Vol. 32 (2001) ACTA PHYSICA POLONICA B No 4

HIGGS BOSON IN MULTI-*b*-JETS FINAL STATES RECONSTRUCTION WITH FULL SIMULATION OF ATLAS DETECTOR

Mariusz Sapiński†

H. Niewodniczański Institute of Nuclear Physics
Kawiory 26a, 30-055 Kraków, Poland

and Donatella Cavalli

Physics Department, Milan University and INFN
Via Celoria 16, I-20133 Milan, Italy

(Received February 6, 2001)

Channels with multi-b-jet final states are very important in the discovery strategies for the Higgs boson search in ATLAS experiment at LHC. Excellent jets reconstruction efficiencies and mass resolution capability of the di-jet system are crucial aspects of the detector performance for the signal observability in these channels. Full simulation and reconstruction of the four representative channels with b-jets in final states is discussed: WH, $t\bar{t}H$ with $H \to b\bar{b}$ and $A \to Zh$, $H \to hh$ with $h \to b\bar{b}$. These channels are used as benchmark ones to study the different complexity of events, level of combinatorial background from signal itself and universality of the algorithms used for jets reconstruction and energy calibration at the wide range of energy/mass scales. Equivalently important aspect of this study is to verify applicability of the fast detector simulation, based on parametrisation of main features of the detector, for studying signal and background rates for the above channels. For that reason the detailed comparisons of the expected efficiencies and acceptances in full (based on Geant 3) and fast simulations are shown at the different stages of the selection procedures. In general good agreement is found between results obtained in both approaches.

PACS numbers: 14.65.Ha, 14.80.Bn

† Supported in part by the Polish State Committee for Scientific Research grants 2P03B11819 and 620/E-77/SPUB/CERN/P-03/DZ 2/99.

1. Introduction

ATLAS is a multi-purpose detector designed for investigation of proton-proton collisions at energy 14 TeV in center of mass, at LHC accelerator [1]. One of the main goals of the detector is Higgs boson search. Channels with multi-b-jet final states seem to be very important for the search for the Higgs boson both in Standard Model and its Supersymmetric extensions [1]:

- In the low mass range, below 130 GeV, discovery potential relays on the $t\bar{t}H$ production. This channel is equivalently performant for searches of the Standard Model (SM) Higgs and of the lightest Higgs boson in the Minimal Supersymmetric Standard Model (MSSM). Selection criteria require reconstruction of both top quarks, in the hadronic and leptonic decay mode. The signal evidence is expected to show up as a peak in the m_{bb} distribution of the spectator di-b-jet system. Just four identified b-jets accompanied by an isolated lepton and di-jet system consistent with the hadronic W-boson decay are required in the final state.

- Much less promising, but nevertheless used as a reference channel for optimizing detector performance, is the WH production. Here, two b-jets from Higgs decay are required to be accompanied by the isolated lepton from W-boson decay. This channel is used as a benchmark one for two mass values, $m_H = 100$ GeV and $m_H = 400$ GeV. The second mass point is not expected to be accessible in WH production, however, both give good benchmark scenario for studying in the wide range the jets transverse momenta, the energy/mass scale calibration, di-jets system resolution and b-tagging capability.

- The $A \to Zh$, $Z \to l^+l^-$, $h \to b\bar{b}$, is promising for the MSSM Higgs boson discovery at low $\tan\beta$ and for masses below top-pair threshold (350 GeV). Here it is studied for the reference values of $m_A = 300$ GeV, $m_h = 80$ GeV. Search strategies require reconstructed $Z \to \ell^+\ell^-$ decay and two b-tagged jets. Reconstruction of the $h \to b\bar{b}$ mass peak and $A \to Zh$ peak is crucial for the possible observability of this signal.

- The $H \to hh \to 4b$ is promising in the similar range of the MSSM parameter space. Here it is studied for the same choice of the Higgs boson masses: $m_H = 300$ GeV and $m_h = 80$ GeV. Search strategies require four b-tagged jets. Reconstruction of the double $h \to b\bar{b}$ decay and $H \to hh$ peak is crucial for the possible observability of this signal.

For all above channels, in addition to the excellent b-tagging, the good resolution of the reconstructed mass distribution is a key element for discovery of the Higgs boson. The expected resolution and acceptance of the selection criteria is studied here with the full and fast simulation of the ATLAS detector. The same physical events, generated with Pythia 5.7 [7], were used in both simulation chains to allow event-by-event comparison. As the above processes represent different levels of the complexity of the events topology, mass of the resonances and jets energy scale, all together they form a representative sample for quantifying expected performance of the detector. Such comparison qualifies credibility of the background studies done in most cases with the fast simulation only.

