ATLAS RRB-D 2001-118
28th September, 2001

Physics Impact of Staging ATLAS Detector Components

1. Introduction

The limited availability of resources as well as technical and schedule constraints have led the ATLAS Collaboration to revise its construction plans for the initial LHC detector. The current plan foresees that the completion of some detector components will be deferred by one to two years during the initial lower luminosity running of the LHC. A thorough evaluation of the physics potential has strongly guided the choice of the staging concept along the various other constraints.

The purpose of this note is to document the physics potential and performance of the initial detector in comparison to the complete detector performance required at the nominal LHC luminosity. In spite of some appreciable degradation the staged ATLAS detector will still allow the Collaboration to investigate the major physics topics for the initial physics run at the LHC. It will also be recalled from the Technical Design Reports that in order to cope with the full design luminosity of the machine, necessary to cover the enormous discovery potential of LHC, the complete detector will be required.

Furthermore, the note will also address the impact that further staging would have on the physics reach. No possibility has been found to extend temporarily the degradation of the detector in a smooth way. The studies have shown that further missing components would jeopardize the performance to a point that major parts of the LHC physics potential would become inaccessible.

2. General Considerations and Constraints for the Initial Detector

An overriding goal for the initial detector configuration and installation plan is to be ready for the LHC commissioning starting in January 2006, for the first collisions in the April 2006 pilot run, and for the first real LHC physics run commencing in August 2006. This plan is also exploring the flexibility available to face future changes that may be imposed by various constraints.

2.1 Technical Constraints

The technical constraints include the following aspects. There is a 9 month delay projected in the availability of the cavern (civil engineering delay) that affects directly the installation time. Today it is apparent that it would not be possible to install the full detector in the remaining time left before closure of the LHC ring at the end of 2005. The sequence of installation is highly conditioned by the minimal size of the cavern, designed such as to minimise the civil engineering costs.

There are also some of the detector components that are on an extremely tight construction schedule, and in spite of dedicated efforts ATLAS might not be able to recover all these delays safely. Finally, when planning for the initial detector one has to keep in mind the limited accessibility to the detector in order to insert missing components later, the risks of dismantling and reinstallation, as well as the significant LHC down-time that could be involved when completing the detector.

2.2 Resources and Funding Constraints

There are several resources and funding constraints that are faced by ATLAS, and that have been presented in a preliminary form to the RRB in April 2001. The expenditures on CORE items are affected by the fact that technical difficulties with industries required in several cases to renegotiate and replace contracts, usually at larger costs than initially planned, as well as by the purchasing power evolution since the initial 1995 cost evaluations. Finalizing the detector design, reacting to test and prototype experience, and understanding better the installation procedures also resulted in the need for some additional items not included in the initial detector cost evaluation.

The construction experience also shows that some of the non-CORE costs are higher than initially expected, in particular for common assembly infrastructure and for manpower needs at the construction sites in the Institutes and centrally at CERN.

The ATLAS Collaboration gratefully acknowledges to great efforts made by Funding Agencies to cover many of these difficulties for deliverables and in-kind contributions for the Common Projects.

The Russian funding is becoming available slower than it was anticipated for the completion of the full commitments within the initial construction years, and an extension is therefore needed. The Collaboration had also to face a funding reduction as a result of a partial withdrawal of one team, as discussed at the previous RRB. New collaborators have covered so far only a part of the under-funding for the LAr calorimeter system (documented in the Memorandum of Understanding, MoU). Furthermore, not all of the so-called U.S. management contingency, that would have been necessary to achieve the full goal of the MoU, will remain available after completion of the currently authorized U.S. baseline deliverables.

A detailed account of the resources situation will be documented elsewhere for this RRB.

2.3 Physics Priorities

The physics priorities for the first physics run in 2006 have been extensively studied. A detector concept to address the great potential for even the initial year of running was arrived at based on:

- SUSY potential (after a few days only already) requires full calorimeter coverage;
- Standard Model Higgs searches, including the low mass region overlapping with the LEP limit, imply electron and muon detection and measurement over a large rapidity range (rather than a full radial high-luminosity redundancy over limited rapidity) and high-performance b-tagging;
- MSSM Higgs searches need in addition tau-lepton identification already at low luminosity.

