ATLAS Detector Performance status, improvements during winter 2010 shutdown and results with initial 2011 data taking period

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Abstract. After the successful 2010 LHC run, where the ATLAS detector recorder $45 \text{ pb}^{-1}$ of proton-proton collision data with 93.6% data taking efficiency and during the recent LHC shutdown period, ATLAS performed vital maintenance and improvements on the various sub-detectors. Maintenance on the Muon Spectrometer included repairs on the readout system as well as updates and leak checks in the gas system. Six TGC chambers have been also replaced. For the Calorimeters, repairs were carried out on the front-end electronics and power supplies to recover detector coverage that have been lost since the last maintenance period. Repairs were also performed on the Inner Detector, but at a smaller scale. Finally the ALFA luminosity detector was installed along the beam line and is being commissioned. This talk summarizes the above repairs and their expected improvement for physics performance and reliability of the ATLAS for the 2011 LHC run.

1. Introduction
The LHC and ATLAS are motivated by seeking answers to some of the most fundamental questions of particle physics, among them the mystery of the origin of mass (Higgs, Brout and Englert mechanism), the search for an underlying symmetry between fermions and bosons (Supersymmetry, SUSY), and the quest for further unification of forces including gravity (Extra-dimensions). There is a great potential that the LHC physics results could have deep implications in the understanding of the evolution of the Universe, and help solving questions like the origin of the Dark Matter, if SUSY would be experimentally established. The ATLAS detector was designed to be able to address these physics topics, and to be ready to explore also unknown New Physics at the new frontier in energy and luminosity offered by the LHC.

2. The ATLAS Detector description
ATLAS (A Toroidal LHC ApparatuS) [1] is a general—purpose detector primarily designed to study $pp$ collisions at LHC energies. It is characterized by cylindrical symmetry, high granularity in the readout cells and coverage close to $4\pi$, which makes it fit to study aspects of heavy–ion ($Pb - Pb$) collisions as well. ATLAS uses a coordinate system where the nominal interaction point is at the center of the detector, the beam direction defines the $z$-axis and the $x$-$y$ plane is

1 On behalf of the ATLAS Collaboration
transverse to the beam. The positive x-axis is defined as pointing to the center of the ring and the positive y-axis is upwards. Side-A of the detector is in the positive z direction and side-C is in the negative z direction. The azimuthal angle $\phi$ is measured around the beam axis. The pseudorapidity $\eta$ is defined as $\eta = -\ln(tan(\theta/2))$ where $\theta$ is the polar angle. Various subsystems are arranged in layers around the beam axis, as shown in Figure 1.

![Figure 1. The ATLAS detector.](image)

The ATLAS detector is forward-backward symmetric with respect to the interaction point. Pattern recognition, momentum and vertex measurements, and electron identification are achieved with a combination of discrete, high-resolution semiconductor pixel and strip detectors in the inner part of the tracking volume, and straw-tube tracking detectors with the capability to generate and detect transition radiation in its outer part. High granularity liquid-argon (LAr) electromagnetic sampling calorimeters, with excellent performance in terms of energy and position resolution, cover the pseudorapidity range $|\eta| < 3.2$. The Hadronic Calorimetry in the range $|\eta| < 1.7$ is provided by a scintillator-Tile Calorimeter (TileCal), which is separated into a large barrel and two smaller extended barrel cylinders, one on either side of the central barrel. In the end-caps ($|\eta| > 1.5$), LAr technology is also used for the Hadronic Calorimeters, matching the outer $|\eta|$ limits of end-cap Electromagnetic Calorimeters. The LAr forward calorimeters provide both electromagnetic and hadronic energy measurements, and extend the pseudorapidity coverage to $|\eta| = 4.9$. The Calorimeter is surrounded by the Muon Spectrometer (MS). The air-core toroid system, with a long barrel and two inserted end-cap magnets, generates strong bending power in a large volume within a light and open structure. Multiple-scattering effects are thereby minimized, and excellent muon momentum resolution is achieved with three layers of high precision tracking chambers. The muon instrumentation includes trigger chambers with timing resolution of the order of 1.5-4 ns. The MS defines the overall dimensions of the ATLAS detector. Two forward detectors have been added to the original ATLAS design: LUCID and the Zero Degree Calorimeters (ZDC), located respectively at 17 and 140 m from the ATLAS Interaction Point (IP), one arm per side. LUCID is dedicated to the measurement of the luminosity delivered to ATLAS by LHC, the ZDC measure neutral particles emitted at zero degrees with respect to the beam axis.

Two magnetic systems are present in ATLAS to bend the trajectory of charged particles and allow the measurement of their momentum: the ID is inside in a thin superconducting solenoidal magnet providing a 2 T axial field, while three large superconducting toroids (one barrel and
two end-caps) arranged with an eight-fold azimuthal symmetry around the calorimeters, provide B−fields with a peak value of 4.1 T in the regions of the MS. A detailed description of the various subsystems can be found in [1]. The overall dimensions of ATLAS are quite impressive: it is 44 m long and has a diameter of 25 m. The ATLAS Collaboration is huge as well, spanning over all inhabited continents and gathering together 174 Institutes, for a total of about three thousand physicists.