2. The $WH \to l\nu b\bar{b}$ channel

The $H \to b\bar{b}$ decay mode is a dominant one for the Higgs masses below mass of the W-boson pair, with a branching ratio of $\sim 90\%$. The observation of this characteristic signature would be important for both the Higgs boson discovery and for the determination of the nature of any resonance observed in this mass region. The associated production with W or $t\bar{t}$ pair, giving an isolated lepton as an additional signature remains as the only possible production process to observe the signal in the $b\bar{b}$ decay mode above the huge QCD two-jet background. The Higgs boson signal might be just reconstructed as a peak in the invariant jet-jet mass spectrum of tagged b-jets.

Prospects for the observability of the Higgs boson in the WH associated production has been studied already for ATLAS TP [3], Physics TDR [1] and [6]. Recently this channel has been discussed also in the context of comparison between TeVatron and LHC physics potentials [4].

Although the expected sensitivity is rather weak for this channel alone, it serves as an excellent benchmark process for studying ATLAS detector capability for b-jets tagging and di-b-jets system reconstruction.

A sample of WH events was simulated with the full and fast simulation of the ATLAS detector. Selection criteria, foreseen by the search strategies, require presence of an isolated lepton with $p_{\mathrm{T}} > 20$ GeV, two b-tagged jets with $p_{\mathrm{T}} > 15$ GeV and veto on any additional jet in the full rapidity range. Table I shows sequential and cumulative acceptances of the above selection criteria. In general good agreement, on the level of 15%, is found between results obtained from both simulations streams.

Figure 1 shows reconstructed peak in the m_{bb} distribution for events from the fast and full simulation passing selection criteria as specified in Table I.

TABLE I

Acceptances of selection criteria for WH, $H \to b\bar{b}$ events with $m_H = 100$ GeV, with the full and fast simulation of ATLAS detector.

Selection	Partial accept. full	Partial accept. fast	Cumulative accept. full	Cumulative accept. fast
$n_{\rm jet} \geq 2$	72%	70%	72%	70%
2 b-jets (perfect b-tagging)	61%	62%	44%	43%
1 lepton with $p_{\rm T} > 20$ GeV and $\lvert\eta\rvert < 2.5$	66%	66%	29%	29%
Jet veto	56%	57%	16%	16%
Mass window $m_{bb} = 100 \pm 20$ GeV	82%	86%	13%	15%

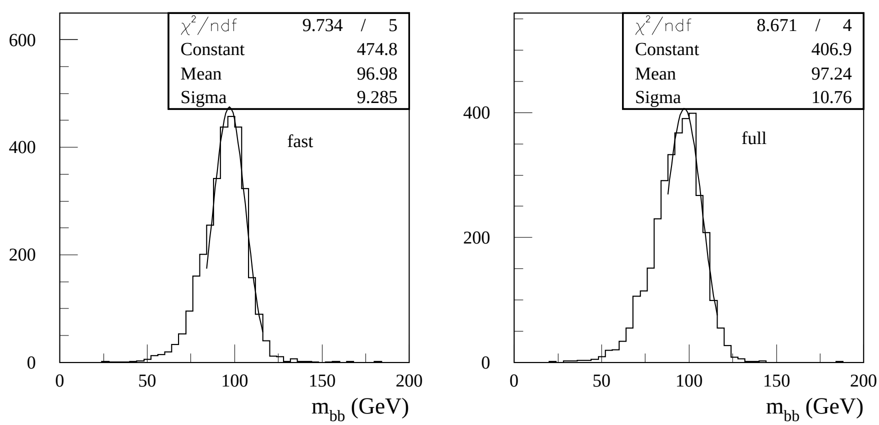

Fig. 1. The m_{bb} distribution of di-b-jet system, reconstructed for events processed with fast simulation (left plot) and full simulation (right plot) of the detector.

The reconstructed peak position of the distribution reproduces the value of the generated Higgs mass with precision of 3% [1]. Results are very well consistent between the full and fast simulations of the detector. This is a very encouraging fact as the jet energy calibration consists of two steps: calibration on detector effects (linearity, energy resolution, granularity, electronic noise, non-compensation of electromagnetic and hadronic calorimeters, *etc.*) and calibration on physics effects (final state radiation, outside-cone energy loss and loss from semileptonic decay) which must be used even for a *perfect detector*. In both simulation the same physics calibration function were used, what means that fast simulation parametrizes well the detector effects.

[1] This result does not represent yet ultimate precision expected for ATLAS detector [1].

The resolution from the full simulation is about 15% worse then the resolution from fast simulation, with only slightly higher fraction of the non-gaussian tail. Peak positions are different by 1%. Within the mass window of ± 20 GeV (that corresponds to $\pm 2\sigma$, assuming 10% mass resolution) cumulative acceptance of 13% (resp. 15%) is achieved with the full (resp. fast) simulation. These include acceptance for 2 b-labelled jets, isolated single lepton [2], jet-veto and mass window.

