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Status of the ATLAS detector and its readiness for early BSM Physics

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Summary. — The general status of the ATLAS experiment at the LHC is reviewed. Particular emphasis is given to the results from the *in situ* commissioning of the detector using calibration and cosmics data taking. The commissioning period has prepared ATLAS for the first beam injection in September 2008. Some results from the beam experience will be described. Finally, given the present knowledge of the detector performance, the readiness of the detector for early studies of Physics beyond the Standard Model will be discussed.

PACS 29.40.Gx – Tracking and position-sensitive detectors.
PACS 29.40.Vj – Calorimeters.

1. – Introduction

The Large Hadron Collider (LHC) at CERN will soon start its activity with unprecedent high energy and luminosity: bunches of 10^{11} protons will collide with a frequency of 25 ns to provide 14 TeV proton-proton collisions at a design luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. ATLAS is one of the general-purpose detectors built to probe the interactions of protons. The high interaction rates, radiation flux, particle multiplicities and energies, as well as precision measurements required for successful physics studies have set important constraints on its design. A detailed and complete description of the detector as installed in the cavern can be found in [1].

The tracker (or ID, Inner Detector) is immersed in a 2 T solenoidal field. Because of the expected high track density at nominal luminosity, and in order to achieve excellent vertex and momentum measurements, the central tracker consists of two parts: high-resolution semiconductor Pixel and microstrip (SCT, or SemiConductor Tracker) detectors in the inner part and a Transition Radiation Tracker (TRT), made of straw tubes, in the outer part of the tracking volume.

Calorimeters cover the range $|\eta| < 4.9$, using different techniques suited to the wildly varying requirements of the physics processes of interest and of the radiation environment over this large η-range. High-granularity liquid-argon (LAr) electromagnetic sampling calorimeters, with excellent performance in terms of energy and position resolution, surround the tracker and cover the pseudorapidity range $|\eta| < 3.2$. The hadronic calorimetry in the range $|\eta| < 1.7$ is provided by a scintillator-tile calorimeter (Tile). In the end-caps ($|\eta| > 1.5$), LAr technology is also used for the hadronic calorimeters. The LAr forward calorimeters provide both electromagnetic and hadronic energy measurements and extend the pseudorapidity coverage to $|\eta| = 4.9$.

The calorimeters are surrounded by the muon spectrometer. The air-core toroid system, with a long barrel and two inserted end-cap magnets, generates a strong bending power in a large volume (1.5 to 5.5 Tm for $|\eta| < 1.4$ and 1 to 7.5 Tm in the region $1.6 < |\eta| < 2.7$) within a light and open structure. Multiple scattering is minimized and excellent muon momentum resolution is achieved with three layers of high-precision tracking chambers. Trigger chambers with a time resolution of 1.5–4 ns complete the functionality of the muon spectrometer.

The Level-1 trigger system uses a subset of the detector information coming from the muon spectrometer and the calorimeters to reject uninteresting events, reducing the data rate to ≈ 75 kHz (limited by the bandwidth of the readout system, which is upgradeable to 100 kHz). Two subsequent levels of trigger using more accurate information coming from the full detector reduce the final data taking to ≈ 200 Hz from the initial 40 MHz rate.

The complete operation of the ATLAS detector has been exercised during several periods of combined cosmics data-taking. They allow for basic detector studies like noise measurements, identification of hot or dead channels and malfunctioning services. Additionally, the trajectories of cosmic-ray particles can be used to align the many components of the detector and to time-in all subdetectors.

The subdetectors' readiness for beam in autumn 2008 will be summarized in the following sections to illustrate the success of the commissioning period, while sect. **5** illustrates the results obtained during the circulation of single beam in September 2008. Finally, sect. **6** describes examples of potential early discoveries in physics beyond the Standard Model with an integrated luminosity of $\approx 200\,\mathrm{pb}^{-1}$, expected to be collected in the first year of operation.

2. – Installation and commissioning of the Inner Detector

The Inner Detector installation started in August 2006 with the SCT and TRT barrels and was completed with the Pixel detector in June 2007.

