PROCEEDINGS OF SCIENCE

Commissioning of the Charged Lepton Identification with Cosmic Rays in ATLAS

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Efficient identification of charged leptons will be a key to the study of many physics processes at the Large Hadron Collider (LHC). The ATLAS detector at the LHC has excellent charged lepton identification capabilities. In the years 2008 and 2009, 300 million cosmic ray events were recorded by the ATLAS detector. These data were used to fully commissioning the muon identification algorithms, to prove the power of the electron identification algorithm and to partially commissioning the τ lepton identification.

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1. Introduction

The Large Hadron Collider (LHC) is designed to collide protons at a centre-of-mass energy of 14 TeV with a luminosity between 10^{33} cm^{-2} s^{-1} and 10^{34} cm^{-2} s^{-1} [1]. Many physics processes which have been out of reach at previous colliders will become accessible by the LHC. These processes range from the production of the Higgs and new gauge bosons to the production of superpartners of the known fundamental particles. All of them, however, are highly obscured by QCD reactions. The QCD reactions are usually accompanied by multiple jets in the final state and leptons of low transverse momenta. Many of the interesting non-QCD processes can be detected in final states with charged leptons of high transverse momenta. For the last years, one of the core activities of the ATLAS collaboration has therefore been the optimization of the charged lepton identification.

The ATLAS detector has recorded millions of cosmic ray events since fall 2008 with two major cosmic ray recording periods, one right after the LHC accident in fall 2008, the other in summer 2009. In fall 2008 216 million cosmic ray events were recorded with different detector configurations. About 20 million events were recorded with the magnets turned on. These data were used to study the performance of the electron, muon and τ lepton identification algorithms. In summer 2009 additional 93 million events were recorded, in the first half of the data taking period with the magnets turned on, in the second half with the magnets turned off. The summer 2009 data were heavily used to improve the muon performance. 20 million events without magnetic field made it possible to align the ATLAS muon spectrometer.

The ATLAS detector is located about 100 m underground. Mainly muons which fly through the access shafts to the ATLAS cavern are detected by the ATLAS detector while the others are absorbed in the rock formation above the ATLAS cavern. So most of the muons are vertical and only traversing the entire ATLAS detector in the barrel part. That restricts the commissioning of the identification algorithms to barrel region. The energy spectrum of the recorded muons peaks at low momenta as usual for cosmic rays, but there is a substantial fraction of events with high p_T muons up to transverse momenta of 100 GeV.

2. Commissioning of the muon identification with cosmic rays

The availability of muons up to 100 GeV energy in cosmic rays makes it possible to commission and study muon identification in great detail.

The ATLAS detector is equipped with a high resolution muon spectrometer in which three layers of muon chambers are used to measure the muon trajectories and momenta. In order to get the muon momentum at the proton-proton interaction point the energy measured in the muon spectrometer is corrected for the energy loss of the muon in the calorimeters. Muons which are reconstructed in this way are called stand-alone muons. If the momentum measurement is combined with the momentum measurement in the inner detector, one referes to those muons as combined muons.

Muons with an energy below 3 GeV are absorbed in the calorimeters. Muons with transverse momenta greater than 5 GeV are indentified with 95% at a low fake rate of about 0.1%. The inefficiency is caused by acceptance gaps of the muon spectrometer like a crack at 0 rapidity for the services of the inner detector and the calorimeters. Combined muons have a momentum resolution between 2% and 3% up to 100 GeV transverse momentum (see Figure 1). At higher momenta the resolution gets worse and reaches 10% at 1 TeV. The stand-alone momentum resolution curve coincides with the combined curve at large transverse momentum. So the momentum resolution at high p_T is given by the muon spectrometer. The stand-alone momentum resolution has three contributions, energy loss fluctuations at low p_T, multiple scattering at intermediate momenta, and alignment and chamber resolution at large momenta.

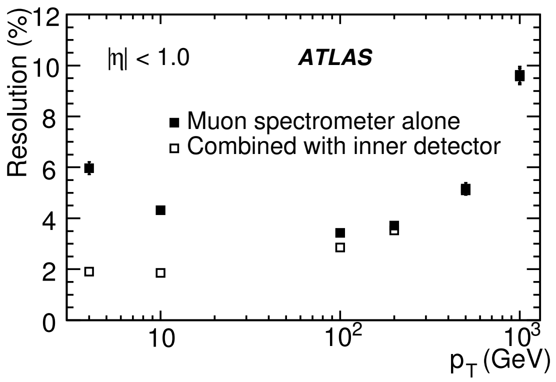

Figure 1: Expected transverse momentum resolution for stand-alone and combined muons in the barrel part of the ATLAS detector [1].