3. LHC Running in 2010
The Large Hadron Collider (LHC), [2],[3],[4] the largest particle accelerator in the world, is located beneath the border between France and Switzerland, in the underground tunnel which used to host the former Large Electron-Positron (LEP) Collider. LHC has two different modes of operation: one is as proton collider with a design centre-of-mass energy of 14 TeV, the other is as Pb−ion collider, accelerating fully ionized lead atoms. For lead ions, the design centre-of-mass energy is 2.76 TeV/nucleon. The rate, R, of events provided by accelerators is proportional to the machine instantaneous luminosity, L, and the event total cross section, \( \sigma \):
\[
R = \sigma \times L.
\]
LHC is expected to reach a luminosity \( L = 2 \times 10^{33} cm^{-2}s^{-1} \) during the first years of operations with protons, while the design luminosity \( L = 10^{34} cm^{-2}s^{-1} \) should be reached later. The design luminosity for \( Pb−Pb \) beams is \( L = 10^{27} cm^{-2}s^{-1} \), substantially lower than the former because the large ion charge makes it more difficult to control beam−beam interactions. A large number of particles are produced when complex nuclei collide, and the inelastic cross section is a strong function of the atomic number A: \( \propto A^{\frac{2}{3}} \).

3.1. Luminosity Determination
The LHC luminosity is determined in real time approximately once per second using a variety of detectors and algorithms that are described later in this note. These measurements are displayed in the ATLAS control room and results for a single “preferred” method are sent to the LHC control room over the network, providing real-time feedback for machine tuning. The basic time unit for storing luminosity information for later use is the Luminosity Block (LB). The length of a LB is approximately two minutes with start and end times set by the ATLAS data acquisition system. All ATLAS data quality information, as well as luminosity, are stored in a relational database for each LB. Offline users therefore can select data samples with specific data quality requirements (for example, pixel detector ON) and then calculate the luminosity for that selection. Because the LB number is updated whenever a trigger prescale is changed and because trigger scalars are also recorded for each LB, offline users can correct the delivered luminosity for data acquisition deadtime and prescale rates. Furthermore, since the list of processed LB is included as in-file metadata for all ATLAS data formats, users can calculate the integrated luminosity properly for subsets of the full data sample. The luminosity tables in the offline database allow for storage of multiple luminosity methods and are versioned so that updated calibration constants can be applied. Corrections for data acquisition deadtime and other sources of data loss are performed when the integrated luminosity is calculated. A tool is provided as part of the ATLAS software release that takes as its input the list of LB that have been analysed (after data quality selection), the trigger used for the analysis (so that corrections for deadtime and trigger prescale can be made) and the luminosity method requested and returns the integrated luminosity of the data sample.

3.2. LHC Delivered Luminosity
From March to November 2010 LHC collided protons at a centre-of-mass energy of 7 TeV, more than 3 times larger than the one achieved by the Tevatron (\( p\bar{p} \)). The instantaneous luminosity continuously increased over this period, passing from \( L = 10^{27} cm^{-2}s^{-1} \) at the beginning of March to the peak value \( L = 2.1 \times 10^{32} cm^{-2}s^{-1} \) in October. Such an improvement was
accomplished both by increasing the number of circulating bunches and thus reducing the time between bunch crossings and increasing the number of protons stacked in each bunch as well as squeezing them into a smaller and smaller area. The average number of additional $pp$ interactions taking place at each bunch crossing, also known as pile-up, was negligible at the beginning and reached a maximum value of about four at the end of the data-taking period, against an expected value of $25$ at full luminosity and $\sqrt{s} = 14$ TeV. The last month of operations was dedicated to $Pb-Pb$ collisions. The centre-of-mass energy reached the value of $2.76$ TeV per nucleon pair, more than one order of magnitude larger than the one provided by RHIC, and the instantaneous luminosity reached the value $L = 3 \times 10^{25} \text{cm}^{-2}\text{s}^{-1}$. The total integrated luminosity delivered by LHC in 2010 was about $48 \text{pb}^{-1}$ with proton beams and $9.7 \text{µb}^{-1}$ with $Pb$–ion beams. The delivered luminosity accounts for the luminosity delivered from the start of stable beams until the LHC requests ATLAS to turn the sensitive detector off to allow a beam dump or beam studies. Very recently the total integrated luminosity recorded by ATLAS also exceeds $1 \text{fb}^{-1}$ (including $959 \text{pb}^{-1}$ in 2011 + $45 \text{pb}^{-1}$ in 2010. (Figure 2). This is a very important milestone for the LHC and ATLAS, which demonstrates the outstanding performance of the accelerator, of the experiment and of the involved teams. The LHC luminosity has been measured in ATLAS using different detectors and methods [5]. The absolute luminosity calibration was obtained using the van der Meer beam separation scans method [6], where the two beams are scanned against each other in the horizontal and vertical planes to measure their overlap function, with a systematic uncertainty of $3.4\%$ [7]. All the sub-detectors of ATLAS operated with a very high efficiency $> 97\%$. In Figure 3 the denominator is the luminosity delivered between the declaration of stable beams and the LHC request to turn the sensitive detectors off to allow a beam dump or beam studies. The numerator is the luminosity recorded by ATLAS. Each bin represents a week. The empty bins are due to weeks in which no stable beams were delivered by the LHC. The inefficiency accounts for the turn-on of the high voltage of the Pixel, SCT and some of the muon detectors and any inefficiencies due to deadtime or due to individual problems with a given subdetector that prevent the ATLAS data taking to proceed.

![Figure 2.](image2.png) **Figure 2.** Cumulative luminosity versus day delivered to (green), and recorded by ATLAS (yellow) during stable beams and for $pp$ collisions at 7 TeV centre-of-mass energy in 2011.