The present expectations are that the LHC luminosity will reach within only a few years the design value (high-luminosity), and studies have been initiated by CERN to explore the enhancement of the physics potential for even higher luminosities in a future LHC upgrade. The detector planning must make it also possible to meet this future challenge with upgrades.

2.4 Initial Detector Configuration

A meaningful detector needs the full Magnet System, no reasonable staging has been identified that would be possible in this case. Furthermore one has to recall that the construction of the barrel toroid is critical for the overall schedule, and in order to have a balanced magnetic force configuration it would not be possible to consider temporary operation with only one end-cap toroid.

The initial Inner Detector configuration will defer one of the three pixel layers (but not the B-layer) and its associated read-out electronics as well as the outermost end-cap TRT wheels. A pixel layer instead of an SCT layer was chosen for staging in order to minimize the future re-installation down-time.

Full Calorimeter coverage is required for the initial LHC physics, in particular for the important Higgs and SUSY searches. As a side-remark it is also needed mechanically to shield the muon chambers within the ATLAS air-core magnet system. The limited staging that is implemented concerns a reduction of read-out drivers (RODs) and possibly a reduced redundancy in HV power supplies. Further staging will be implemented for the instrumentation with the so-called cryostat-gap scintillators used for energy corrections in the transition regions between barrel and end-caps.

The staging in the Muon System affects the so-called EES and EEL MDT chambers, including supports and electronics, in the transition region between barrel and end-caps and part of the end-cap end-wall MDT chambers. Only half of the CSC layers (mechanics and electronics) will be part of the lower luminosity initial detector.
Further staging will concerns eventually part of the outermost barrel chambers if the installation time would impose this.

The High Level Trigger and DAQ System will be initially designed to the reduced costs, in a way that it can be readily upgraded. Furthermore also the processor farm that is part of the Common Projects will be implemented in an expandable way, starting from a reduced system.

3. Physics Implications of the Initial Detector Configuration

For the complete detector as described in the ATLAS Technical Design Reports (TDRs) Figure 1 shows the expected significance for a Standard Model Higgs signal as a function of mass over the region $m_H < 200$ GeV. This region is particularly crucial because it is favoured by the fit to the LEP/Tevatron/SLC electroweak data and because it is the most difficult one at the LHC. It can be seen that for masses below 130 GeV discovery (i.e. a signal significance of at least 5σ) can be achieved with only 10 fb^{-1} of integrated luminosity, i.e. during the first physics run in 2006-2007, by combining ATLAS and CMS. For masses larger than 130 GeV, where the gold-plated $H \rightarrow 4$ channel becomes accessible, 5σ discovery is possible by the individual experiments with the same integrated luminosity.

In the region $m_H < 130$ GeV, two complementary channels provide most of the sensitivity: $H \rightarrow \gamma\gamma$ (which requires precise EM calorimetry over $|\eta| < 2.4$) and ttH production followed by $H \rightarrow bb$, which requires calorimetry, muon trigger chambers and high-performance b-tagging. As it can be seen from Table 1, both these channels contribute in a similar way to the expected signal significance in ATLAS.

