Bringing the ATLAS Muon Spectrometer to Life with Cosmic Rays

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Abstract

The muon spectrometer of the ATLAS experiment at the Large Hadron Collider is the largest device ever built to track high energy particles. It has been designed to provide muon identification and measurement in the hard environment of proton-proton collisions at high energy and high luminosity at the LHC. An impressive number of elements, spread over the large volume of the spectrometer, were commissioned for many months with cosmic rays and were ready to take data when the first beam was circulated in the LHC. A systematic study of the detectors performance was done in the following months. More than 200 million cosmic ray triggers were taken in different conditions. We present the status of the muon detectors and the main results from the reconstruction of this event sample, showing that the ATLAS muon spectrometer is well advanced towards physics data taking.

Key words: LHC, Muon Spectrometer, Cosmic, Muon Trigger

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1. The ATLAS Muon Spectrometer

The Muon Spectrometer (MS) of the ATLAS\textsuperscript{[1]} experiment at LHC was designed and built to provide an efficient muon trigger with bunch crossing (BC) identification capability and high precision in momentum resolution. Three toroid magnets, one in the Barrel and two in the end-caps, host the particle detectors for the trigger and for precision tracking. The bending power, which ranges between 1 and 7.5 T·m, depending on the pseudorapidity, and the low amount of material crossed by the muons in the spectrometer, allow the precise determination of the transverse momentum over a wide pseudorapidity interval, $|\eta| < 2.4$, with a resolution better than 10% up to 1 TeV for $|\eta| < 1.1$. The muon curvature is measured by means of three precision chambers positioned along its trajectory. In order to meet the required precision in the very high momentum region each muon station is expected to provide a measurement of the muon trajectory, in the precision plane, with an accuracy of about 50\,\mu m.

Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC) provide the information to the muon trigger in the Barrel and in the Endcaps respectively, while Monitored Drift Tubes (MDT), and Cathode Strip Chambers (CSC) in the forward region ($|\eta| > 2$), precisely measure the position in the bending plane.

Two RPC chambers are attached to the middle Barrel chambers providing the low-PT trigger information. The high-PT trigger is provided by the RPC modules installed on the outer Barrel chambers combined with the middle chambers signals. The RPC are also used to provide the coordinate along the MDT tubes that cannot be measured by the MDT chambers. Similarly in the end-cap two TGC doublets and one triplet are installed close to the middle station and provide the low- and high-PT trigger signals. The TGC are also measuring the coordinate of the muons in the direction parallel to the MDT wires. To this purpose some TGC chambers are also installed close to the inner MDT to improve the measurement accuracy of this coordinate.

The size of this system is impressive, about 1 million channels, grouped into more than 5000 chambers. Its operation is particularly complex due to the non uniform magnetic field and the strong temperature gradients. To fully realize the challenge, the required 50\,\mu m resolution has to be compared to the spectrometer dimensions along the bending coordinate, 20m for the diameter of the Endcaps, 36m for the length of the Barrel. Figure 1 presents, as an example, a cosmic ray event in which the curvature of the track cannot be appreciated without zooming in the Inner Detector or the Muon Spectrometer. Both the inner solenoid and the Barrel toroid field are on, and the muon track turns out to be a typical cosmic ray with a momentum of about 25\,GeV/c. The sagitta for 1 TeV muons will be 40 times smaller. Alignment and calibrations, which should contribute for less than 30\,\mu m to the resolution, play an essential role.

Figure 2 shows the contributions to the momentum resolution for muons reconstructed in the Muon Spectrometer as a function of transverse momentum. The resolution of the Muon Spectrometer for transverse momenta below 100\,GeV/c is dominated by the fluctuations in the energy lost in the calorimeters and by the multiple scattering. For this reason the reconstruction in the Muon Spectrometer (standalone reconstruction) needs to be complemented at low momenta by the reconstruction in the Inner Detector. The resulting track parameters are obtained combining the two tracks.
2. The Cosmic runs

In the 2008 fall period the ATLAS detector has been operated for several months. The first beams where circulated in the LHC machine but no beam-beam collisions where delivered. The ATLAS detector has been collecting during this period mainly cosmic runs. Figure 3 displays the statistics collected between the 13 September 2008 and the end of October. The solenoidal and toroidal fields were on in the periods marked with color codes. Level-1 muon triggers from RPCs and TGCs provided most of the statistics. These triggers were used to commission the Muon Spectrometer and the other detectors.