![Figure 3.](image3.png) **Figure 3.** ATLAS data taking efficiency in 2011.
3.3. Data Quality

ATLAS data taking is segmented by run and luminosity block (LB). A run corresponds nominally to an LHC fill, and a LB is a length of time over which detector conditions are assumed to be constant. A decision comes in the form of a ‘traffic light’ coloured flag, whose evolution across LBs is stored in the conditions database. Red and green mean bad and good for analysis respectively, whilst yellow is a temporary value used to defer a decision to a later time. Other states exist which are only meaningful as diagnostic information. Before the flags become inputs to analyses, experts converge on the ‘good’ and ‘bad’ states. Example decisions include those coming from the DQMF (Data Quality Monitoring Framework) [8], [9], the DCS (Detector Control System) [10], and the control room shifter. They are summarized into a single decision per physical subdetector region (such as ‘pixel detector barrel’ or ‘monitored drift tube endcap’) by the ‘Data Quality Calculator’. An expert reviews the automated decision and may decide to override it. Regions are summarized across subdetectors into ‘combined performance’ flags used to select ranges of good runs and luminosity blocks. Along with information about the LHC state, these flags can be used to build a ‘Good Run List’, an XML document describing ranges of data suitable for particular types of physics analyses. Events collected from the experiment are filtered into different streams for specific uses. There exists three types of stream: physics, calibration and express. The physics streams will ultimately end up in user analyses, the calibration stream is used to compute calibration constants and the express stream undergoes rapid processing (usually 1-2 hours after the data is recorded). The histogram analysis framework produces, per active stream, 20,000 histograms (100 MB) per run, along with 700 histograms (6 MB) per ten luminosity blocks. Originally, these were all dumped as ‘png’ images so that they could be served over the web to shifters and experts as static content, but the disk space and CPU usage per run were not sustainable. Given that the vast majority of histograms are not looked at for each run, it is better to generate the image files as they are requested and to cache them for a short time. This has been implemented and has lead to a saving in disk space, whilst not impacting the load of the server.

3.4. Trigger and Data Acquisition Performance

Reading out a detector may involve some dead time, during which further events are lost. In case of very high acquisition rates, data storage can also become a serious issue. In 2010 the average bunch-crossing rate of LHC in \( pp \) operations was close to 1 MHz (it will approach \( \approx 40 \text{MHz} \) at design luminosity), and an online way to identify interesting events was clearly needed. When studying \( pp \) collisions, we are mostly interested in events where hard interactions between proton constituents occur. These produce particles at high momentum transverse to the beam axis. The other, much more frequent, events on the contrary produce most of the activity close to the beam line. The ATLAS online event selection is realized in three stages. At each level, events are kept in pipelines waiting for the decision of the following step. Loose granularity information from the calorimeters and the muon spectrometer are the main input to the first trigger level, whose average rate was about 20 kHz in 2010. At the second level, portions of each event are studied at full granularity. In 2010, the rate of events accepted by the second trigger level was decreased to about 3.5 kHz. Finally, the third trigger level is based on full analysis of complete events. The typical rate of \( pp \) collision events written to disk in 2010 was about 300 Hz, higher than the design rate of 200 Hz. Due to lower luminosity, the trigger configuration for \( Pb - Pb \) running was aimed at avoiding biasing the selected sample. The main input to the first trigger level came from ZDC. The other trigger levels were used to reject background like beam–gas interactions, but no selection based on physics objects was applied.
4. Inner Detector Performance

The ID consists of three subsystems: a pixel detector, a silicon strip tracker (SCT) and a transition radiation straw-tube tracker (TRT) that also distinguishes between electrons and hadrons by measuring the amplitude of signals due to both ionization and transition radiation. The Pixel detector consists of three layers of pixels both in the barrel and in the end-cap regions, for a total of 80 million channels, with the innermost layer located at 5 cm distance from the beam line. The design values of the spatial resolution are 10µm in the bending plane (R-φ) and 115µm in the beam direction (z). The SCT consists of 4 (9) double layers of silicon strips in the barrel (end-cap) with a spatial resolution of 17µm (R-φ) and 580µm (z in the barrel, or R in the end-caps). In order to match the required performance in tracking and momentum resolution, the position (alignment) of the Pixel and SCT modules must be known with an accuracy of a few microns. With ATLAS 2010 collision data, the track based detector alignment is performed using an iterative procedures that minimizes the hit residuals (distance between the hit and the reconstructed track). Figure 4 shows the local x residual distribution (the projection of the residual onto the module local x direction) for all hits-on-tracks in Pixel barrel modules. Here the residual is calculated by re-fitting the track with the hit-on-track under study removed. For the aligned geometry the measured width of 25µm is already close to the value of 18µm from simulations.

The TRT detector is composed of 4 mm diameter straw tube layers, interleaved with transition radiation material allowing for e- π identification in the range 0.5 - 150 GeV. In the barrel region the tubes are assembled in 73 layers, parallel to the beam. Each of the end-cap TRT is composed of 160 layers of radial tubes (perpendicular to the beam).

The TRT provides substantial discrimination between electrons and pions over the wide energy range between 1 and 200 GeV by utilizing transition radiation in foils and fibres. The readout discriminates at two thresholds, the lower set to register minimum-ionising particles and the higher intended for transition radiation (TR) photon interactions. The fraction of high-threshold TR hits as a function of the relativistic γ factor is shown in Figure 5 for particles in the forward region. This region is displayed because there are more conversion candidates and they have higher momenta than in the barrel.

The high part of the distribution is constructed using electrons from photon conversions while the low component is made using charged particle tracks with a hit in the B-layer and treating them as pions. All tracks are required to have at least 20 hits in the TRT. To ensure high purity (about 98%), the conversion candidates are also required to have a vertex more than 40 mm away from the beam axis. The pion sample excludes any photon conversion candidate tracks.