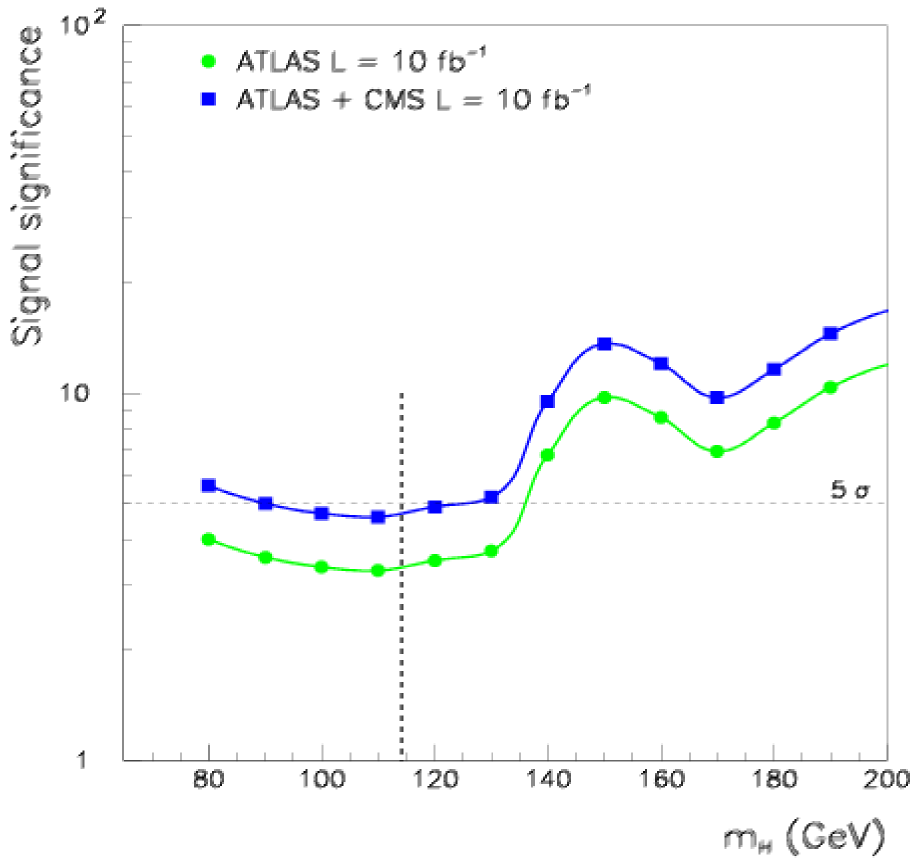

Figure 1. Expected significance for a SM Higgs signal as a function of mass with the complete (TDR) ATLAS detector (circles) and by combining ATLAS and CMS (squares) for an integrated luminosity of 10 fb^{-1} per experiment. The dashed vertical line indicates the lower limit set by LEP (114.1 GeV).

Table 1: Expected number of signal events (S), background events (B), signal-to-background ratio (S/B) and signal significance (S/√B) in ATLAS for a SM Higgs of mass ~115 GeV, for an integrated luminosity of 10 fb^{-1} and for the complete detector (TDR).

	$H \to \gamma\gamma$	ttH → tt bb	Both channels
S	150	15	
B	3900	45	
S/B	0.04	0.3	
S/√B	2.4	2.2	3.2

The physics implications of staging detector parts are discussed one by one below.

3.1 Staging of One Pixel Layer

The impact of one missing pixel layer (which is not the B-layer) has been studied with a full GEANT-based simulation of Higgs signal and background events. For a fixed b-tagging efficiency of 50%, the rejection against light-quark (u, d, s) jets deteriorates by ~30% with a 2-layer pixel detector compared to a 3-layer detector. The impact on the ttH channel is a significance loss of about 8%, which can be compensated by accumulating 15% more luminosity.

3.2 Staging of the Outermost End-Cap TRT Wheels

Staging of these wheels, which cover the rapidity range $1.7 < |\eta| < 2.4$ and improve the momentum resolution provided by the precision layers by typically a factor of 1.5, will imply a deterioration of the track momentum resolution by a factor of 1.5 over about 20% of the Inner Detector acceptance.

The most serious physics implication in the initial run is expected to be a loss in significance for the $H \rightarrow 4\mu$ signal over the mass region $m_H < 200$ GeV. Indeed, in this region the mass resolution obtained by combining the Inner Detector and the Muon Spectrometer ($\sigma_m \sim 1.4$ GeV for $m_H = 130$ GeV) is driven by the Inner Detector ($\sigma_m \sim 1.6$ GeV with the Inner Detector alone for $m_H = 130$ GeV, compared to $\sigma_m \sim 2.1$ GeV from the Muon Spectrometer alone). This is because the decay muons have typical momenta of smaller than 40 GeV, an energy range where multiple scattering in the calorimeters limits the Muon Spectrometer performance.

A study performed with a full GEANT-based simulation of the $H \rightarrow 4\mu$ channel for $m_H =$ 130 GeV has shown that , due to the limited rapidity coverage of the outermost end-cap TRT wheels, the mass resolution degrades marginally in the staged TRT scenario compared to the full TRT detector. However this is only true if the complete Muon Spectrometer is available. If, in addition, one includes the staging of the MDT chambers over the same rapidity region, then the mass resolution degrades by ~15% and therefore the $H \rightarrow 4\mu$ significance by ~7%.