However, waiting for the complete connection of services (including cables and pipes for the cooling system), the very fist commissioning of the Pixel and SCT detectors started in April 2008. The evaporative cooling plant suffered a major failure of its compressors at the beginning of May 2008 and its repair and cleaning were then in the critical path for the closure of the full detector. In early August 2008 a successful bake-out of the beam pipe was however possible, the latter being particularly critical because it requires the evaporative cooling system fully operational to protect the Pixel layers from overheating. In spite of the little time left, the ID was ready for beams in September, with 96% of the Pixel modules, 99% of the barrel and 97% of the end-cap SCT modules and 98% of the TRT.

After the LHC incident, a very intense commissioning period started with the purpose of calibrating the detector. In autumn, the ID was included in a long combined data-taking period, collecting 7.6 million tracks.

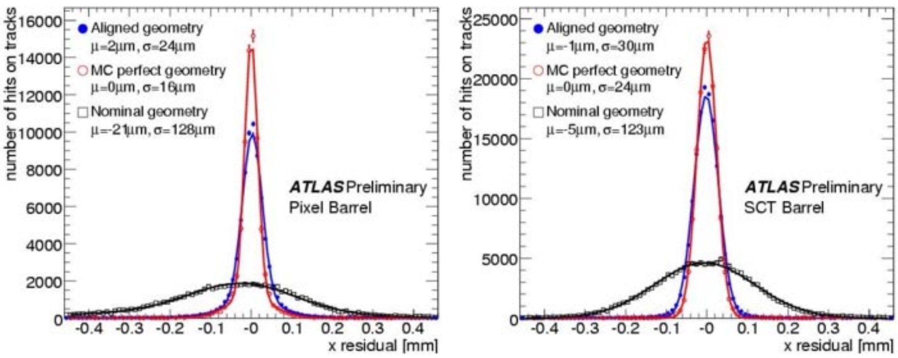


Fig. 1. – Residual distribution in x, the precision coordinate, integrated over all hits-on-tracks in the Pixel (left) and SCT (right) barrel before alignment and using a preliminary aligned geometry. As a comparison, prediction by Monte Carlo study with perfect detector alignment is shown. The residual is defined as the measured hit position minus the expected hit position from the track extrapolation. Tracks are selected to have $p_{\mathrm{T}} > 2\,\mathrm{GeV}$ and to go through the Pixel innermost layer.

One of the most important commissioning goals with the cosmics data is the alignment of the detector in order to achieve the designed tracking accuracy. Alignment is performed in steps of increasing number of degrees of freedom: subdetectors with respect to each other first, then layers, then individual modules. The distribution of residuals from straight track fitting for the barrel region of the Pixel and SCT subsystems before and after alignment is shown in fig. 1. The obtained alignment accuracy is close to the expected performance predicted by the Monte Carlo study with perfect detector alignment. Residual resolutions indicate remaining misalignment of $O(10\,\mu\mathrm{m})$.

3. – Installation and commissioning of the calorimeters

The LAr and Tile calorimeters have undergone a very long period of commissioning in ATLAS with cosmics since 2006, when the installation of the detectors was completed. After the detector closure in summer 2008, the LAr calorimeters had only 0.02% of isolated dead channels, plus some 0.8% of dead read-out channels, including one missing (out of eight) hadronic end-cap low-voltage power supplies which failed after closure of the detector. The Tile calorimeter operated with 0.2% isolated dead cells and 2 out of 256 sectors off due to power supply problems. The performance of the Lar and Tile calorimeters in terms of energy response, noise and timing has been extensively studied and calibration was performed.

4. – Installation and commissioning of the muon spectrometer

In the fall of 2008, the status of the muon spectrometer was the following: less than 1% precision chambers with a problem, and more than 99% of the alignment system working. For the trigger chambers all TGC were working, and three of the 16 RPC sectors were still under final timing adjustments.