To simulate more realistically performance of the detector an electronic noise should be added to simulated energy deposition in each cell of the calorimeter. This noise comes from 200000 channels of electromagnetic calorimeter and it might spoil measurements of quantities, which use information from many cells like jet energy and $E_{\mathrm{T}}^{\mathrm{miss}}$. In simulation parametrized noise is added to each cell with Gaussian distribution with σ^{noise} corresponding to the characteristic of the electronics. Afterwards only cells with energy greater than the threshold value, expressed in σ^{noise}, are counted for the reconstruction of the jet energies. For this simulation the cut on the cell energy was optimized at the level of $1\sigma^{\mathrm{noise}}$ (see [12] for more detailed discussion).

The Higgs boson will be not accessible in the associated WH production for the mass of 400 GeV because of very low branching ratio. Nevertheless, it is used as the benchmark signature for studying reconstruction performance in the wider range of the energy/mass scale.

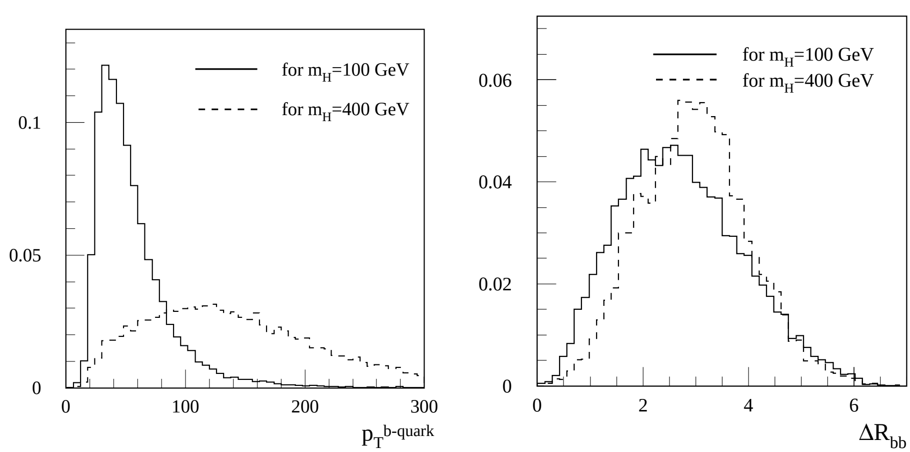

Fig. 2. The $p_{\mathrm{T}}^{b-\mathrm{quark}}$ and ΔR_{bb} distributions for the Higgs mass of 400 GeV (dashed) and 100 GeV (solid).

[2] In all these analyses, the isolated single lepton (lepton track and isolation selection) is always reconstructed with the fast simulation only. It was checked in [1] that for isolated leptons fast and full reconstructions agree very well.

Fig. 2 shows comparison of the distributions for the transverse momenta of the b-quarks from Higgs decay, $p_{\rm T}^{b-\rm quark}$, and the cone separation between pair of the b-quarks for the Higgs mass of 100 GeV and 400 GeV. With the Higgs mass increasing from 100 GeV to 400 GeV the average transverse momentum of b-jets rises from 56 GeV to 136 GeV. The peak position of the distribution of the cone separation of the pair of b-jets is shifted towards back-to-back configuration, from $\Delta R_{bb} = 2.7$ to $\Delta R_{bb} = 3.0$.

TABLE II

Acceptances of selection criteria for $WH, H \rightarrow b\bar{b}$ events with $m_H = 400$ GeV, with the full and fast simulation of ATLAS detector. Compared is also acceptance assuming a resolution $\sigma = 10\%\ m_H$.

	Partial accept.		Cumulative accept.	
Selection	full	fast	full	fast
2 b-jets (perfect b-tagging)	72%	78%	72%	78%
Mass window				
$m_{bb} = 400 \pm 70$ GeV (full)	70%	–	50%	–
$m_{bb} = 400 \pm 50$ GeV (fast)	–	75%	–	58%
$m_{bb} = 400 \pm 80$ GeV	76%	88%	55%	69%