Although this effect might seem to be marginal, given the availability of the $H \rightarrow 4e$ channel (which is not affected by the staging of the tracking systems), it is important to stress that in the case of an early discovery with only a few signal events, observation of a convincing excess in both channels (4e *and* 4μ) would increase the robustness of the discovery and the confidence that the observed signal is indeed new physics.

3.3 Staging of the Cryostat-Gap Scintillator

This detector covers the rapidity region $1.0 < |\eta| < 1.6$ and together with other devices (LAr end-cap presampler, Intermediate Tile Calorimeter) contributes to improving the energy measurements for electrons, photons and jets in the transition region between the barrel and the end-cap calorimeters. Without these devices the energy resolution would be seriously deteriorated by the large amount of material (e.g. coming from the cryostat walls). For instance, the energy resolution for electrons of energy 30 GeV would deteriorate from 5% to 20% at $|\eta| \sim 1.5$ if both the presampler and the gap scintillator were absent.

To evaluate in a conservative way the impact of the missing gap scintillators, it was assumed that electrons hitting the transition region are discarded because their energy resolution would be too much degraded. The impact on a possible $H \rightarrow 4e$ signal will be a loss in significance of about 8%. It should be noted that no loss is expected for $H \rightarrow \gamma\gamma$ since photons crossing the region $1.4 < |\eta| < 1.6$ have been discarded in Table 1 because the calorimeter performance in this region is not good enough to provide the needed rejection against the reducible jet backgrounds to a possible H $\rightarrow \gamma\gamma$ signal.

Finally, the implications of the missing scintillator on physics channels involving jets and missing energy (e.g. SUSY final states) are expected to be small.

3.4 Staging of Precision Chambers in the Muon System

First, we note that the trigger chambers are necessary right from the beginning over the full envisaged rapidity coverage since they provide the trigger for final states containing muons.

The staging of part of the precision chambers, along the lines described in the previous Section, is expected to have an impact mainly on new heavy particles decaying into high-momentum muons, for which the momentum resolution is driven by the external Muon Spectrometer. This is the case for instance of the heavy Higgs bosons of the MSSM (A and H bosons) for masses around 250 GeV or larger, which should be detected over a large fraction of the parameter space through their decays into two muons. For example, the mass resolution for a possible A/H $\rightarrow \mu\mu$ signal with mass 300 GeV is 10.8 GeV if the information of the Inner Detector and the Muon Spectrometer is combined, 12 GeV with the Muon Spectrometer alone and 20 GeV with the Inner Detector alone. Therefore, missing chambers in the Muon Spectrometer are expected to have a clear impact on this channel.

The staging of the transition chambers (EES/EEL) and of the end-wall MDT chambers will cause a degradation of the momentum resolution of the Muon Spectrometer alone by up to a factor of 4 over the relevant rapidity region. If also the information of the Inner Detector is used to reconstruct the muons, the loss in significance for a A/H signal with mass 300 GeV will be smaller than 5% if only the EES/EEL chambers are missing and about 10% if also the end-wall MDT chambers are missing.

The absence of half of the CSC chambers was found to have negligible impact on the physics performance (e.g. pattern recognition) in the initial LHC phase at low luminosity.

3.5 Summary of the Staging Impact on Physics

Table 2 summarises the main expected physics implications of the proposed staging for the initial detector configuration during the first physics run.

Table 2: Physics impact of the staging for the initial detector configuration.

Staged items	Main impact expected on	Loss in significance
One pixel layer	ttH $\rightarrow$ ttbb	~ 8%
Outermost TRT wheels + MDT	H $\rightarrow 4\mu$	~ 7%
Cryostat Gap scintillators	H $\rightarrow$ 4e	~ 8%
MDT	A/H $\rightarrow 2\mu$	~ 10% for m ~ 300 GeV

The main conclusion is that the discovery potential for a Higgs signal in several final states will be degraded by about 10%. Although this result is acceptable, it means that 20% more luminosity (i.e. 20% more LHC running time) will be needed to compensate for this loss. This might enhance the advantage of the Tevatron, which, on the time scale of 2007, might reach enough integrated luminosity for a 5σ discovery of a Higgs boson of mass below 120 GeV.