The primary performance goal for the muon spectrometer is to obtain a standalone transverse-momentum resolution of approximately 10% for 1 TeV tracks, which translates

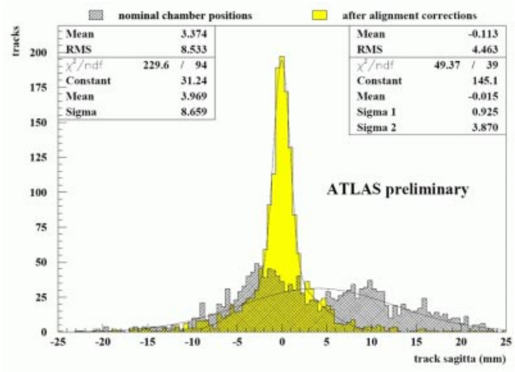


Fig. 2. – (Colour online) "Track" sagittas (the distance in the precision coordinate of the EM segment from the line joining the EI-EO segments) before (gray) and after (yellow) applying alignment corrections determined by the optical alignment of the end-caps. The "after alignment corrections" yellow histogram has a mean value compatible with zero, and a width of 1.5 mm, compatible with the expected multiple-scattering width, thus proving that the optical alignment can provide the required accuracy on the chambers alignment.

into a sagitta along the z (beam) axis of about 500 μm to be measured with a resolution of $\approx 50\,\mu$m. As the single chamber resolution is $\approx 40\,\mu$m, the precision on the relative position of chambers must be $\approx 40\,\mu$m. To achieve this accuracy on the chambers position, an optical alignment system of 12 thousand sensors tracks any displacement with great precision and provides an initial absolute precision. Figure 2 shows that the achieved accuracy is close to the required one in the end-caps, that had a better starting point thanks to a survey done during commissioning period. For the barrel, on the other hand, the present accuracy is still poor ($\approx 200\,\mu$m in large barrel sectors, ≈ 1 mm in small barrel sectors) and track alignment will be needed to get more precise initial alignment constants.

5. – Operation with circulating beam

The circulation of a single-beam in September 2008 has allowed for additional detector performance tests, mainly timing and energy calibration. The first beam passed through ATLAS on September 10^{th} during the official LHC start-up day. Then, during several days, proton bunches containing $2\cdot 10^9$ protons of 450 GeV energy were being injected into the LHC ring and circulated without acceleration. ATLAS was running with the Pixel detector and SCT barrel off; SCT end-caps, forward calorimeters and muon chambers at reduced HV for safety reasons.

Two types of events were recorded: *beam-splash* events illuminating the full detector and generated by proton collisions with the collimators, located 140 m upstream from ATLAS, closed for this purpose; *beam-halo* events with circulating beams, typically with lower-energy deposition depending on beam conditions.

Events were triggered by the Minimum Bias Trigger Scintillators (MBTS), placed on the front face of the end-cap calorimeter cryostats and by the beam pick-up detectors (BPTX) positioned in the beam pipe 175 m upstream of the interaction point. Other ATLAS Level-1 trigger components were active but not used to select events.

In *beam-splash* events many particles hit the entire detector at the same time. Therefore it is possible to check and eventually correct the time calibration in the full detector

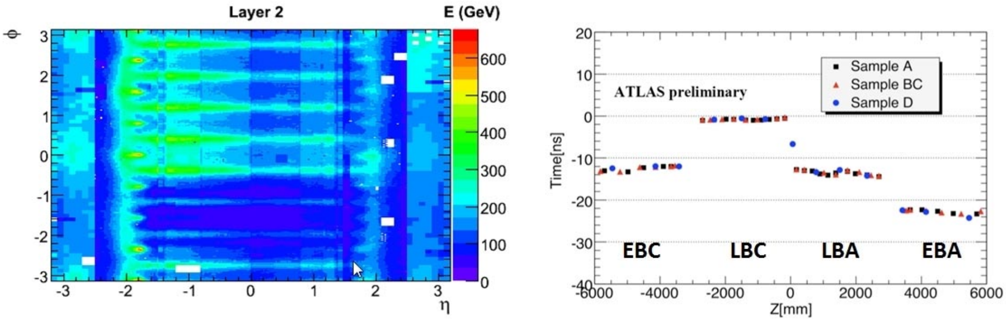


Fig. 3. – (Colour online) On the left, the 2-dimensional plot presents, for layer 2 of the LAr Calorimeter, the accumulated energy per cell over 100 *beam-splash* events (Beam 2, incoming from negative η). To select the signal, only cells with $E > 5$*noise are summed. Zones without signal correspond to problematic channels which have been masked using the database. On the right plot, timing of TileCal signals recorded with single beam data on Sept. 10, 2008 (Beam 2, incoming from negative z). The average time over all cells with the same ϕ (azimuth) coordinate is shown as a function of the z-coordinate (along beam axis), for all three radial samplings (represented with different colors). Timing corrections based on laser data and ToF assuming tracks parallel to the z-axis have been applied. The visible discontinuities at $z = 0$, ± 3000 mm are due to the uncorrected time differences between the four TileCal partitions.