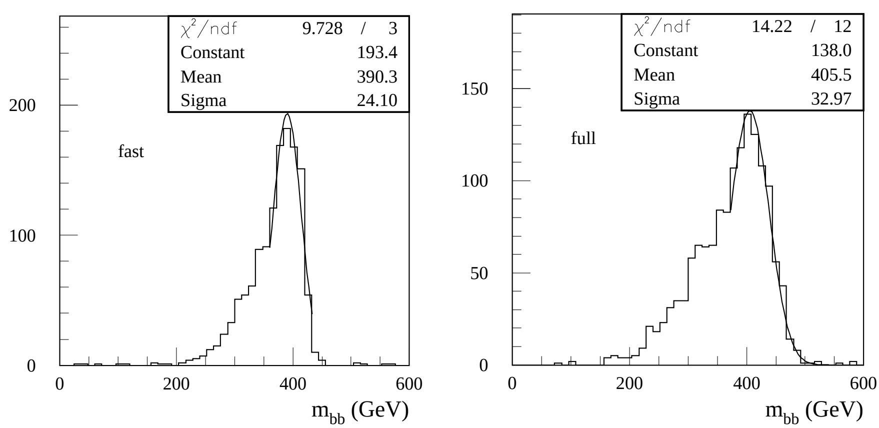

Fig. 3. The m_{bb} distribution of di-b-jet system, reconstructed for events processed with fast simulation (left plot) and full simulation (right plot) of the detector.

With the same physics calibration as for the $m_H = 100$ GeV case, precision on the reproduction of the invariant mass m_{bb} peak position is better than 3% (see Fig. 3). The amount of tails outside the $\pm 2\sigma$ window is of 25-30% (see Table II). Reconstructed distributions are asymmetric and have large tails for low mass values due to final state radiation, and this effect can be partially corrected by adding so called "neighbour" jets in a cone about $\sqrt{(\Delta\eta^2 + \Delta\phi^2)} = 0.9$ around. Expected m_{bb} resolution is better then 10% of the mass of the Higgs, ie. about 25 GeV (resp. 33 GeV) for the fast (resp. full simulation case). In $\pm 2\sigma$ GeV mass window about 75% of events from the fast simulation and about 70% from the full simulation are accepted. In ± 80 GeV mass window the acceptances are 88% (resp.78%) for fast (resp. full) simulation.

3. The $t\bar{t}H$ channel

Prospects for the observability of the Higgs boson in the $t\bar{t}H$ associated production has been studied in [9]. The analysis was recently completed by the discussion of the background estimation based on the parton shower and matrix element calculations [13]. The expected sensitivity is very promising at LHC: above 5σ for an integrated luminosity of 100 fb^{-1} for this channel alone and Higgs mass below 120 GeV.

The selection procedure is rather complicated. It requires four b-tagged jets (from top-quarks and Higgs decay) accompanied by an isolated lepton and di-jet pair consistent with the mass of W-boson. Both semileptonic and hadronic decays of top-quarks are required to be fully reconstructed. Evidence of the Higgs boson is searched for as a peak in the m_{bb} spectrum of remaining b-quarks.

Sequential steps of the selection procedure are following [9]:

- Require at least 6 reconstructed jets in rapidity range $|\eta| < 2.5$ with $p_{\mathrm{T}} > 20$ GeV, four of them identified as b-jets. They have to be accompanied by isolated lepton with $p_{\mathrm{T}} > 20$ GeV.

- Require that exists solution for the $W \to \ell\nu$ mass equation which allows to reconstruct semileptonic W decay (longitudinal momentum of neutrino calculated from transverse missing energy). In both simulation streams only information from fast reconstruction is used.

- Require that exists di-jet system of the non-b-tagged jets consistent with the W-boson hadronic decay (Fig. 4).

- Optimize matching of the b-jets with the existing combinations of the $W \to jj$ and $W \to \ell\nu$ and recalibrating m_{jj} to W-mass.

- Require both top-quarks being reconstructed inside the respective mass windows (Fig. 6 and Fig. 5).

- Reconstructed mass of the remaining pair of b-jets in the mass window (Fig. 7).

Table III collects partial and cumulative acceptances of the selection procedure. In total, fast simulation gives acceptances being 5%-10% higher. Obtained resolutions for top-pair reconstruction are in both, hadronic and leptonic modes, on the level of 5% m_t. This is understandable, as the best combinations with two out of four b-jets is always searched for. As the dominant background to this channel is the $t\bar{t}jj$ production, similar resolutions are expected also for the reconstruction of the background events.

TABLE III

Acceptances of selection criteria for $t\bar{t}H$, $H \to b\bar{b}$ events with $m_H = 100$ GeV, with the full and fast simulation of the ATLAS detector.

Selection	Partial accept. full	Partial accept. fast	Cumulative accept. full	Cumulative accept. fast
$n_{jet} \geq 6$	37%	37%	37%	37%
4 b-jets (perfect b-tagging)	49%	47%	18%	17%
1 isolated lepton	84%	84%	15%	14%
Solution for $W \to \ell\nu$ exists	64%	65%	9.6%	9.1%
2 jets in mass window $m_{jj} = 80 \pm 30$ GeV	70%	71%	6.8%	6.5%
Both tops in mass window $m_{l\nu b} = 175 \pm 15$ GeV (full) and $m_{jjb} = 175 \pm 17$ GeV (full)	59%	–	4.0%	–
$m_{l\nu b} = 175 \pm 16$ GeV (fast) and $m_{jjb} = 175 \pm 17$ GeV (fast)	– –	62%	–	4.0%
$m_{l\nu b}, m_{jjb} = 175 \pm 18$ GeV	65%	66%	4.5%	4.4%
the other 2 b-jets in mass window $m_{bb} = 100 \pm 30$ GeV with $\pm 2\sigma$ window for tops with ± 18 GeV window for tops	57% 59%	60% 61%	2.3% 2.6%	2.4% 2.6%
2 b-jets in mass window $m_{bb} = 100 \pm 40$ GeV with $\pm 2\sigma$ window for tops with ± 18 GeV window for tops	63% 64%	68% 68%	2.5% 2.9%	2.8% 3.0%