The nominal transverse momentum resolution:

\[ \frac{\sigma_{p_T}}{p_T} \approx 3.8 \times 10^{-4} p_T(\text{GeV}) \oplus 0.015 \]  

and the tracking performance of the Inner Detector was assessed via the observation of well measured particle decays, like \( K_0^0, \phi, \text{D mesons and } \Omega, \Xi, \Lambda \text{ baryons} \). Clear signals of all these resonances were obtained in data. Figure 6 shows the reconstruction of \( K_0^0 \) decaying to a pair of pions and Figure 7 shows the \( J/\psi \) decaying to a pair of muons. The signal lineshape fits are both Gaussian with a third-order polynomial to model the background. The masses and the widths of the two signals are free parameters of the fit. The uncertainty on the yield is statistical only, whereas the uncertainty on the fitted mass corresponds to a ~1 per mille uncertainty on the \( p_T \) scale calibration.

Those studies allowed the momentum scale to be determined at the per mill level for the low transverse momentum \( (p_T) \) region, and for higher momentum at the % level (for momentum up to 100 GeV), as verified from the resolution in the measured invariant mass of the mentioned particles. The resolution was found as expected to be dominated by multiple scattering in the
low $p_T$ region. Photon conversions are particularly suitable to track the distribution of dead material and have been used to tune the Inner Detector simulation program.

The tracking efficiency as a function of transverse momentum ($p_T$), averaged over all pseudorapidity, rises from $\simeq 10\%$ at 100 MeV to $\simeq 86\%$ for $p_T$ above a few GeV. The resolution on the position of the primary vertex enables the identification of multiple interactions in the same bunch crossing on an event-by-event basis, as made clear in Figure 8. Secondary vertices such as those produced by B-hadrons, that typically travel a few mm before decaying, can be resolved as well.

Events produced in Pb–ion collisions are characterised by particle multiplicities much larger than the ones found in $pp$ events. As a consequence, the performance of the ID is not as good as in $pp$ collisions, and different tracking algorithms are used. Nevertheless, the agreement
between data and simulated events with respect to the average number of hits found in the various subsystems of the Inner Detector is rather good both for pp and Pb−ion collision events, as shown in Figure 9 meaning that we have a good understanding of the detector behaviour in both conditions.

**Figure 8.** A pp collision event at 7 TeV recorded by ATLAS where four different interactions are piling up. The zoomed image shows the reconstructed primary vertices.

**Figure 9.** Number of TRT hits on track (integrated and averages as function of η) for Pb−ion collision and comparison with Monte Carlo expectations.

5. Calorimeter Performance

The ATLAS Calorimeters are located just outside the Inner detector. They must absorb and measure the energy of photons, electrons, isolated hadrons and hadron jets. They also allow the measurement of the missing transverse energy carried by high momentum neutrinos or, possibly, new weakly interacting particles. The Electromagnetic Calorimeter uses lead as absorber and liquid argon as the active medium, which is robust against radiation doses. An accordion geometry was chosen to minimize dead areas. By neglecting the noise term, the ultimate energy resolution can be written as:

$$\frac{\sigma_E}{E} \simeq \frac{10\%}{\sqrt{E}} \oplus 0.7\%$$

(2)

The Hadron Calorimeter is made of iron and scintillating tiles in the central region, where radiation doses are moderate. More radiation−hard technologies are used in the forward region, where liquid−argon is again used as the sensitive material. The ultimate energy resolution can be described as:

$$\frac{\sigma_E}{E} \simeq \frac{50\%}{\sqrt{E}} \oplus 3\%$$

(3)

Electron and photon identification is based on the presence of energy clusters in the electromagnetic calorimeter, and little or no energy in the hadron calorimeter. A track in the Inner Detector pointing to the electromagnetic cluster is expected for electrons, whereas no tracks are present for photons. As an example of the photon identification capability of ATLAS, Figure 10 shows the measured invariant mass of diphoton candidates selected in pp collision events in the region around the π⁰ mass [13] with the first data of 2009 at √s = 900 GeV. From the comparison of its mass to the Particle Data Group (PDG) value the energy scale was checked within 2%.

Good electron identification performance allowed us to reconstruct all known e⁺e⁻ resonances from a few GeV (J/ψ) up to the Z boson. The em scale has been determined on 7 TeV centre-of-mass-energy data using the Z boson decays to a pair of electrons. Events with two opposite charge electrons reconstructed with transverse energy $E_T > 20$ GeV and constraint their mass
to follow the well known Z line shape derived from simulation. This method was applied in different em regions. Figure 11 shows the distribution of this calibrated Z mass, after applying the corrections to the electron energy. Electrons from Z boson decays have $p_T$ in the tens of GeV range and can be easily identified even in the high occupancy environment of Pb–ion collisions. As an example, Figure 12 shows a Z boson candidate produced in a Pb–ion collision at $\sqrt{s} = 2.76$ TeV. Massive gauge boson production had never been observed at other heavy–ion colliders.

Figure 10. Diphoton invariant mass spectrum in the region around the $\pi^0$ mass. A fit is superimposed to the points representing data. The histogram refers to Monte Carlo prediction, where the number of entries is normalized to the one found in data.

Diphoton and dielectron invariant mass spectra covering the range from tens of MeV to hundreds of GeV are exceptionally sensitive calibration data. They were used to understand the alignment and energy resolution of the Electromagnetic Calorimeter.

Understanding and measuring the performance of jets is crucial for many physics analyses at the LHC. Hadron jets are reconstructed with the anti–kt algorithm [14], with distance parameters of 0.6 and 0.4, starting from clusters of cells of energy above a set threshold in the hadron calorimeter. The uncertainty of the jet energy calibration is the dominant experimental uncertainty for numerous physics results with jets. The energy resolution depends on both the jet transverse momentum and the jet pseudorapidity. It has been evaluated on data for jets with transverse momenta above 20 GeV up to the kinematic limit of 3.5 TeV and $\eta$ up to 4.5. To give an idea of the $p_T$ range of jets produced at LHC, Figure 13 shows its distribution as measured with the data and as expected from Monte Carlo simulation. A remarkable agreement over six orders of magnitude is apparent.