with very few events and to time-in the ATLAS trigger systems. Figure 3 (left) shows the energy deposition in the LAr calorimeter in *beam-splash* events: the 8-fold structure in ϕ due to the end-cap toroid material in front of calorimeters, for particles coming from outside the detector, as well as a lower response at the bottom of the detector ($\phi = -\pi/2$), due to additional material (mainly detector support structure) are clearly visible. Moreover a reduced flux, and correspondingly reduced energy deposition, is seen along the beam direction (η).

Muon energy deposition from *beam-halo* events has been used to check timing in the Tile calorimeter. Figure 3 (right) shows the timing of signals in the detector after the time-of-flight correction. Once these corrections have been applied, time dispersion in each partition is ≈ 2 ns with a residual offset (to be fixed) between partitions within 1 BC. This demonstrates that the time equalization performed with laser calibration data was extremely accurate.

6. – Readiness for BSM physics

During the LHC run in 2009/2010, it is expected that the integrated luminosity will be $\approx 200\,\text{pb}^{-1}$ [2, 3]. The data collected will be initially extremely useful for the purpose of improving trigger performance, timing, alignment and in general, the detector performance [4]. In this perspective, Standard Model benchmark signals will be used not only as a measurement by itself but also to understand the detector complexity. A window on an energy scale never reached before will be opened and a search for deviations from Standard Model predictions will potentially allow observation of extraordinary new physics signatures.

In the following paragraphs, two examples of BSM measurements are reported. They represent certainly a small fraction of the measurements that will be possible. They have

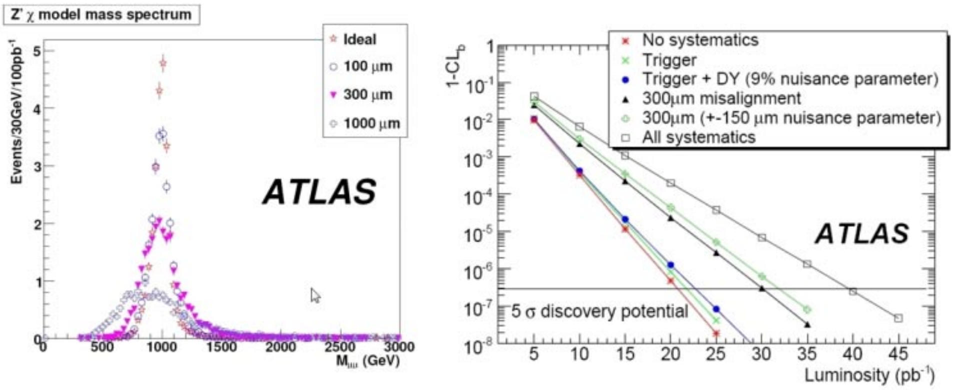


Fig. 4. – Left: reconstructed invariant mass of the Z'_χ model for different misalignment scenarios and an integrated luminosity of $100\,\mathrm{pb}^{-1}$. In the ideal case the position of the chambers in the muon spectrometer is known to be about $40\,\mu$m. Right: results of 1-CL$_b$ for $m = 1\,\mathrm{TeV}$ Z'_χ bosons. The horizontal line indicates the 1-CL$_b$ value corresponding to 5σ discovery.

been chosen because they are relatively less sensitive to the large detector performance uncertainties expected in the first period of data-taking([1]).

6˙1. *Dilepton resonances at high mass*. – New heavy states forming a resonance decaying into opposite sign dileptons are predicted in many extensions of the Standard Model. Due to the simplicity of the final state, the dilepton channel is considered a potential discovery channel with early ATLAS data [4]. The strictest direct limits on the existence of heavy neutral particles come from direct searches at the Tevatron; the highest excluded mass is currently almost 1 TeV. The LHC with a center-of-mass energy of 14 TeV should ultimately increase the search reach for new heavy particles to the 5–6 TeV range.

