ATLAS cosmic ray results

Christian Schmitt on behalf of the ATLAS Collaboration
Institut für Physik, Johannes Gutenberg-Universität Mainz,
Staudinger Weg 7, 55099 Mainz, Germany
E-mail: Christian.Schmitt@cern.ch

Since September 2008, ATLAS has recorded several hundred million cosmic-ray events. These events have been very useful in the commissioning of the individual ATLAS subdetectors and the assessment of their individual performance. Given the nature of the cosmic events traversing all of the ATLAS subdetectors, these events are also a precious source to assess the combined performance of the real ATLAS detector before first collisions.

Keywords: ATLAS; Cosmic ray data; Commissioning.

1. The ATLAS detector

The ATLAS detector\cite{ATLAS} has been designed and built to provide excellent physics performance in the difficult environment of the Large Hadron Collider (LHC) at CERN with its 14 TeV proton-proton collisions at a bunch crossing rate of 40 MHz with up to $10^{11}$ protons per bunch providing a design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$.

The layout of the ATLAS detector is as follows: it consists of an Inner Detector (ID) within a solenoidal field of 2 Tesla, calorimeters and a muon system operating inside an air-core toroid system. The ID provides momentum and vertex measurements of charged particles using discrete, high-resolution semiconductor Pixel and strip detectors (SCT) in the inner part and straw-tubes in the outer part (TRT). The TRT has also the capability to generate and detect transition radiation to improve the electron identification. The energy measurements are provided by an electromagnetic calorimeter that uses liquid argon as active medium to detect photons and electrons and a scintillator-tile calorimeter in the central part and a liquid argon calorimeter in the forward region for hadrons. The calorimeters are surrounded by the muon spectrometer, consisting of precision tracking chambers, monitored drift tubes (central and end-cap) and cathode strip
chambers (forward), as well as trigger chambers made out of resistive plate (central) and thin gap (end-cap and forward) chambers.

2. Cosmic muon runs

After the LHC incident\(^1\) in September 2008 a global cosmic run has been started that lasted until end of October 2008. During this time more than 200 million cosmic ray events have been recorded (Fig. 1). Given the different sizes of the individual ATLAS subdetectors the rate of cosmic muon events differs between about 700 Hz for the Muon system and about 1 Hz for the Pixel detector. This required that muons crossing the Inner Detector had to be recorded under all circumstances while the other events could be prescaled. For this a track trigger at the second trigger level was used which achieved an efficiency of nearly 100\% (Fig. 1). For more details concerning the trigger commissioning with cosmic ray data see.\(^3\)

In summer of 2009 a second global cosmic run has recorded over 90 million events in just two weeks. The measured data taking efficiency of ATLAS, averaged over simulated LHC stores of 6h-14h, was about 83\%.

Different configurations of the magnetic fields, i.e. the toroid or the solenoid were either on or off, have been used in both data taking periods to allow dedicated alignment studies.\(^4\) In addition events triggered by a random trigger have been recorded during the data taking periods to be able to study the noise in the different detectors (esp. the calorimeters).

---

**Fig. 1.** Integrated number of recorded events (left) showing also the different magnetic field configurations used. Efficiency of the track trigger at the second trigger level (right) as a function of the transverse impact parameter of the track. The drop in the efficiency for the silicon based algorithms at higher impact parameter is due to the acceptance of the silicon detectors.
3. Subdetector commissioning studies

Nearly all of the ATLAS subdetectors have been tested extensively before the installation in the cavern and also afterwards in dedicated cosmic runs. With the global cosmic runs enough data has now been recorded with all subdetectors present to allow for an assessment of the actual ATLAS performance before first collisions.

One of the first things to be studied in the Inner Detector is the individual subdetector calibration and performance. The ATLAS track reconstruction relies on a high efficiency and a low noise occupancy of the silicon based detectors. Using the cosmic muon tracks, the efficiency has been found to be well above 99% (Fig. 2 shows as example the efficiency in the SCT) while the noise occupancy is very low: less than one out of the 80 million channels in the Pixel detector will show a noise induced signal per bunch crossing and also the SCT noise occupancy is well below the specification of $5 \cdot 10^{-4}$. For the TRT the onset of the transition radiation could be observed for high energetic muons and the results are in good agreement with the ones from the testbeam.