The difference less than 10% in the estimated total efficiency still indicates good agreement between full and fast simulations. The amount of expected tails is systematically only by 3% to 10% worse with the full simulation for each of the reconstructed resonances.

A similar lost in acceptance should be observed for the top-pair reconstruction with the full simulation of the $t\bar{t}$ background which is dominant background to discussed signal. These would lead to the significance $(S/\sqrt{B})$ being lower only by 5% if estimated with the full simulation.

From Table III and figures 4–7 one can see that fast and full simulation lead to results agreeing within 10% in sense of acceptances and mass resolutions. This is very encouraging taking into account complicated topology of this channel and several steps of the reconstruction procedure.

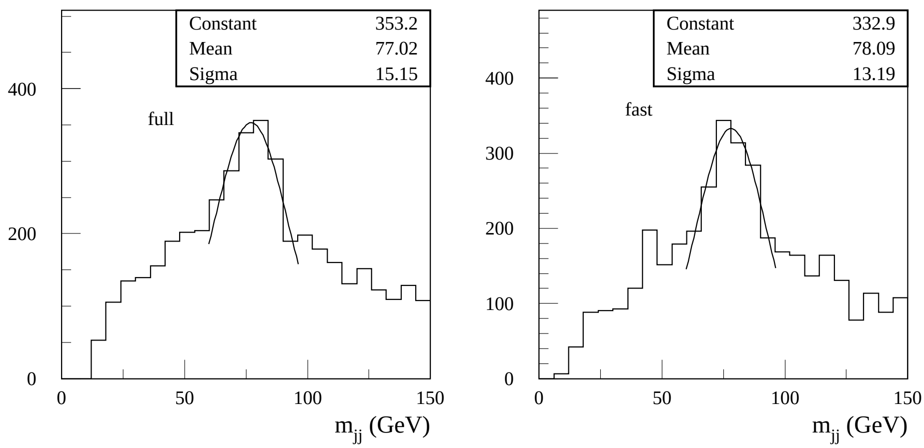

Fig. 4. Mass distributions of the 2 jets from W decay. Results from the full simulation (left) and fast simulation (right) are shown.

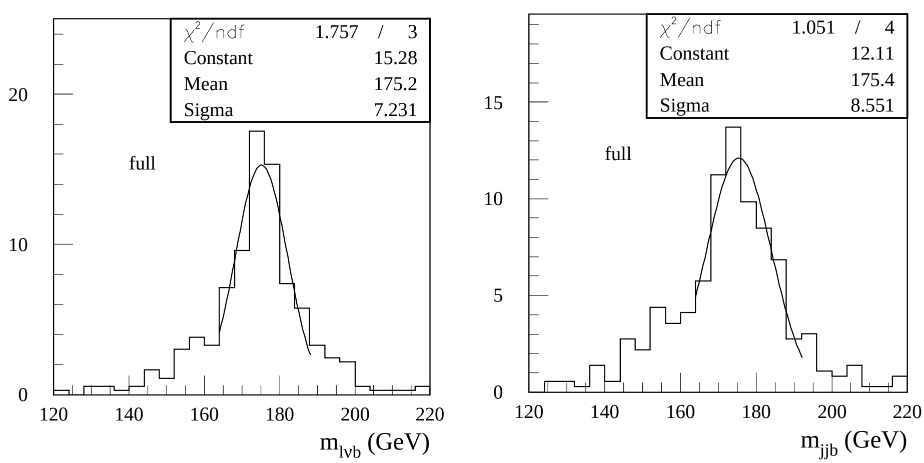

Fig. 5. Full simulation: mass distribution for reconstructed top quarks in the $t \to l\nu b$ and $t \to jjb$ channels.