In the first year of data taking, even with a small integrated luminosity and a not perfectly aligned detector, discovery of new particles with mass of $\approx 1\,\mathrm{TeV}$ will still be possible: Figure 4 shows the necessary integrated luminosity needed to discover a resonance at 1 TeV mass in the dimuon channel. Since at large p_T an important contribution to the muon momentum resolution comes from the alignment of the muon spectrometer, the effect of different misalignment scenarios is also reported in the plots. Misalignment leads to a broadening of the peak (left) and a larger luminosity will be needed to achieve the 5σ discovery (right). However the amount of integrated luminosity needed for discovery ranges from 20 to $40\,\mathrm{pb}^{-1}$.

6˙2. *SUSY*. – SUperSYmmetry (SUSY) is one of the favoured theories for physics beyond the Standard Model. The basic prediction of SUSY is the existence, for each Standard Model particle, of a corresponding superpartner, with spin differing by half a unit. In order for the theory to conserve baryonic and leptonic quantum numbers, a new multiplicative quantum number, R-parity, is introduced. The consequences of

([1]) All the plots shown assume a center-of-mass energy of 14 TeV. However in 2009/2010 run, LHC will not exceed a center-of-mass energy of 10 TeV. Moving from 14 TeV to 10 TeV requires about twice as much data for equivalent sensitivity.

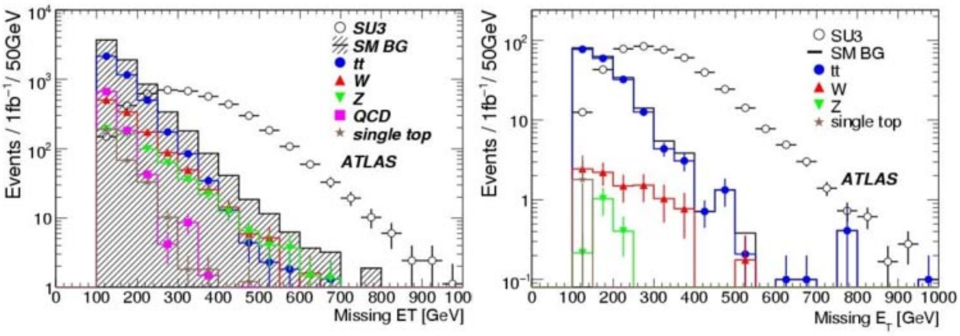
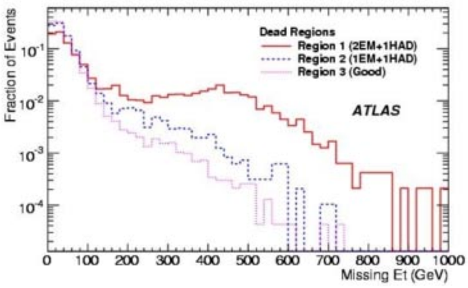


Fig. 5. – (Color online) $E_{\mathrm{T}}^{\mathrm{miss}}$ for the background processes and for a SUSY benchmark model ($SU3$) in the zero-lepton mode (left) and in the one-lepton mode (right) for an integrated luminosity of $1\,\mathrm{fb}^{-1}$. Events are selecting by requiring at least four high-energy jets, $E_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$ and zero or one, respectively, isolated lepton. The black circles show the SUSY signal. The hatched histogram shows the sum of all Standard Model backgrounds; also shown in different colours are the various components of the background.

R-parity conservation are that supersymmetric particles must be produced in pairs and that at the end of their decay chain, the lightest SUSY particle (LSP), stable and weakly interacting, will remain. Therefore, events from R-parity conserving SUSY models are generally characterized by the presence of many hard jets, and sometimes leptons, coming from the decay cascade down to the LSP, as well as a large amount of missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) due to the LSP which will escape direct detection in the ATLAS volume.

Figure 5 shows the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution for events passing the selection criteria in the two inclusive channels with one-lepton or zero-lepton requirement. The one-lepton search mode is expected to play a major role in the SUSY search, especially at the beginning, since the requirement of an isolated lepton will be effective in suppressing QCD background. However the zero-lepton mode has the best estimated 5σ reach.