It should also be noted that possible penalties on the pattern recognition performance (e.g. track reconstruction efficiency and fake rates) coming from the less robust tracking systems have not been included in the studies shown here. These penalties are expected to be acceptable in the initial phase at low luminosity and much more significant when running at the LHC design luminosity, as discussed in the next Section.

Finally, the staging of part of the calorimeter RODs is expected to have an impact mainly on the maximum affordable trigger rate, which will be limited to ~50 kHz at the first level trigger. This will leave ATLAS with no safety margin on the expected rate predictions for the initial run.

4. High Luminosity Reach and Requirements

Running at the LHC design luminosity requires not only complete angular coverage, but also radially complete tracking devices, for several reasons:

- In order to exploit at best the LHC potential, efficient and precise reconstruction of very high-p_T muons, such as those produced in the decay of heavy objects (e.g. a Z', heavy Higgs bosons), is needed. This requires a complete Muon Spectrometer, since if the third station of chambers were missing, the momentum resolution would be degraded by more than a factor of 3 for muons of p_T = 100 GeV and the measurement and identification would be very poor for 1 TeV muons.

- Robust pattern recognition in the presence of the pile-up and radiation expected at the design luminosity requires high redundancy, especially for the stiff high-momentum tracks. The number of layers in the tracking devices presented in the ATLAS TDR was carefully optimised taking into account background levels (i.e. radiation damage and occupancy), reconstruction efficiency and fake-track rates. It should be noticed that there are large uncertainties (up to a factor of 10) on the expected background levels, for instance in the external Muon Spectrometer. As an example, if there were only 3x2 layers in the first station of the Muon Spectrometer (as initially planned before the optimisation studies done for the Muon TDR), instead of the 4x2 layers presently under construction, and the occupancy in this station were a factor of ten larger than expected, then the reconstruction efficiency for muons of a few hundred GeV would decrease by about 2% and the fake track rate would increase by a factor ~1.5. The impact would be larger if the luminosity increased to beyond 10^{34} cm^{-2} s^{-1}, as it could be expected from a natural optimisation of the machine performance or as a consequence of specific LHC machine upgrades.

- The possibility of performing efficient b-tagging depends on the number of precision layers in the Inner Detector. It has already been mentioned that for ttH events with a Higgs mass around 100 GeV the b-tagging performance deteriorates by ~30% if one pixel layer is missing. This loss in performance is larger for higher p_T (and therefore denser) b-jets, such as those which might be produced in SUSY events or in the decays of heavy exotic resonances that will be looked for during the phase at high luminosity. For instance, for b-jets of p_T~200 GeV the b-tagging performance is degraded by more than 50% in a detector with only two pixel layers compared to the complete ATLAS detector. One should also take into account that inevitable losses in the detector efficiency will occur during the ATLAS lifetime. On the other hand, the machine performance may improve with time and therefore the LHC may deliver luminosities in excess of the design value. Both these factors justify even further the need for a robust layout.

5. Physics Impact of Staging Scenarios Beyond the Initial Detector Configuration

Additional staging of detector components has been considered, and five test cases have been studied. These are discussed below.

5.1 Staging of Calorimetry in One End-Cap

If one of the LAr end-cap calorimeters (EM, HEC, FCAL) were not ready, then the full calorimetry in one of the two end-caps would be staged, since the EM, HEC, and FCAL calorimeters are housed in the same cryostat. This would have a dramatic impact on both Higgs and SUSY searches. For instance, the signal significance of both $H \rightarrow \gamma\gamma$ and $H \rightarrow 4e$ would be degraded by 30%, which would require a factor of 1.6 more luminosity to compensate, because the significance for both these channels decreases essentially linearly with decreasing detector coverage.