For the Barrel, in the runs analyzed in this paper, only a coarse time alignment was in place. For this reason in the Barrel level-1 trigger configuration it was decided to base the trigger decision only on the phi view, which suffered less from this problems. In order to achieve a good suppression of fakes the trigger required a majority logic of 3 hits out of 4 lowPT layers. In phi view a pointing requirements was also applied. The coarse trigger time alignment has also an impact on the determination of the t0 for the MDT chambers as discussed below. It’s also worth to notice that a peculiar timing set-up was chosen: trigger sectors of the top part were artificially delayed by 5 BC respect the bottom ones in order to maximize the probability to trigger muons hitting the latter. This was due to the request from the inner detectors to use as main source of trigger the bottom sector that, given the geometry of the pit shaft, are the one that maximize the number of muon passing through them.

The data taken in fall 2008 have been complemented in January and April 2009 by some runs involving only RPCs or only the Muon Spectrometer, during which the synchronization of the trigger and the readout latencies were sensibly improved.

In the Endcaps the trigger scheme is based on the coincidence logic between several layers of TGC gas-gaps. The trigger timing was aligned as for the high momentum muons coming from the IP. All the delays due to different Time-Of-Flight and cable lengths (more than 10k cables) were properly set and cross-checked using a test pulse system achieving a timing at a level of 4ns. For most of the 2008 cosmic run period, only the level-1 triggers generated from bottom part of TGC was used in the data taking (see Figure 4). This was chosen to avoid triggering on the cosmic muons crossing first the top of one TGC wheel and later the bottom of the opposite ones. These events would be triggered by the former and would be out of time in the Inner Detector with respect to muons coming from collisions.
3. Detector Performance

A subset of high statistic runs acquired in stable conditions has been used to evaluate the detector performance identifying the problematic channels, checking the cabling, measuring noise and efficiency. This very detailed information has been used to fix most of the problems during the winter shutdown, allowing a sizeable improvement of the detector performance in view of the first collisions. The same data were used also to check and improve alignments and to provide the MDT calibrations. Results from CSCs are not included in these paper since data form this detector were not acquired in the cosmic data taking period being considered.

3.1. RPC

For the RPCs the main problems in 2008 were due to readout, trigger, gas and ambient temperature. Due to synchronization problems 11 out of 64 trigger sector logic boards were masked in the readout system. Some other trigger towers were not operated because of broken optical links or because of initialization problems. A layer of an entire spectrometer sector was turned off due to a broken gas line that prevented the proper flushing of the gas mixture inside the gas volumes. An ambient temperature up to 26°C was also observed in the upper part of the spectrometer due to high power dissipated by the on chamber trigger and readout electronics. In order to avoid detector damage three sectors on the top of the apparatus were operated at lower high voltage (9200 instead of 9600 Volts) resulting in lower efficiency operation. As a result of all these problems the trigger and readout coverage of the RPC was reduced to approximately 60%. The coverage in April 2009 was increased to 95.5%. Noise studies were also performed, dedicated random trigger run were acquired and the single counting rate for each readout strip was measured. Only 0.05% of the strips showed a single counting rate above 10Hz/cm². In randomly triggered events the average number of RPC hits was 20. The fraction of dead channel was measured to be 1.5%, mainly due to front-end electronics problems which can be easily fixed. RPC efficiencies for chambers operated at the nominal voltage were found to be in good agreement with expectations [2].

3.2. TGC

For the TGCs in the fall 2008 cosmic ray run the total amount of dead and masked channel was about 0.22%. None of the dead and masked channels caused a hole in the trigger acceptance thanks to the coincidence trigger logic redundancy (3 out of 4 and 2 out of 3 majority requirements for low-PT and high-PT triggers). Figure 5 shows the distribution of wire efficiency of doublet chambers. Inefficiency of several percent due to support materials inside chambers is included the measured value. Most of chambers have more than 70% efficiency and most of low efficiency values are due to high voltage failures. The mean layer efficiency for chambers without high voltage failure is 93% and the efficiency of the 3 out of 4 layer coincidence is estimated to be 97.3%. The right panel of Figure 5 shows the turn-on curve of TGC wire efficiency. The nominal HV value was 2800 V in 2008.