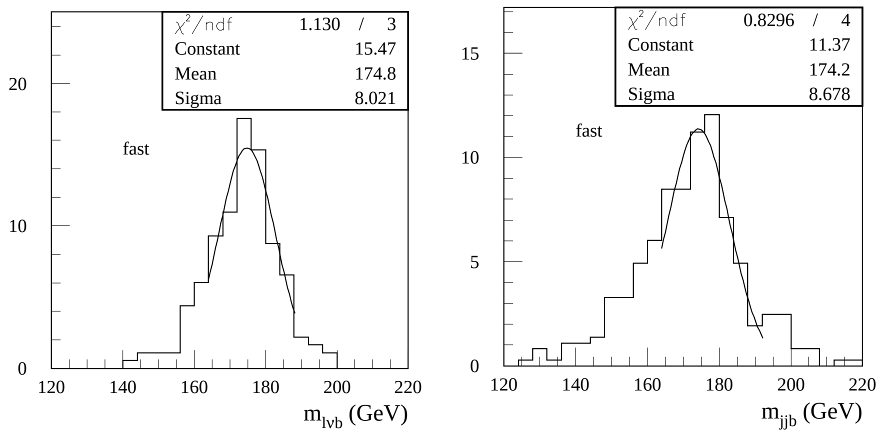

Fig. 6. The same as Fig. 5 but for the fast simulation of the ATLAS detector.

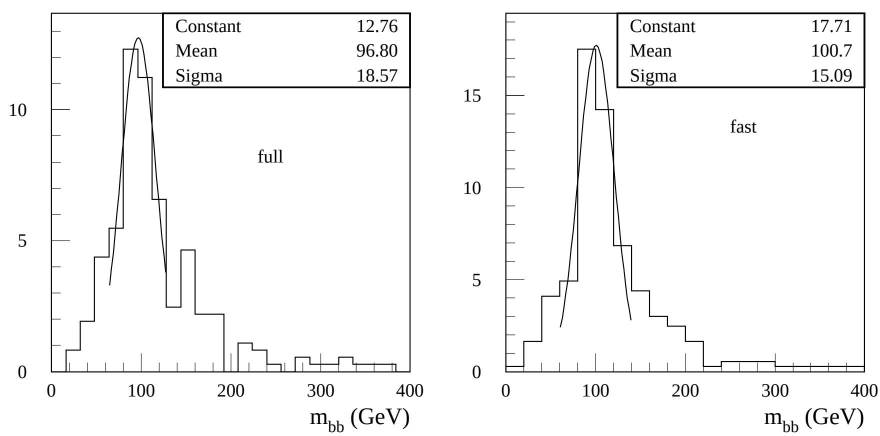

Fig. 7. Mass distributions of the di-b-jet system of the remaining two b-jets. Results from the full simulation (left) and fast simulation (right) are shown.

4. The $A \to Zh$ channel

The $A \to Zh \to 2\ell 2b$ is promising for the MSSM scenario with small $\tan\beta$ and Higgs mass below threshold for the $A \to t\bar{t}$ decay. Here it is studied for the following values of the Higgs boson masses: $m_A = 300$ GeV and $m_h = 80$ GeV. Search strategies require reconstruction of the Z-boson leptonic decay, two b-tagged jets, reconstruction of the h$\to b\bar{b}$ and $A \to Zh$ decays. Dominant background for this channel is $Zb\bar{b}$ and other contributing backgrounds are ZZ, Zjj and $t\bar{t}$.

In the presented analysis leptonic decay of Z-boson is reconstructed only with the fast simulation of the detector. Resolution obtained from the fast simulation for $Z \to \ell\ell$ channel agrees well with the one expected from the full simulation of the detector [1] . Therefore results obtained on the reconstruction of the resonant $m_{\ell\ell bb}$ distribution with this mixed full/fast reconstruction should be very close to the one expected with the full reconstruction only.

The following selection, with acceptances shown in Table IV, is expected:

- Reconstructed Z-boson leptonic decay from two isolated lepton with $p_{\rm T} > 20$ GeV.
- At least two jets, reconstructed with $p_{\rm T} > 15$ GeV and identified as b-jets.
- The mass of the bb pair within mass window $m_{bb} = m_h \pm 18$ GeV for fast simulation and full simulation.
- The $m_{\ell\ell bb}$ invariant mass within mass window $m_{\ell\ell bb} = m_A \pm 20$ GeV, after applying the h-boson mass constraint to pair of b-tagged jets, and Z-boson mass constraint to pair of electrons.

TABLE IV

Acceptances of selection criteria for $A \to Zh$ with $h \to b\bar{b}$ and $Z \to \ell^+\ell^-$ events, with the full and fast simulation of ATLAS detector.