The alignment of the muon spectrometer is crucial for high momentum muons, the alignment of the inner detector already for muons with intermediate transverse momenta. The inner detector is aligned with tracks by minimizing track residuals. The muon spectromter is aligned by a system of optical sensors which monitors relative movements of the muon chambers with respect to each other. The relative positions of the muon chambers have to be determined once with straight muon tracks which are available in runs with turned off magnets.

The inner detector was aligned for the first time with cosmic muon tracks in fall 2008. The track residuals in Figure 2 are highly improved by the alignment procedure. They have a width of 30 μm after the alignment procedure which must be compared to 24 μm expected for a perfectly aligned inner detector. The alignment accuracy which could be achieved with the available statistics is 18 μm. If one reconstructs muon tracks in the summer 2009 data with the alignment constants from fall 2008, one obtains residuals with 36 μm width indicating that the geometry of the inner detector was stable at the level of 20 μm.

Straight tracks are used for the initial alignment of the muon spectrometer. The apparent sagitta of the straight muon trajectories is of the order of a millimeter before the alignment in agreement with the mechanical alignment accuracy and is shifted to 0 after the alignment. Figures 3 shows the mean values of the apparent sagittas after the alignment with tracks for the chambers in the top half of the barrel muon spectrometer. These are all below 100 μm, but not all within the desired accuracy of 30 μm. The same analysis shows that the bottom part could be aligned with an accuracy better than 200 μm with the available statistics. Sufficient statistics to reach the 30 μm goal were collected end of October 2009. The analysis of the new data is work in progress.

In order to measure the muon performance after the alignment of the inner detector and the

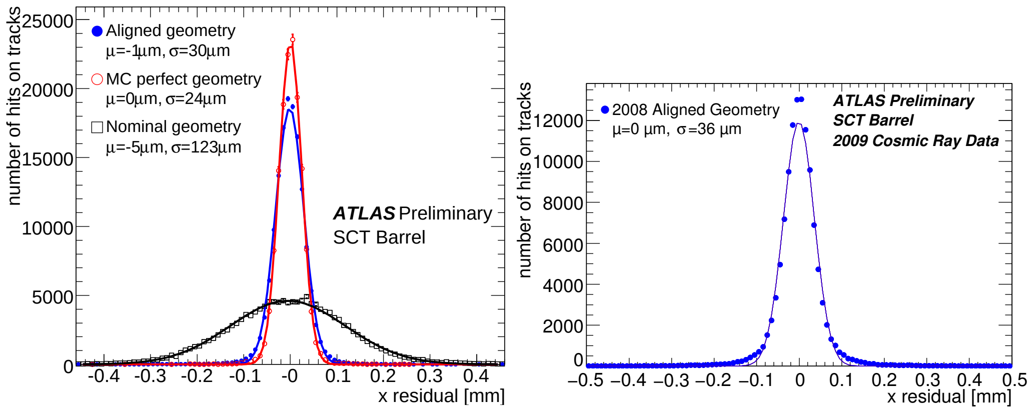

Figure 2: (a) Track residuals in the semiconductor tracker before and after the alignment with cosmic muon tracks of 2008 data in comparison with the Monte-Carlo predictions for the perfectly aligned detector. (b) Track residual in 2009 data after the application of the alignment correction determined with 2008 data.

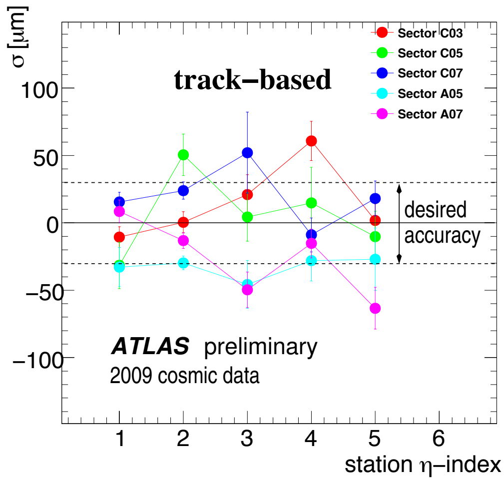

Figure 3: Mean values of the apparent sagittas of straight muon tracks in the top sectors of the barrel muon spectrometer. The muon chambers at $\eta \approx 0$ have η index 1, the chambers at the out ends of the barrel at $\eta \approx 1$ have η index 6.

muon spectrometer, muon tracks mimicking dimuon events are selected. Those muon tracks are split into a bottom part and a top part. The comparison of the top and bottom tracks provides performance measures.