Figure 14 shows the final fractional jet energy scale systematic uncertainty as a function of jet $p_T$ for the barrel region. For example it is found to be less that 2.5% in the region of jet transverse momenta between 60 and 800 GeV. The overall precision on the energy scale is currently $\approx 7\%$ [15]. It is expected to reach the 3–4% level once ongoing studies with beam data on jet–balance and E/p measurements for isolated hadrons will have been finalized. The impact of pile–up will also be quantitatively evaluated.

Missing transverse energy, $E_T^{miss}$, in an event is a measure of the energy imbalance in the transverse plane and it indicates the presence of undetected particles (like neutrinos). Such imbalance may also rise from detector effects or relative miscalibration of the scales of the many detectors, as well as for beam backgrounds and cosmics. Being measured from all particles seen
Figure 12. A heavy-ion collision with a candidate Z to $\mu^+\mu^-$ decay. The two muons shown in purple (first display) or red (second display) are the candidates to originate from the Z decay.

in the detector, it is expected to scale with the amount of energy in the event. The calorimeters allow for the measurement of the missing transverse energy $E_{T}^{\text{miss}}$. The key performance figure is the transverse energy resolution as a function of the total transverse energy. It has been measured in the ATLAS detector with the 7 TeV collision data [16] and found to be in reasonable agreement with the simulation (Figure 15.)

Figure 13. Distribution of the transverse momentum of jets as reconstructed in the data (black points) and as expected from Monte Carlo simulation (histogram).

Figure 14. Fractional jet energy scale systematic uncertainty as a function of $p_T$ for jets in the pseudorapidity region $0.3 < |\eta| < 0.8$ in the calorimeter barrel. The total uncertainty is shown as the solid light blue area. The individual sources are also shown, with uncertainties from the fitting procedure if applicable.

Figure 15. Resolution of the transverse missing energy ($E_{T}^{\text{miss}}, E_{y}^{\text{miss}}$) as a function of the total transverse energy, $\sum E_T$, for pp collision data at $\sqrt{s} = 7$ TeV. Full dots represent the data while the line is a fit to the resolution obtained in Monte Carlo simulations. ATLAS-CONF-2010-057
6. MuonSpectrometer Performance

Muons are identified through their capability of penetrating through the Calorimeters and reach the Muon Spectrometer. The deflection of muons by the magnetic field generated by a system of air core toroid coils in the muon spectrometer is measured by three layers of precision gaseous detector up to $|\eta| < 2.7$. The position in the non bending plane is provided by the muon trigger detectors. A minimum momentum of $\simeq 3$ GeV is required for muons to emerge from the upstream material. The detector has the capability of measuring the momentum of muons without the help of the Inner Detector, with nominal resolution $\sigma_{p_T}/p_T < 3\%$ up to 200 GeV and $\sigma_{p_T}/p_T \simeq 10\%$ at 1 TeV. Matching to the Inner Detector can obviously improve the momentum resolution and reduce the background from kaon decays as well as non–containment of hadrons within the calorimeters. Relative efficiencies have been studied on single muons exploiting the redundancy of detector technologies and reconstruction algorithms and the minimum ionizing particles identification in the calorimeters. Fake rates studies are based on the mis-tag rate for pions and kaons identified in hadronic resonances ($K_0^s$ and $D^*$) and on the momentum unbalance between inner detector and muon spectrometer measured momenta, due to late decays of pions and kaons.

The four technologies adopted in the MS have been fully commissioned and a fraction of channels very close to 100% is operational for MDT and TGC, and more than 97% and 98% for RPC and CSC, respectively.

At high momentum, the transverse momentum resolution of stand-alone muons is dominated by the calibration of the muon precision chambers and the internal alignment of the muon spectrometer. The precision muon drift chambers (MDTs) measure the drift time which is then converted into a drift distance using the conversion function, which is determined from data in a calibration procedure. Each drift channel has a constant time offset (‘$t0$’) for which the measured time has to be corrected to obtain the drift time. The $t0$s are determined from data. Chamber alignment and sagitta resolution are studied using cosmic-ray tracks collected without magnetic field. The segment sagitta is defined as the distance from the Middle-station segment to the straight line connecting the segments in the Inner and Outer stations. The segment sagitta distribution for each sector is fitted to a double Gaussian (see Figure 16). The mean of the narrow Gaussian is used for track-based alignment of the spectrometer, while the sigma corresponds to the sagitta resolution. The sagitta resolution is parametrized into two separate components: multiple scattering and intrinsic resolution, respectively dominating at high and low momenta. Using the solenoidal magnetic field of the Inner Detector to determine the momentum of the muon tracks, the intrinsic component of the sagitta resolution is isolated and found to be between 80 and 100 $\mu$m.

To measure the momentum resolution of the MS without requiring a comparison with the ID, the top and bottom sections of a cosmic-ray track traversing the whole detector are compared. The momentum resolution is the width of the fitted distribution of relative $p_T$ differences ($\Delta p_T/p_T$) between the top and bottom halves of the track. Fitting the momentum resolution against the momentum of the tracks (see Figure 17) allows the extraction of its three components: energy loss correction ($P_0$), multiple scattering ($P_1$), and intrinsic resolution ($P_2$). Extrapolating the fitted function to 1 TeV momenta gives a resolution of $11 \pm 2\%$ for tracks crossing small MDT chambers and $25 \pm 2\%$ for tracks crossing large ones. The difference between small and large chambers is due to the difference in integrated magnetic field along the muon paths. The design goal for 1 TeV muon tracks is a $p_T$ resolution of approximately 10%.

$$\frac{\sigma_{p_T}}{p_T} = \frac{P_0}{p_T} \oplus P_1 \oplus P_2 \times p_T \quad (4)$$

In the ATLAS detector, four kinds of muons are distinguished depending on the way they are reconstructed:
**Figure 16.** Sagitta resolution in the Small Barrel Sectors of the MS as a function of muon momentum. Muon momentum is taken from ID measurements. Data is fitted by the function containing multiple scattering term and intrinsic resolution term.