Selection	Partial accept. full	Partial accept. fast	Cumulative accept. full	Cumulative accept. fast
2 b-jets (perfect b-tagging)	55%	58%	55%	58%
2 isolated electrons with $p_{\rm T} > 20\ GeV$	79%	79%	43%	46%
bb-pair in mass window $m_{bb} = 80 \pm 18$ GeV	86%	88%	37%	40%
$\ell^+\ell^-$ - pair in mass window $m_{\ell\ell} = 91.2 \pm 6$ GeV	81%	81%	30%	33%
m_{llbb} with m_h mass constraint $m_{llbb} = 300 \pm 20$ GeV	82%	83%	25%	27%
m_{llbb} with m_h and m_Z mass constraints $m_{llbb} = 300 \pm 20$ GeV	80%	82%	24%	27%

Table IV shows very good agreement between acceptances obtained with both simulation chains. The expected resolutions are below 10% of the mass of the reconstructed resonances $h \to bb$ and $A \to Zh \to llbb$.

Fig. 8 and Fig. 9 show m_{bb} and m_{llbb} distributions in fast and full simulation for reconstructed angle and jet energies [3].

[3] PYTHIA 5.7 which was used to generate this channel, produce A-bosons with a long tail for high values of mass m_A. A cut on generated A-boson mass lower than 320 GeV was applied.

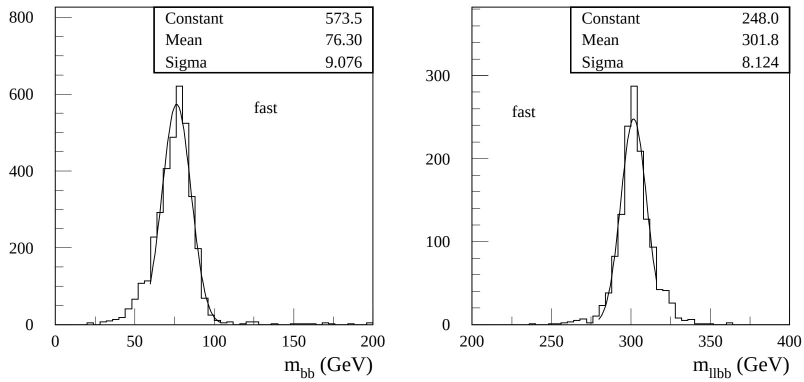

Fig. 8. The m_{bb} (left) and m_{llbb} (right) distributions with fast simulation of the ATLAS detector. The m_h-mass constraint is used.

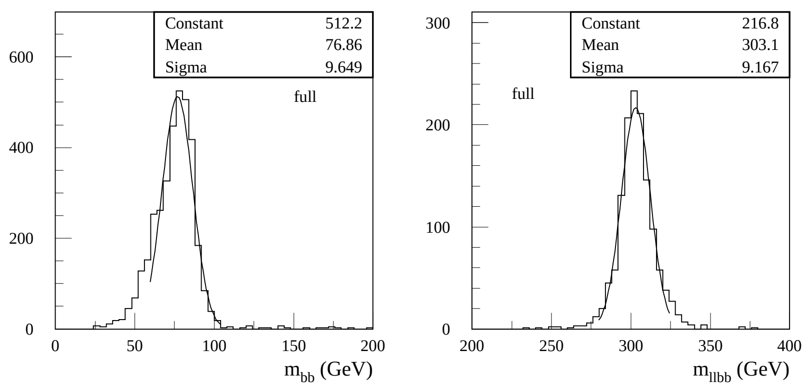

Fig. 9. The same as Fig. 8 but with the full simulation.

5. The $H \to hh$ channel

The $H \to hh \to 4b$ is promising for the MSSM scenario with small $\tan\beta$ and Higgs mass below threshold for $H \to t\bar{t}$ decay. Here it is studied for the following values of the Higgs boson masses: $m_H = 300$ GeV and $m_h = 80$ GeV. Search strategies require four b-tagged jets; reconstruction of the double $h \to b\bar{b}$ decay and reconstruction of the $H \to hh$ decay. The jet spectrum in this channel is relatively hard, with an average p_{T} of 100 GeV for the hardest and 36 GeV for the fourth jet. As the dominant background comes from continuum QCD multi-b-jet production, optimized resolution of the resonant peaks (in m_{bb} and m_{bbbb} distributions) and relatively high threshold on the reconstructed jets are the only handles to suppress this background [4]:

[4] For the analysis presented here we adopt thresholds which are lower than the ones foreseen by the present LVL1 trigger menu.

The following selection is foreseen:

- At least four jets, reconstructed with $p_{\mathrm{T}} > 30$ GeV and identified as b-jets.
- The best combination of two pairs of b-tagged jets to have a pair of invariant mass within mass window $m_{bb} = m_h \pm 2\sigma$ GeV, where $\sigma = 7.8$ GeV for fast simulation and 8.9 GeV for full one.
- The m_{bbbb} invariant mass within mass window $m_{bbbb} = m_H \pm 26$ GeV, after applying the h-boson mass constraint to both pairs of b-tagged jets.

Acceptances of these cuts are collected in Table V.

TABLE V

Acceptances of selection criteria for $H \to hh$ with both $h \to b\bar{b}$ events, with the full and fast simulation of ATLAS detector.