In the LAr calorimeter the cosmic muons have been used to verify the signal reconstruction and the uniformity of the response. Figure 3 shows the drift time uniformity as a function of $\eta$ position in the detector. Using the observed non-uniformity of 1.37% in this drift time distribution the uniformity of the calorimeter response could be calculated to be 0.37%. In addition to cosmic muon events, random events have been used to measure the noise in the calorimeter and its long-term stability. Similar studies have been carried out in the Tile Calorimeter. By using the tracks reconstructed in the ID, the cell response could be mapped as a function of the $\phi$ position.
of the tracks intersecting the Tile calorimeter (Fig. 4). When the tracks intersect the calorimeter near the center of the cells, the cell response is consistent with the average expected muon response while for tracks intersecting well outside the cell, the measured calorimeter response is at the pedestal value. The rising and falling of the cell response at the cell boundaries is due to the wide transverse impact parameter ($d_0$) distribution of the cosmic tracks. A very good uniformity is observed as well as a good alignment between the Tile Calorimeter and the ID.

In the Muon Spectrometer the cosmic ray muons have been used to study all aspects of the detector from single hit efficiency over segment efficiency until the final alignment of the muon chambers. The details of these studies can be found in ref. 8.

4. Combined performance studies

In parallel to the subdetector commissioning studies also the combined performance of several subdetectors working together can be studied using these cosmic events. In the following a summary of these studies will be given.

The cosmic muons traverse the full Inner Detector, i.e. they cross both the upper and the lower hemisphere. This fact can be exploited to measure the tracks parameter resolution directly in data: by splitting the tracks at the center of the detector and reconstructing both halves separately, two independent collision like tracks are obtained representing the same
Fig. 4. Cell response of the 2nd layer cells in the Tile calorimeter (the thickest layer) as a function of reconstructed track $\phi$. The curves in the figure are summed over all track eta directions. The vertical dashed lines correspond to the nominal position of the cell edges.

Fig. 5. Momentum resolution of the cosmic tracks as a function of the momentum in comparison with the expectation from the simulation of the perfectly aligned detector. A comparison of the obtained track parameters yields the corresponding resolution of this track parameter. Figure 5 shows the obtained momentum resolution as a function of the muon momentum in comparison to the expectation from a perfect detector. The results show that with the current understanding of the detector, esp. the alignment, the momentum
Fig. 6. Comparison of the lateral shower width in the $\phi$ direction of photons observed in cosmic ray data to cosmic ray simulation showing the very good agreement between the two.

The interaction of the cosmic muon with the material of the ATLAS detector produces mainly photons due to bremsstrahlung. These photons can be used to study the shower shape variables used for photon identification. Figure 6 shows a comparison of the lateral shower width in the $\phi$ direction in the EM calorimeter for both data and cosmic simulation. The very good agreement shows that this as well as the other variables used for photon identification will provide a robust photon identification for early LHC data.

The interaction of the muon with the material in the ID can produce delta electrons due to ionization processes with energies above the electron cluster reconstruction threshold of 3 GeV. The signature of those events is an energy deposit in the EM calorimeter, a muon crossing the ID and a second track originating from inside the ID. By using the standard cut based ATLAS electron identification which exploits both the calorimeter and the transition radiation in the TRT a clean electron sample could be extracted as can be seen in Figure 7. The background shape has been estimated using a sample containing muon bremsstrahlung events and the normalization is taken from a binned maximum likelihood fit to the data.

Even though there are no real tau leptons produced in the cosmic ray events, a muon that undergoes bremsstrahlung can lead to a signature that is similar to a tau lepton candidate. These events can therefore be used to verify the agreement between data and simulation of the relevant variables.
Fig. 7. $E/p$ distribution for the electron candidates. The line shows the result from the background fit showing a very good signal to background ratio. A clear peak at $E/P \sim 1$ is observed indicating that the events are indeed electrons.

for the tau identification. Figure 8 shows as an example one of the tau identification variables, the centrality fraction defined as the ratio of the energy contained in a cone of radius 0.1 and the energy in a cone of radius 0.4, for tau candidates found by the calorimeter based algorithm. A very good agreement between data and simulation is observed in this and also the other variables used for tau identification.