**Figure 17.** Transverse momentum resolution evaluated with the top bottom method as a function of $p_T$ for small sectors as measured with the Muonboy algorithm. The fitted curve is a phenomenological description of the stand-alone momentum resolution; it is the quadratic sum of an energy loss fluctuation term $p_0/p_T$, a multiple scattering term $p_1$, and a spectrometer resolution term $p_2*p_T$. (See equation 4)

*Stand-alone muon:* The muon trajectory is only reconstructed in the muon spectrometer, and is extrapolated to the beam line while correcting for the energy loss in the calorimeter.

*Combined muon:* The measurement of the stand-alone muon is combined with the measurement in the inner detector.

*Segment tagged muon:* A track in the inner detector is identified as a muon if its extrapolation to the muon spectrometer can be matched to (a) track segment(s) in the muon chambers.

*Calorimeter tagged muon:* A track in the inner detector is identified as a muon if the associated energy deposition in the calorimeters is compatible with a minimum ionizing particle (mip).

As a demonstration of the good performance of the spectrometer, Figure 18 shows the invariant mass of two opposite charge muons of $p_T > 15$ GeV that are coming from a common vertex. The $J/\psi$ and $Z$ resonances are used to study in detail the performance of the MS in the low and high $p_T$ regime respectively. The muon reconstruction efficiency as measured on data with “tag and probe” techniques [17],[18] was found to be consistent with the simulation predictions; for example the average efficiency for muons of $p_T > 5$ GeV is 98%. The $J/\psi$ decays gave a unique opportunity to probe the efficiency measurement down to very low values of $p_T$. The $K_s^0$ decays to a pair of pions were used to study the muon fake rate (i.e the muon background from decays in flight or reconstruction ghosts) which was found to be of the order of 1 per mill [19].

7. **Forward detectors in 2010**

7.1. **LUCID**

LUCID is a Cherenkov light detector primarily dedicated to online luminosity monitoring. LUCID is a relative luminosity detector. Its main purpose is to detect inelastic proton-proton scattering in the forward direction, in order to both measure the integrated luminosity and to provide online monitoring of the instantaneous luminosity and beam conditions. LUCID consists
of twenty aluminium tubes which surround the beam pipe and point toward the interaction point. The 1.5 m long mechanically polished tubes with a diameter of 15 mm are placed in a light-weight aluminium gas vessel which ensures that the tubes are filled with \( C_4 F_{10} \) gas at a constant pressure of about 1.2 bar, providing a Cerenkov threshold of 2.8 GeV for pions and 10 MeV for electrons. The two LUCID detectors are installed in the ATLAS end-cap regions, at a distance of approximately ±17 m from the interaction point, at a radial distance of approximately 10 cm from the beam line, and cover \( 5.61 < |\eta| < 5.93 \). The electronics of LUCID implement various algorithms to monitor the luminosity delivered by LHC (before any trigger decision) in individual bunches. All algorithms need an independent calibration to provide absolute values of delivered luminosity. The LUCID detector was optimized for high luminosity, but performed very well in early data taking with a luminosity of less than \( L = 10^{27} \text{cm}^{-2}\text{s}^{-1} \).

7.2. ZDC

The primary purpose of the ATLAS Zero-Degree Calorimeters (ZDC) is to detect forward neutrons and photons with \( |\eta| \geq 8.3 \) in both proton-proton and heavy–ion collisions. The ZDCs play a key role in determining the centrality of heavy–ion collisions and contribute to minimum bias and diffractive physics in proton-proton collisions. With a time resolution of about 100 ps, a coincidence of the two ZDCs can be used to greatly reduce backgrounds from beam-gas and beamhalo effects. The ZDC consists of two arms located at 140 m from the IP in slots in the LHC TAN (Target Absorber Neutral) [20], occupying space that would otherwise contain inert copper shielding bars. ZDCs is consisted of four modules on each arm: one electromagnetic (EM) module (about 29 radiation lengths thick), and 3 hadronic modules (each about 1.14 interaction lengths thick). The modules are composed of tungsten with an embedded matrix of quartz rods which are read out by photomultiplier tubes. The modules are 9 cm by 9 cm laterally to the beam, and 15 cm thick.

7.3. ALFA

The ALFA Roman pots and detectors are located at 240 m from the interaction point with a purpose of measuring elastic scattering at small angles in the Coulomb-Nuclear Interference region. The system consists of four Roman pot stations, two on each side of the interaction point.

\( \text{Figure 18. } \) Dimuon invariant mass spectrum of two opposite charge muons of \( p_T > 15 \text{ GeV} \) that are coming from a common vertex.

\( \text{Figure 19. } \) Combined muon reconstruction efficiency with respect to the inner tracking efficiency as a function of the pseudorapidity of the muon for muons with \( p_T > 20 \text{ GeV} \). The panel at the bottom shows the ratio between the measured and predicted efficiencies.
point, each housing two vertically movable detectors. The Roman pots house scintillating fiber
detectors arranged in 20 u/v detection planes, providing a spatial resolution of about 30µm. The luminosity calibration will be obtained during special runs using a dedicated high β* optics
which features a parallel-to-point focusing to allow for a direct reconstruction of the scattered proton kinematics.