The main expected signatures for SUSY are events with many hard jets and large missing transverse energy. If calorimetry is missing in one end-cap, then the missing energy signature would be lost because events with a priori no escaping particles (like QCD multi-jet production) will have a larger missing transverse energy due to particles lost in the uncovered region. This is illustrated in Figure 2, which shows the distribution of the event effective mass (a variable related to the scalar sum of the missing transverse energy and the transverse energy of the leading jets in the event) for ATLAS with full calorimetry coverage (i.e. over $|\eta| < 5$) and for a detector without LAr calorimetry in one end-cap (i.e. over the region $1.4 < \eta < 5$). In this latter case, the SUSY signal produced by squarks and gluinos, here shown for masses of ~ 700 GeV, would be overwhelmed by the QCD background.

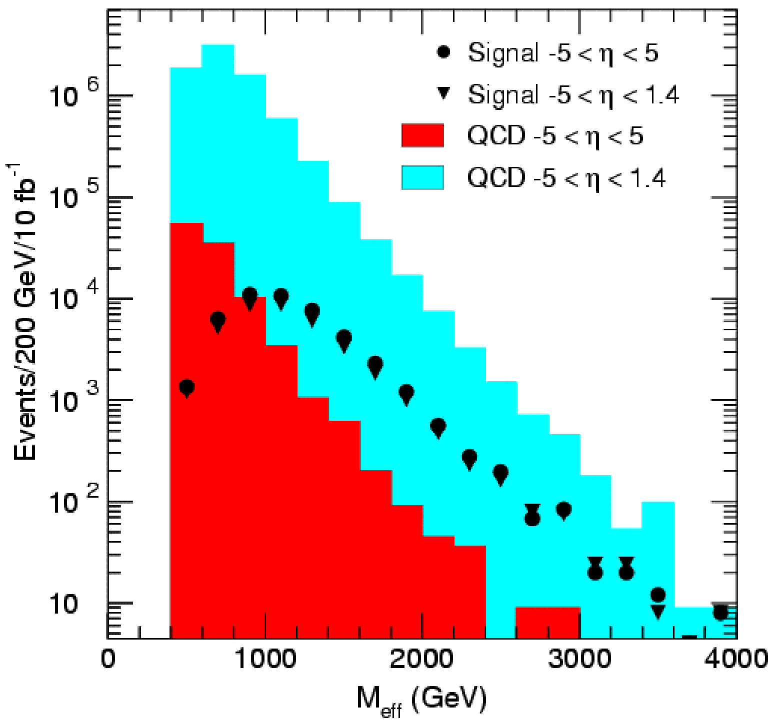

Figure 2. Expected distribution of the "effective mass" variable (see text) for the SUSY signal (points) and the QCD background (histograms) for the full

calorimeter coverage and for a scenario with no LAr calorimetry in one end-cap.

5.2 Further Staging of the Pixel Detector

If two or three pixel layers were staged, the capability of tagging b-jets would be lost. The main consequence is that the ttH $\rightarrow$ ttbb channel could not be detected and therefore the total ATLAS sensitivity to a Higgs signal for masses below 130 GeV would decrease from 3.2 to 2.4 (see Table 1). This not only means that 18 fb^{-1} instead of 10 fb^{-1} would be needed to recover for this loss, but also that the robustness provided by two independent channels would be lost. Similar conclusions apply to the observation of the Higgs bosons of the MSSM and to SUSY signatures involving b-jets. In addition top-quark physics, which is one of the main LHC goals in the initial phase at low luminosity, will be jeopardised.

5.3 Further Staging of the TRT

If the full TRT detector were absent, the track momentum resolution would be degraded by a factor of 1.5-2 over the full coverage of the Inner Detector. This alone, i.e. even neglecting pattern recognition, level-2 trigger and electron identification problems, would cause a degradation of the significance for the H $\rightarrow 4\mu$ channel by 15%, and also impact, to a lesser extent, other physics channels with muons in the final state.

5.4 Further Staging of Muon Precision Chambers

If the precision chambers of the Muon Spectrometer (MDT, CSC) were absent, ATLAS would jeopardise the capability of discovering an early signal due to the heavy Higgs bosons of the MSSM. For instance, the significance of a possible A/H $\rightarrow \mu\mu$ signal would decrease by more than 35%. It should be noted that this physics channel, together with A/H $\rightarrow \tau\tau$, is one of the few processes available to observe a heavy Higgs signal over a large fraction of the MSSM parameter space.