Figure 5: The distribution of TGC wire efficiency of doublet chambers (left) and the high voltage dependence of wire efficiency of doublet chambers (right)

3.3. MDT

In the MDT chambers the detailed checks performed on these data allowed to identify 1.5% of problematic channels out of which only 0.1% have permanent problems (broken wire), while most of the other could be fixed for 2009 run. The measured average tube efficiency amounts to 98.5%, while noisy tubes (with an occupancy exceeding 5%) are less than 0.2%. As stated above achieving the required precision with these detectors requires very good alignment and calibration.

3.4. Alignment

As long-term mechanical stability in a large structure such as ATLAS cannot be guaranteed at this level, a continuously running alignment monitoring system [3] is required in order to fully exploit the intrinsic resolution of the spectrometer. This system is based on optical and temperature sensors, and is designed to detect slow chamber displacements, occurring at a time-scale of hours or more. The information from the alignment system is used in the off-line track reconstruction to correct for the chamber misalignment. No physical adjustments are made to the chamber positions after the initial positioning. Optical and temperature sensors are calibrated, so that they can be used to make absolute measurements of muon chamber positions in space, rather than only following their movements with time, relative to some initial positions. Initial positions could be accurately measured by external surveys for the Endcaps while for the Barrel the planned alignment strategy is to get an initial track-based alignment from dedicated runs without magnetic field and use the optical alignment system to follow up station movements due to the switching on of the toroidal field and temperature effects.

During the cosmic data taking most of the sensors were operational. The effect of the application of the optically derived alignment constants to the sagitta measurement in straight tracks (field off) in the Endcaps is visible in figure 6, which shows that the designed accuracy has been nearly reached in the Endcaps. In the Barrel the direct application of the optical corrections to the nominal chamber positions, checked with straight tracks, gives an accuracy of 200μm in the large sectors and of 0.5 to 1mm in the small ones. A track based alignment run on these data allowed to prove that the required 30μm precision can be achieved, as discussed in [4].
3.5. MDT Calibration

The space-time relation for the MDT chambers is obtained through the auto-calibration technique using high statistics samples of muon tracks. To obtain the required statistics in p-p collisions a dedicated high rate stream will be extracted from the level-2 trigger and distributed to remote Calibration Centers, producing constants which will be validated and made available in the Conditions Database in less than 24h [5]. This mechanism has been extensively tested during the cosmic data taking. However the pointing requirements applied in the level-2 trigger reduce significantly the statistics in cosmic events, therefore the calibrations for this data taking period were performed on the standard data sample. Two specific problems had to be faced in cosmic events. The low statistics collected in some regions, which did not allow the standard calibration procedure to converge, and the timing of the events, which prevented the usage of the standard definition of the \( t_0 \) reference time.

Where the auto-calibration could not converge a space-time relation obtained from a monitoring chamber, fed with the same gas but located on the surface, corrected for the temperature, was used [6].

The \( t_0 \) was extracted as a free parameter from the fit to each track segment [7]. This procedure allowed to correct both for the intrinsic time jitter of the cosmic tracks arrival time with respect to the 40MHz clock and for the additional synchronization differences between the different trigger sources present in these data.

4. Correlations

The information provided by the different technologies involved in the Muon Spectrometer and related to the same particle is of course used in input to the same reconstructed track. Before performing this combination it can be checked that correlations are indeed observed between RPCs and MDTs and between TGCs and MDTs as shown in Figure 7. Exploiting the fact that muon tracks crossing the calorimeters and the Inner Detector are reconstructed in the Muon Spectrometer as two independent tracks, it is also possible to measure the momentum difference between top and bottom tracks, which is found to be on average 6GeV/c in agreement with the expected energy loss for a track crossing twice the calorimeters. Good correlations have been observed also between the track parameters measured in the Muon Spectrometer and in the Inner Detector, despite the fact that the relative alignment between the two subsystems has not yet been performed.

5. Conclusions

The cosmic events collected in 2008, mostly with muon triggers, are used for detailed studies of the Muon Spectrometer detector and standalone reconstruction. Most of the problems observed in the 2008 cosmic runs have been understood and fixed. Cosmic data to be collected in summer 2009, with a full trigger coverage and an improved time alignment, will be used for detailed studies of combined reconstruction performance, dead material, alignment with respect to the Inner Detector.

The ATLAS Muon Spectrometer is alive and ready for beam.

References