Figure 20 shows the location of each of these detector systems relative to the ATLAS central
detector (only one arm is shown, but all the detector systems are symmetrically located on each side of the interaction region).

8. Highlights from physics results
With all the ingredients described so far, we can start to talk about physics. The selection of
results presented in the following sections are to a large extent focussed on data collected in the
2010 and early 2011 running periods of LHC, when the pile−up probability was negligible. The
delay between data collection and availability of results is due to the need to understand the
detector and the effects of pile−up, as well as tune Monte Carlo simulations using real data. However, updates based on full statistics are expected soon.

8.1. Results from Proton-Proton collisions
The total cross section for pp collisions at 7 TeV amounts to ≃ 75mb. Most of the interactions
result in events characterized by the production of particles with transverse momentum not exceeding a few GeV. Hard jets, with transverse momentum of tens of GeV or more, are produced
in a small fraction of the collisions (10−5%). Vector boson production is equally rare, and even
rarer is the production of top quarks. Given the luminosity delivered by LHC in 2010, the
physics studied so far is often referred to as “rediscovery of the Standard Model”, although
searches for new physics are starting to improve limits on production of exotic particles. The
full rediscovery of the Standard Model in just one experiment was at any rate quite an exciting
exercise.

8.1.1. Production of top quarks tt
The top quark is by far the heaviest quark, with a measured
mass of 172 GeV. At LHC top quarks are mostly produced in pairs. Their mass is so high that
there is no time for them to hadronize before decaying. The branching fraction to a W boson
and a b quark is close to 100%, so that the final tt event topology is fully determined by the
decay of the W bosons. Events where at least one of the W bosons decays leptonomically can be
separated from the high multi–jet QCD background with the best signal–to–noise ratio. The capability to identify jets originating from $b$–quarks ($b$ tagging) is the key to rejecting W+jets events where no top quarks are produced. The semileptonic channel, where one of the W boson decays leptonically and the other decays into a jet pair, can be used to measure the top mass via the invariant mass of the three jets coming from the $bq\bar{q}$ system.

The measurement of the top-quark pair-production cross-section $\sigma_{t\bar{t}}$ is one of the milestones for the early LHC physics program. A precise measurement of $\sigma_{t\bar{t}}$ allows for precision tests of perturbative QCD, where uncertainties on $\sigma_{t\bar{t}}$ are now at the level of 10% [21]. In addition $t\bar{t}$ production is an important background to the search for the Higgs boson and various searches for physics beyond the Standard Model. ATLAS has measured the production cross section of $t\bar{t}$ [22] combining the results of two topologies: single lepton (electron e or muon $\mu$) with large missing transverse energy and at least four jets, and dilepton ($e\mu$, $\mu\mu$ or $e\mu$) with large missing transverse energy and at least two jets. The result is $\sigma_{t\bar{t}} = 189\pm 9(stat.)\pm 15(syst.)\pm 6(luminosity)pb$, which is in excellent agreement with the Standard Model prediction. Figure 21 shows various cross-section measurements from Tevatron and LHC results overlaid with the theoretical predictions as a function of centre-of-mass energy. Figure 22 shows the summary measured $\sigma_{t\bar{t}}$ using several analyses in each decay channel, including errors bars for both statistical uncertainties only and all systematics.

**Figure 21.** $t\bar{t}$ production cross–section at hadron colliders as measured by CDF and D0 at Tevatron ($p\bar{p}$ collisions), CMS and ATLAS at LHC ($pp$ collisions). The theoretical predictions for $p\bar{p}$ and $pp$ collisions include the scale and PDF uncertainties and assume a top–quark mass of 172.5 GeV. The present result is indicated by the red circle.

**Figure 22.** Plots of measured $\sigma_{t\bar{t}}$ using several analyses in each decay channel, including errors bars for both statistical uncertainties only (blue) and all systematics (red). The combined result is based on the $L+jets$ b-tag multivariate and the dilepton counting analyses. The approximate NNLO prediction is shown as a vertical dotted line with its error in yellow.
8.1.2. First Searches for New Physics

First searches for new physics included heavy particles decaying into jets, for which the signature would be a bump in the dijet invariant mass spectrum, as well as new interactions giving rise to special features in the dijet angular distributions. In fact, QCD calculations predict that high-$p_T$ dijet production is dominated by $t-\text{channel}$ gluon exchange, leading to angular distributions that are peaked at $|\cos\theta^*|$ close to 1, where $\theta^*$ is the polar scattering angle in the two–parton center–of–mass frame. By contrast, models of new processes characteristically predict angular distributions that would be more isotropic than those of QCD. Many models of new physics predict the existence of additional heavy gauge bosons, where the charged ones are commonly denoted $W'$. Such particles are most easily searched for in their decay to a charged lepton (either electron or muon) and a neutrino.

Search for $Z'$: ATLAS detector has been used to search for high mass resonances decaying into $e^+e^-$ or $\mu^+\mu^-$ pairs in the invariant mass spectrum above 110 GeV with $\sim 167 \text{pb}^{-1}$ in the $e^+e^-$ and $\sim 236 \text{pb}^{-1}$ in the $\mu^+\mu^-$ final state of 7 TeV $pp$ collision data. Among the possibilities for such resonances, this note focuses on new heavy neutral gauge bosons $Z'$ [23],[24],[25]. The benchmark model for $Z'$ bosons is the Sequential Standard Model (SSM) [23], in which the $Z'$ ($Z'_{SSM}$) has the same couplings to fermions as the Z boson. Figure 23 presents the invariant mass ($m_{e^+e^-}$) distribution after final selection. The dielectron invariant mass distribution is well described by the prediction from SM processes. Similarly, results for the $\mu^+\mu^-$ channel are presented in Figure 24. A good agreement between the data and the SM prediction are again observed. No evidence for such a resonance is found. Limits on the cross section times branching probability, compared to the stacked sum of all expected backgrounds, with three example $Z'_{SSM}$ signals overlaid.