The bremsstrahlung photons of the cosmic ray muons can deposit enough energy in the calorimeters for the jet algorithm to be able to reconstruct this deposit as a jet. In fact jet energies of up to several TeV have

Fig. 8. Comparison between Data and simulation of the centrality fraction of tau candidate events.
been observed.\textsuperscript{7} These jets from cosmic ray muons can be an important background for e.g. searches for new physic processes and it is therefore crucial to be able to suppress them. Given that the origin of these jets is a photon produced either in the electromagnetic (em) or the hadronic calorimeter, a very strong variable for the suppression of these jets is the electromagnetic fraction of the jets, as can be seen in Figure 9: the em fraction is either close to zero for a photon that is produced in the hadronic calorimeter or close to one for a photon produced in the em calorimeter whereas typical jets from collision events have a broader spectrum peaking around 0.8.

The recorded events from the random trigger, taken in parallel to the cosmic data taking periods, have been very useful to understand the missing energy reconstruction. In these events the only contribution to the missing energy is from the electronic noise in the individual subdetectors. Figure 10 shows nicely the long-term stability of the missing energy over a period of 45 days.

Cosmic ray muons crossing the innermost Pixel layer are, besides the difference in the timing, indistinguishable from isolated muons produced in collision events. The collected data sample can therefore be used to study the combined muon reconstruction where a muon is found in the Muon Spectrometer and combined with a corresponding track from the Inner Detector. Comparing the track parameters between the two independently reconstructed tracks, a very good agreement could be observed (Fig. 11).
Fig. 10. Deviation of the mean of the missing energy distribution in x-direction ($\mu$) from its average value $<\mu>= (0.103 \pm 0.005)$ GeV. Good stability is seen over the period of 45 days.

Fig. 11. Scatter plot of the $\phi_0$ coordinate reconstructed in the Muon Spectrometer versus the same coordinate reconstructed in the Inner Detector (left). As expected a nice correlation is observed. The muons loose about 3 GeV of energy when passing through the material in front of the Muon Spectrometer. A good agreement with this prediction is seen by comparing the momentum in the ID and the Muon Spectrometer (right).

5. Summary & Conclusions

Since the LHC incident on September 19, two dedicated cosmic data taking periods allowed the record of more than 300 million cosmic ray events. This data has been very useful in assessing the individual subdetector performance as well as the performance of the combined reconstruction: the inner detector hit efficiency for active modules is well above 99% for the
Pixel and the SCT and the TRT has seen the onset of the transition radiation. The calorimeters show a uniform response to the cosmic ray particles and the electronic noise is very low and stable over several months. The muon spectrometer is also performing as expected.

The track parameter resolution is already close to that expected from a perfectly known geometry and also the shower shape variables in the calorimeters are well described by the simulation showing that these are robust variables for electron and photon identification. A clean signal of high energetic delta ray electrons could be extracted from the cosmic ray data sample. The missing energy and the jet reconstruction has been studied in detail and methods to suppress the fake jets from cosmic ray events overlapping with collision event have been established. The identification variables for the tau identification are also well described in the simulation which gives confidence that a tau signal can be established using these variables with collision data. Last but not least the combined muon reconstruction also behaves as expected with a nice agreement in the energy loss in the calorimeter material and the momentum difference in data and simulation.

By making use of these cosmic data events ATLAS is well prepared for the restart of the LHC in autumn this year.

References
1. F. Bertinelli, *The status of the LHC*, these proceedings.
4. B. Cooper, *Alignment of the ATLAS Inner Detector tracking system*, these proceedings.
5. V. Perez Reale, *Commissioning of the ATLAS Pixel Detector with cosmic ray data*, these proceedings.
7. A. Gibson, *Commissioning of the ATLAS Liquid Argon Calorimeter*, these proceedings.