The width of the difference distribution of the momenta of the top and bottom tracks is a measure for the momentum resolution. The solid triangles in Figure 4 show the achieved momentum resolution as a function of the transverse muon momentum. Below 100 GeV, the solid triangles are very close to the stars representing the nominal resolution. A degradation of 20% with respect to the nominal resolution is observed above 100 GeV. The momenta of the top and bottom tracks systematically deviate by up to 2% from each as a consequence of the residual misalignment of the inner detector. But, overall, below 100 GeV the performance is close to nominal. Significant improvements are expected after the alignment with *pp* collision data.

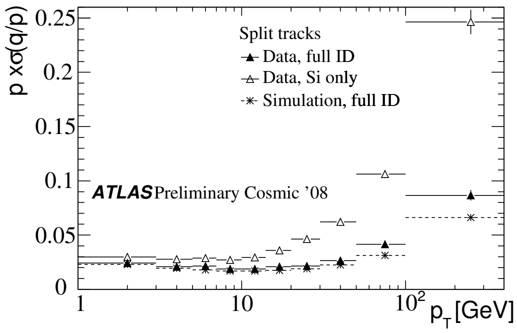

Figure 4: Muon momentum resolution in the inner detector in cosmic ray events.

The stand-alone momentum resolution is also in agreement with the nominal resolution below 100 GeV transverse momenta, but is significantly degraded at higher p_T (see Figure 5). There are two sources of the degradation: firstly the residual misalignment of the muon spectrometer, secondly the limited resolution of the drift time measurement of the muon chambers which is caused by the fact that cosmic muon are asynchronous with the artificial LHC clocks serving as a time reference.

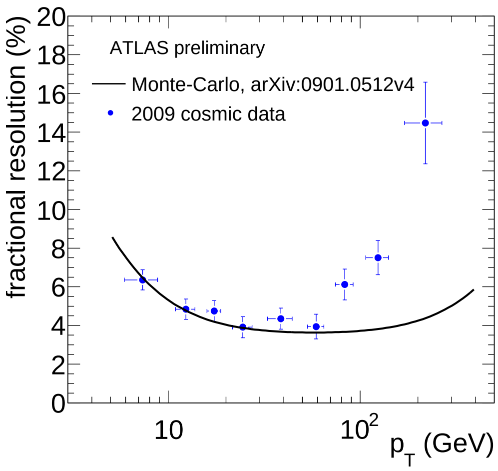

Figure 5: Comparison of the stand-alone muon momentum resolution in cosmic ray events with Monte-Carlo predictions [2].

Also the muon detection efficiency was measured with cosmic-ray data and found to be in agreement with expectations from Monte-Carlo studies.

The results presented in the section show that the muon performance in the barrel of the ATLAS detector is close to nominal for transverse muon momenta below 100 GeV after the commissioning with cosmic rays.

3. Commissioning of the electron identification with cosmic rays

It is not only possible to test the muon identification algorithms with cosmic ray data, but also the electron identification algorithms. Electrons are identified as inner detector tracks associated with an electromagnetic cluster fully contained in the electromagnetic calorimeter. Depending on the electron selection cuts, three quality levels, loose, medium, and tight electrons are distinguished in ATLAS . Track hit requirements are imposed on medium electrons in order to reject electron positron pairs from photon conversions. The tight selection makes use of the transition radiation. The detection of transition radiation by the transition radiation tracker is a sign for light relativistic charged particles and therefore a powerful tool in the detection of electrons in cosmic rays events. The electron identification efficiency and jet rejection depends on the quality levels of the electrons. For $p_T > 17$ GeV, an efficiency of 88% at a jet rejection of 570 is achieved for loose electrons while the tight selection has an efficiency of 65% for a jet rejection of 10^5.

The cosmic rays detected by ATLAS are muons, but the cosmic muons interact with the detector material and with low rate they knock off δ electrons with energies of several GeV in the detector material. Such events are characterized by a low momentum track which accompanies the muon track and is stopped in the electromagnetic calorimeter. Events with δ electrons are selected with the following cuts. The transverse energy of the stopped track should be greater than 3 GeV ensuring that no low energy muon was stopped. Medium electron cuts guarantee that the shower in the electromagnetic calorimeter has a shape compatible with an electron. Electrons are expected to have a ratio $\frac{E}{p}$ of the energy deposited in the electromagnetic calorimeter and the momentum measured in the inner tracking detector near 1 while $\frac{E}{p} \sim 0$ is expected for minimum ionizing particles as muons; in contrast to muons, electrons as light relativistic particles produce transition radiation.