Search for $W'/W^*$: A first limit on the production of $W'$ was set by assuming the same couplings as those of the Standard Model W boson (Sequential Standard Model) and considering the $W' \rightarrow l^\pm \nu$ ($l$ = $e$ or $\mu$) decay channels. Combined limits assuming flavor independence has been set by ATLAS. The kinematic variable used to identify the $W'/W^*$ is the transverse mass:

$$m_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos \theta_{l\nu})}$$

which displays a Jacobian peak that, for $W' \rightarrow l^\pm \nu$, falls sharply above the resonance mass. Here $p_T$ is the lepton transverse momentum, $E_T^{\text{miss}}$ is the magnitude of the missing transverse
momentum (missing $E_T$), and $\phi_{pT}$ is the angle between the $p_T$ and missing $E_T$ vectors. Figures 25 and 26 show the $m_T$ spectrum in $e\nu$ and $\mu\nu$ channels, respectively, after final selection for the data, for the expected background, and for three examples of $W'$ signals at different masses. Both direct production of leptons and indirect from $\tau-$leptons are included. The agreement between the data and expected background is good. No excess beyond SM expectations is observed. A $W'$ with SSM couplings is excluded for masses below 1490 GeV at 95% CL. The exclusion for $W'$, the charged partner of the chiral bosons described in [26], with couplings set in accordance with reference [27] is 1470 GeV.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure25.png}
\caption{\textit{tf} Spectrum of $m_T$ for the electron channel after final event selection. The points represent ATLAS data and the filled histograms show the stacked backgrounds.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure26.png}
\caption{Spectrum of $m_T$ for the muon channel after final event selection. The points represent ATLAS data and the filled histograms show the stacked backgrounds.}
\end{figure}

8.2. Results from Pb – Pb collisions

Collisions of lead ions at ultra–relativistic energies are expected to produce a dense state with temperatures exceeding two trillion Kelvin. If deconfinement is indeed reached, the relevant degrees of freedom are not hadrons, but quarks and gluons. In this medium, high–energy quarks and gluons are expected to transfer energy to the medium by multiple interactions with the ambient plasma. The study of events produced at ultra–relativistic heavy–ion collisions is typically carried out by labelling the events according to their geometry, or centrality: the larger the centrality, the larger the number of interacting nuclei and the event activity. At ATLAS, the level of event activity is characterized by using the total transverse energy ($\sum E_T$) deposited in the Forward Calorimeters as shown in Figure 27. Bins are defined in centrality according to fractions of the total lead–lead cross–section selected by the trigger and are expressed in terms of percentiles ($0 – 10\%$, $10 – 20\%$, $20 – 40\%$ and $40 – 100\%$) with 0% representing the upper end of the $\sum E_T$ distribution.

An interesting observation, the so called “jet quenching”, which is the production of highly unbalanced jets with one jet produced at the periphery of the collision, gives hints of how the parton shower develops in this dense medium. The jet quenching is expected in central heavy–ion collisions and actually at Relativistic Heavy Ion Collider experiments (RHIC) quenching in two particle correlation is observed. With the data collected by the ATLAS detector observations have been made of a centrality dependent dijet asymmetry in these collisions [17]. Events with two jets were selected requiring the leading jet to have transverse energy $E_T > 100$ GeV and the second jet $E_T > 25$ GeV. The transverse energies of dijets in opposite hemispheres were observed to become systematically more unbalanced with increasing event centrality leading to a large number of events which contain highly asymmetric dijets as it is shown in Figure 28.
Figure 27. Distribution of uncorrected $\sum E_T$ in the Forward Calorimeter (FCal). Bins in event activity or “centrality” are indicated by the alternating bands and labeled according to increasing fraction of lead–lead total cross section starting from the largest measured $\sum E_T$.

This was the first observation of an enhancement of events with such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

Figure 28. Dijet asymmetry distributions for $R = 0.4$ jets in three collision centrality bins: 0 – 10% (top), 30 – 40% (middle), 60 – 80% (bottom) for $\sqrt{s_{NN}} = 2.76$ TeV $Pb+Pb$ collisions with a leading jet with 100 < $E_{T1}$ < 125 GeV (left), 125 < $E_{T1}$ < 150 GeV (middle), 150 < $E_{T1}$ < 200 GeV (right). For all of the plots, comparison to HIJING events with embedded PYTHIA dijets for the same conditions on reconstructed jets as the data is shown (yellow).

9. Summary and Conclusions
2010 was an extremely exciting year for LHC. The accelerator reached all the announced goals, and the detectors performed equally well. ATLAS data collection was very smooth, and data have been under deep scrutiny to understand the details of the detector behaviour as well as
tune detector—related effects in simulations. The ATLAS collaboration has delivered a plethora of physics results with the 2010 data. Overall, 2010 was the year of Standard Model rediscovery, as is frequently said. No evidence for physics beyond the Standard Model has been found yet, although previous limits on the production of new particles start to be extended, even with limited statistics. A lot of new results are just about to come. Some model tuning is apparently needed for diffractive physics. Ultra—relativistic lead—ion collisions carried most of the surprises, with the first impressive evidence for jet—quenching. And we are just at the beginning of a very promising period to come. All these achievements were possible thanks to the fantastic LHC machine team and to the many years of dedicated work in commissioning of the ATLAS detector.

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