Selection	Partial accept.		Cumulative accept.	
	full	fast	full	fast
4 b-jets (perfect b-tagging) (with $p_{\mathrm{T}} > 30$ GeV and $\|\eta\| < 2.5$)	14%	13%	14%	13%
Both pairs in mass window $m_{bb} = 80 \pm 2\sigma$ GeV (σ values in text)	67%	65%	9.4%	8.5%
4 b system in mass window $m_{bbbb} = 300 \pm 26$ GeV	79%	77%	7.5%	6.5%

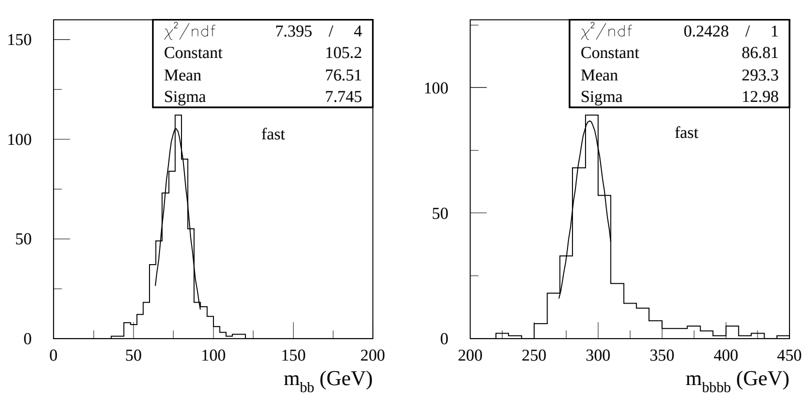

Fig. 10. The m_{bb} (left) and m_{bbbb} (right) distributions with fast simulation of the ATLAS detector. The m_h-mass constraint is used.

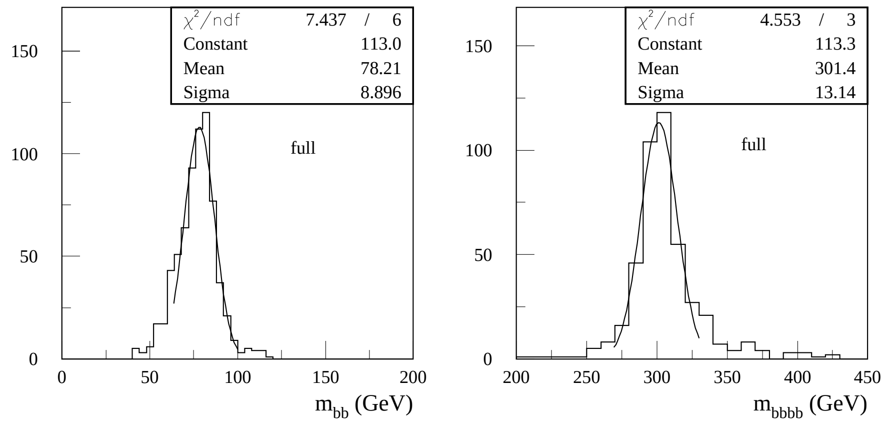

Fig. 11. The same as Fig. 10 but with the full simulation.

In Fig. 10 and Fig. 11 one can see m_{bb} and m_{bbbb} distributions for full and fast simulations. Also in this comparison both simulation streams agree very well; the largest difference in cumulative acceptance and width of $h \to b\bar{b}$ resonance, does not extend 15%.

6. Conclusions

Several channels from the Higgs searches scenarios with multi-b-jet final state were studied with the fast and full simulations. They represent a rich sample of events with different energy/mass scales and complexity of topology.

In general good agreement between results from the full and fast simulation was found on the expected resolution for reconstruction of the resonant peaks and the overall acceptances. It was shown also that the proposed calibration algorithm for the detector and physics effects works well in the large range of the jets energy scale.

With the final estimates, agreement better then 3% on the reconstructed position of the resonance was achievable in the mass range 100–400 GeV. Up to 10% agreement was also found on the level of expected tails for each of the reconstructed resonances. In the most complicated but most promising case of $t\bar{t}H$ reconstruction, final acceptance was lower by less then 10% only by the end of the selection with the full simulation of the detector with respect to the one achieved on the fast simulation level.

This work has been performed within the ATLAS Collaboration, and we thank collaboration members for helpful discussions. We have made use of the reconstruction and physics analysis framework and tools which are the result of collaboration efforts. In particular we acknowdegle invaluable help from Martine Bosman, David Rousseau, Gilbert Poulard and Santiago Gonzalez de la Hoz. In several technical points we benefit from the assistance of Steve O'Neale and Maya Stavrianakou. All the work was carefully followed by Elżbieta Richter-Wąs to whom we are greatly indebted.

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