85 ionization electron candidate events could be extracted from 3.5 million cosmic ray events. When one plots the amount of transition radiation versus $\frac{E}{p}$ for the electron candidate in Figure 6 one gets two areas, the background region with either low $\frac{E}{p}$ or no transition radiation and the signal region with 36 electrons with $\frac{E}{p}$ close to 1 and transition radiation. The observed number of electrons in the signal region is in agreement with Monte-Carlo prediction. The commissioning of the electron identification with cosmic rays is described in more details in an article by J. Kraus in the same volume [3].

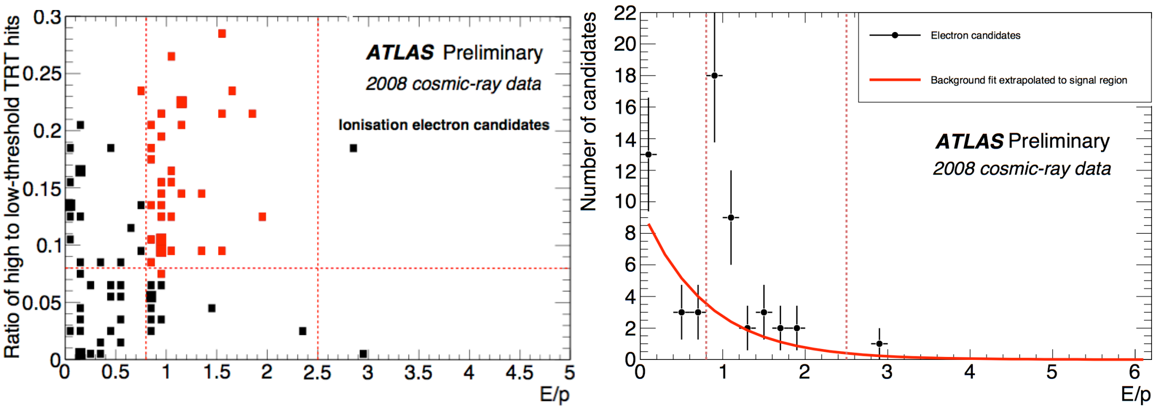

Figure 6: Left: The amount of transition radiation produced by the 85 electron candidates as a function of their $\frac{E}{p}$ ratio. The signal region drawn in red is characterized by the production of transition radiation and $\frac{E}{p} > 1$. Right: Excess of events with $\frac{E}{p} \sim 1$ after the cut on the amount of transition radiation indicated in the left plot.

4. Commissioning of the τ-lepton identification with cosmic rays

There are no τ leptons in cosmic ray events. So τ lepton identification can only be partially commissioned with cosmic ray data. τ leptons are identified through their decays. Leptonic decays are hard to distinguish from single leptons. Hadronic decays can be identified via an analysis of the corresponding jet. There are no hadronic jets in cosmic rays events, but events with electrons or hard muon bremsstrahlung can mimic hadronic jets. It is therefore possible to compare τ identification variables for fakes in cosmic ray events with Monte-Carlo events. This comparison has been done and agreement between real data and Monte-Carlo predictions has been found. As an example the excellent agreement of the measured fraction of the energy in the core of a τ jet candidate with the corresponding Monte-Carlo prediction is shown in Figure 7.

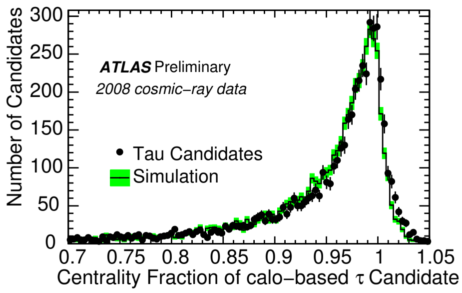

Figure 7: Centrality fraction of calorimeter based τ candidates, i.e. $E_T(\Delta R < 0.1)/E_T(\Delta R < 0.4)$.

5. Summary

Cosmic ray events were used to commission the charged lepton identification in ATLAS. The τ lepton identification could only be partially commissioned because there are no leptons in the cosmic ray events. The distributions of identification variables of fake τ candidates in cosmic ray events were found to agree with Monte-Carlo predictions. The power of the electron identification, especially with the use of transition radiation, was demonstrated by identifying electrons produced by highly energetic muons in the ATLAS detector. The muon identification could be fully commissioned with cosmic ray data by aligning the inner detector and muon spectrometer with muon tracks with an accuracy ensuring nominal momentum resolution for transverse muon momenta below 100 GeV. The muon identification efficiency is as expected. So ATLAS is well prepared for the initial standard-model physics studies with leptonic final states at the LHC.

References

[1] The ATLAS Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider", JINST **3** (2008) S08003.

[2] The ATLAS Collaboration, "Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics", arXiv:0901.0512 [hep-ex].

[3] J. Kraus on behalf of the ATLAS Collaboration, "First observation of electrons in the ATLAS detector", this volume.