Even if the signal is enhanced with respect to background, it will clearly be crucial to understand the Standard Model background and the detector effects on the tails of the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution. In real data there will be sources of fake $E_{\mathrm{T}}^{\mathrm{miss}}$ which are not fully modeled in MC simulations such as, for example, the mis-modeling of material distributions and instrumental failures. As the details of these fake $E_{\mathrm{T}}^{\mathrm{miss}}$ sources are understood with time, analysis techniques will be developed to minimize their associated effect on the backgrounds while maintaining high selection efficiencies for signals with genuine missing energy. While it is difficult to predict in advance the exact sources of mis-modeled fake $E_{\mathrm{T}}^{\mathrm{miss}}$, it is nevertheless possible to simulate hardware failures in the Monte Carlo samples and evaluate their effects. An example is a study based on samples with simulated dead regions of the calorimeter. Figure 6 (left) shows the large $E_{\mathrm{T}}^{\mathrm{miss}}$ tails seen when holes in calorimeter coverage have been introduced. The EM Fraction Method suppresses events with large fake $E_{\mathrm{T}}^{\mathrm{miss}}$ by finding the closest calorimeter jet to the $E_{\mathrm{T}}^{\mathrm{miss}}$ direction vector and looking at its EM fraction (ratio between the electromagnetic energy and the sum of electromagnetic and hadronic energy). Figure 6 (right) shows the EM fraction distributions: small EM fractions are due to a dead LAr EM calorimeter crate, whereas large EM fractions are due to a dead hadron calorimeter crate. The fake $E_{\mathrm{T}}^{\mathrm{miss}}$ can be partially suppressed by requiring the EM fraction to be in a window from 0.40 to 0.96.



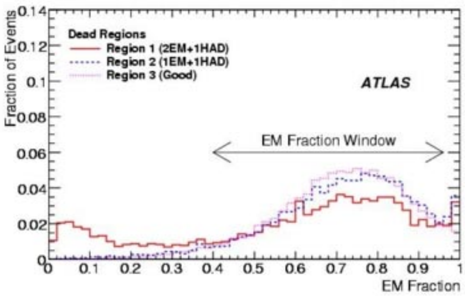


Fig. 6. – $E_{\mathrm{T}}^{\mathrm{miss}}$ (left) and EM fraction (right) in a high-p_T ($560 < p_T < 1120\,\mathrm{GeV}$) g+jet MC sample with killed cells. Based on the location of these hardware failures the calorimeter is divided into three regions of fake $E_{\mathrm{T}}^{\mathrm{miss}}$: Region 1 with EM endcap and hadronic endcap problems, Region 2 with EM barrel problems and Region 3 with no problems.

Even if SUSY particles searches require a good knowledge of the detector performance, a mass reach of $\approx 400\,\mathrm{GeV}$ should be possible with less than $100\,\mathrm{pb}^{-1}$ of good data, even at a center-of-mass energy of 10 TeV. This would compete with the actual limit of 400 GeV obtained by Tevatron experiments. Running at lower energy ($< 8\,\mathrm{TeV}$) would suppress considerably the sensitivity.

7. – Conclusions

The installation of the ATLAS detector has been completed in 2008. It was ready for the first beam injection, thanks to the commissioning effort performed with the use of cosmics data. A few percent of the subdetector channels were not operational and, when possible, they are being repaired. During the long winter 2009 shutdown, problems and weaknesses that have been identified will be fixed. As the plan is to run during 2009/2010 for an extremely long run of almost ten months, this preparation has to be very thorough, considering that access and possible maintenance will be limited during that time. In order to be ready for collisions and for measurement of SM and possibly new physics, global commissioning of the ATLAS detector will restart with cosmics data taking, with all subdetectors turned on, two months before the beam injection.

REFERENCES

[1] Aad G. *et al.* (ATLAS Collaboration), *JINST*, **3** (2008) S08003.
[2] Myers S. and Zimmermann F., *LHC Performance Workshop, Chamonix 2009* (CERN-ATS) 2009-001, pp. 318-323.
[3] Ferro-Luzzi M., *LHC Performance Workshop, Chamonix 2009* (CERN-ATS) 2009-001, pp. 273-281.
[4] Aad G. *et al.* (ATLAS Collaboration), *Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics*, CERN-OPEN-2008-020, Geneva, 2008.