text{ GeV}$, we expect at best ~ 110 reconstructed $H \rightarrow b\bar{b}$ decays from WH production, above a resonant background of $\sim 150 \text{ } WZ$ events and a non-resonant background of ~ 4800 events, and ~ 100 reconstructed $b\bar{b}$ pairs (of which ~ 50 from $H \rightarrow b\bar{b}$ decay) from $t\bar{t}H$ production, above a background of ~ 4000 events. The main difficulty in extracting these two channels is obviously in the low rate, the need for accurate control of all the background sources and for extremely good b -tagging performance. It is interesting to note that, beyond these common features, the two signal channels could be quite complementary to each other and also to other possible channels in this mass range, i.e. $H \rightarrow \gamma\gamma$ and WH , with $H \rightarrow \gamma\gamma$.

Table 22: *For an integrated luminosity of 10^4 pb^{-1} at the LHC, expected rates for the $t\bar{t}H$ signal, $t\bar{t}$ and $Wjjj$ backgrounds and expected signal significance, in the appropriate mass window, as a function of m_H , for events with three tagged b -jets and for a lepton identification efficiency of 90%. The results are shown for procedure (3) and for the first two b -tagging performances described in the text.*

$m_H = 80 \text{ GeV}$	$t\bar{t}H$	$t\bar{t}$	$Wjjj$	$S/\sqrt{B}$
$\epsilon_b = 30\% \ R = 100$	37	570	180	1.4
$\epsilon_b = 50\% \ R = 50$	154	3520	800	2.3

$m_H = 100 \text{ GeV}$	$t\bar{t}H$	$t\bar{t}$	$Wjjj$	$S/\sqrt{B}$
$\epsilon_b = 30\% \ R = 100$	22	700	180	0.7
$\epsilon_b = 50\% \ R = 50$	91	3660	800	1.4

$m_H = 120 \text{ GeV}$	$t\bar{t}H$	$t\bar{t}$	$Wjjj$	$S/\sqrt{B}$
$\epsilon_b = 30\% \ R = 100$	14	680	180	0.5
$\epsilon_b = 50\% \ R = 50$	51	3940	800	0.7

The reasons for this complementarity are:

- No single channel emerges as a clean signature for the Higgs boson in this mass range, especially if $m_H \sim m_Z$ (in many SUSY models, this is possibly the most likely scenario);
- The $t\bar{t}H$ channel is the only one that does not have to contend with background from the Z -resonance, due to the very small value of the $t\bar{t}Z$ cross-section with respect to the $t\bar{t}H$ cross-section for $m_H = m_Z$. On the other hand it is plagued by combinatorial background from the large multiplicity of b -quarks present in the final state;
- After a few years of running at low luminosity, it is quite possible that the combination of these four channels could lead to convincing evidence for a Higgs signal if it were there;
- The $H \rightarrow b\bar{b}$ channels are unlikely to be accessible as easily at high luminosity as at the initial low luminosity, since the lepton trigger threshold and the jet p_T -threshold would certainly have to be raised in order to cope with the increased trigger rates

and with pile-up background. On the other hand, the $H \rightarrow \gamma\gamma$ channels are difficult to extract at low luminosity because of the small branching ratio and low signal to background ratio, but certainly the quality of the signal extraction depends less crucially on the luminosity than for the $H \rightarrow b\bar{b}$ case.

From the results of these studies, it seems clear that these channels should be used as important benchmarks to optimise and evaluate as carefully as possible the ATLAS b -tagging performance. The $H \rightarrow b\bar{b}$ channel at low to intermediate luminosities may be the best way to probe the region $80 < m_H < 100$ GeV, whereas the $H \rightarrow \gamma\gamma$ channel at high luminosity is better for $100 < m_H < 150$ GeV.

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References

- [1] CDF Collaboration, FERMILAB-PUB-94/097-E.
- [2] G. Unal, private communication.
- [3] G. Jackson, talk presented at the Workshop on Electroweak Symmetry Breaking and TeV-Scale Physics, UC-Santa Barbara, Feb. 1994.
- [4] A. Stange, W. Marciano and S. Willenbrock, Phys. Rev. D50 (1994) 4491.
- [5] J. F. Gunion and T. Han, UCD-94-10.
- [6] J. F. Gunion, UCD-94-24.
- [7] T. Sjöstrand, “High-Energy-Physics Event Generation with PYTHIA 5.7 and JETSET 7.4”, CERN preprints CERN-TH.7111/93 and CERN-TH.7112/93.
- [8] B. Van Eijk and R. Kleiss, Proc. Large Hadron Collider Workshop (Aachen), eds. G. Jarlskog and D. Rein, (CERN 90-10, Geneva, Dec. 1990), Vol. II, p.183; M. DellaNegra et al., Proc. Large Hadron Collider Workshop (Aachen), eds. G. Jarlskog and D. Rein, (CERN 90-10, Geneva, Dec. 1990), Vol. II, p.509.
- [9] W. T. Giele et al., CAVENDISH-HEP-90/26.
- [10] L. Mangano, Nucl. Phys. 405 (1993) 536; we thank G. Unal for providing us with the code and its interface to HERWIG.
- [11] G. Marchesini et al., Comput. Phys. Commun. 67 (1992) 465.

- [12] E. Reya et al., Proc. Large Hadron Colliderorkshop (Aachen), eds. G. Jarlskog and D. Rein, (CERN 90-10, Geneva, Dec. 1990), Vol.II, p.296;
 G. Unal and L. Fayard, Proc. Large Hadron Colliderorkshop (Aachen), eds. G. Jarlskog and D. Rein, (CERN 90-10, Geneva, Dec. 1990), Vol.II, p.360;
 T. Moers et al., Proc. Large Hadron Colliderorkshop (Aachen), eds. G. Jarlskog and D. Rein, (CERN 90-10, Geneva, Dec. 1990), Vol.II, p.418.
- [13] S. D. Ellis, R. Kleiss and W. J. Stirling, Phys. Lett. B154 (1985) 435;
 F. A. Berends et al., Phys. Lett. B224 (1989) 530.
- [14] T. Han and S. Willenbrock, Phys. Lett. B273 (1990) 167.
- [15] CTEQ Collaboration, J. Botts et al., Phys. Lett. B304 (1993) 159.
- [16] C. Peterson et al., Phys. Rev. D27 (1983) 105.
- [17] J. Dai, J.F. Gunion and R. Vega, Phys. Rev. Lett. 71 (1993) 2699.