5.5 No Muon Instrumentation in One End-Cap

If both, precision and trigger chambers were missing in one end-cap toroid, e.g. over the region $\eta > 1.1$, then the acceptance for final states relying on muon trigger and identification would be strongly reduced. As an example, Figure 3 shows the rapidity distribution of the muon with the largest rapidity for H $\rightarrow 4\mu$ events after kinematics cuts. It can be seen that in most events at least one muon is in the region $|\eta| > 1.1$.

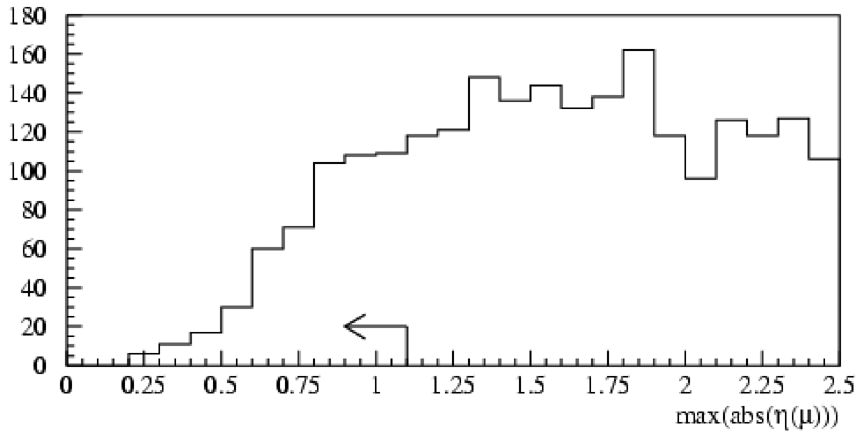

Figure 3. Rapidity distribution of the muon with the largest $|\eta|$ in $H \rightarrow 4\mu$ events with $m_H = 130$ GeV.

Therefore, assuming that events where two or more muons escape in the non-instrumented region are lost, because they cannot be identified efficiently, the signal significance would degrade by 20%.

We note that the impact would be very strong also on any high mass exploratory physics (for example $Z' \rightarrow \mu\mu$) that could become accessible in case the LHC luminosity would exceed the current expectation for the first physics run.

In conclusion, additional staging of the ATLAS detector, which in some cases such as calorimetry or TRT implies a full block of detectors missing, would lead to unacceptable implications on physics, thereby questioning the interest and opportunity of a first physics run in 2006. Indeed, the significance for a Higgs signal in the most promising channels would be degraded by about 30%, requiring a factor 1.5-2 more luminosity to reach the same discovery potential, and the detector might become blind to SUSY particles.

6. Conclusions

This note summarizes the main physics impact of the staging adopted by the ATLAS Collaboration for the initial detector configuration for the first LHC physics run starting in Summer 2006 and aiming at an integrated luminosity of 10 fb^{-1}. The staging strategy has been carefully chosen such as to preserve as much as possible the main goals and opportunities of the LHC. Yet some losses are unavoidable, in particular the Higgs signal significance in several final states will be degraded by about 10%. Although this result is acceptable, it means that 20% more luminosity (or running time of the LHC) will be needed to compensate for this loss. Furthermore, robustness and redundancy in the pattern recognition had to be sacrificed in order to achieve this overall staging compromise for the initial luminosity detector configuration.

To exploit the full and very rich physics potential of the LHC high-luminosity running will be mandatory. This regime is expected to be reached gradually as from mid-2007 onwards. In order to cope with the expected background conditions the full robustness and redundancy of the ATLAS detector will be required, according to its design criteria as specified in the Technical Design Reports. This means restoring both the pattern recognition capabilities and the resolutions for the large variety of expected and unexpected signals. Otherwise the planned increase in luminosity of the machine could not be exploited. The staged components must therefore be installed in Spring 2007 after the initial run.

Additional staging for the initial phase has been studied for several test cases. As also described briefly in this note it has been found that this would lead to unacceptable cuts into the physics reach, to a point that the interest and opportunities of a first physics run in 2006 would be severely put into question, and with the risk that the resources needed to operate the LHC would be wasted to a large extent.