Muon performance and related ATLAS first physics

María Moreno Llácer for the ATLAS collaboration
IFIC - Instituto de Física Corpuscular (CSIC-UV), Edificio Institutos de Investigación, Apdo. Correos 22085, E-46071, Valencia - España
E-mail: mamolla@cern.ch

Abstract. Muon final states provide clean signatures for many physics processes at the LHC. Therefore, an excellent identification of muons and momentum resolution in a very wide energy range is required. The performance of the ATLAS muon reconstruction and identification is here studied with the cosmic rays data recorded during the commissioning period and the first LHC proton-proton collision data at $\sqrt{s} = 7$ TeV. Measured resolutions, efficiencies, muon isolation and residual distributions of reconstructed muon tracks are well reproduced by the Monte-Carlo simulation. In addition, the first observation in the ATLAS experiment of W and Z bosons in the muon channel at $\sqrt{s} = 7$ TeV collisions is described. The selection yields to 40 $W \rightarrow \mu\nu$ and 2 $Z \rightarrow \mu\mu$ candidates in a total integrated luminosity of approximately of 6.4 $nb^{-1}$ and 7.9 $nb^{-1}$ respectively, in agreement with Monte-Carlo expectations.

1. Introduction
ATLAS (A Toroidal LHC Apparatus) [1] is one of the four major experiments at the LHC (Large Hadron Collider), in which protons are colliding at a center of mass energy of 7 TeV. It consists of three main sub-systems: the inner detector (ID), the calorimeters (electromagnetic and hadronic) and the muon spectrometer (MS). It uses a superconducting magnet system with a central solenoid around the inner detector and large air-core toroid magnets for the muon spectrometer. The commissioning of the ATLAS detector with physics data already started while the detector was being mechanically and electrically completed by collecting cosmic rays with the parts of the detectors that were becoming available. Several global cosmic rays runs with near all sub-detectors operating at full coverage and with different magnetic field configurations were undertaken. Around 500 million events were recorded in 2008 and 2009 providing the first opportunity to study the performance of the combined reconstruction algorithms with real data. First collisions at 7 TeV took place in March 2010 and near 300 $nb^{-1}$ were collected by ATLAS at the time of the conference. These data have been used to study the detector performance in detail and re-discover the Standard Model. Some examples of this wide spectrum of physics results are presented in this report.

2. Muon reconstruction algorithms
LHC physics requires an excellent muon identification and a very precise momentum measurement in a very wide energy range. For that, four kinds of muon candidates are distinguished in ATLAS depending on the way they are reconstructed: stand-alone muons, combined muons, segment tagged muons and calorimeter tagged muons. The highest quality category of muons are combined muons, i.e. muons that are formed by combining an inner...
Figure 1: Transverse impact parameter (left) and momentum (right) resolution determined from data as a function of transverse momentum. Resolutions of full inner detector (solid triangles) and silicon-only (open triangles) tracks are compared to those from full tracks in Monte-Carlo simulation (stars).

detector track with a muon spectrometer track. Unless stated, we will only consider combined muons in this article.

3. Performance of the muon reconstruction with cosmic ray data

In the absence of LHC beams, the only source of physics signals in the ATLAS detectors are cosmic rays interactions in the atmosphere, which produce muons that can penetrate to the ATLAS cavern and deposit energy in all detector sub-systems. Cosmic rays have been used as part of the commissioning effort throughout the detector installation procedure, starting in 2005. Several global runs with all the detectors operating near full coverage were taken in 2008 and 2009 and more than 500 million cosmic rays were recorded.

Cosmic rays in ATLAS come mostly from above, and arrive mainly via two large access shafts used for the detector installation. Muons crossing the central region sometimes pass near the nominal interaction point. By selecting on track impact parameter with respect to the interaction point, it is possible to identify a sample of projective muons similar to collision-like events. Several analysis have been performed with these data for the inner detector [2] and the muon spectrometer [3].

For the inner detector, the track parameters resolutions have been estimated by splitting the full track into two tracks, an upper and a lower one and comparing their track parameters. On the left plot of Figure 1 one can see the transverse impact parameter resolution as a function of the muon momentum for data and Monte-Carlo. The resolution is dominated by multiple scattering at low $p_T$ and by the intrinsic resolution in the intermediate and high $p_T$ regions.

On the right plot of Figure 1 the relative momentum resolution is shown. The resolution is degraded at high momentum, as expected since particles at high $p_T$ bend less in the magnetic field and make the determination of the curvature more difficult. A fractional momentum resolution of less than 2% is reached for muons of $p_T < 50$ GeV.

In Figure 2 the relative momentum resolution for muons reconstructed in the muon spectrometer is shown. The resolution function can be fitted with the sum in quadrature of three terms, the uncertainty on the energy loss corrections $p_0$, the multiple scattering contribution $p_1$ and the intrinsic resolution $p_2$:

$$\frac{\sigma_{pT}(\text{MuonSpectrometer})}{p_T} = \frac{p_0}{p_T} + p_1 + p_2 p_T$$

(1)
Figure 2: Transverse momentum resolution for stand-alone tracks in the muon spectrometer as a function of the muon transverse momentum.

The results of the fit are in agreement with the expected values but for the intrinsic term, which is sensitive to the alignments which are still in progress. The resolution is close to the nominal one for $p_T < 50$ GeV.

4. Performance of the muon reconstruction with collision data at 7 TeV

Already with the first LHC proton-proton collisions (March 2010), ATLAS devoted a substantial amount of work to understand the detector performance to assure solid physics measurements [4], [5]. In this section, a few examples of performance studies based on a fraction of the processed data at the time of the conference are presented. The data are compared to expectations based on Monte-Carlo simulations. The latter samples were generated at $\sqrt{s}=7$ TeV with PYTHIA [6] using MRST LO [7] PDF, simulated with GEANT4 [8] and fully reconstructed with the same reconstruction algorithms used for data.

4.1. Inclusive muon spectrum

At a center of mass energy of 7 TeV, the main source of muons are light mesons, heavy mesons and Gauge bosons. The left plot of Figure 3 shows the transverse momentum distribution of the reconstructed muons compared to the Monte-Carlo predictions. For the Monte-Carlo, different components in the muon spectrum are distinguished: muons originating from pions or kaons decays which, due to their long lifetime, may cross large part of the detector before decaying and that are reconstructed in the inner detector (green), prompt muons from decays of short-lived particles (red) and others (white). According to the simulation, the spectrum is dominated by light meson decays at low $p_T$, while the contribution from prompt muons becomes more important at high transverse momentum.

4.2. Momentum resolution

The right plot of Figure 3 shows the relative difference of the momentum measured in the inner detector and in the muon spectrometer. The distribution has a narrow core and a tail to positive values. The shape of the distribution is similar in the Monte-Carlo simulation. According to the simulation, the tail of the distribution to positive values is caused by muons from pion and kaon decays-in-flight. There is a larger tail in the measured data than in the simulated distribution, the cause of which was found to be remaining misalignments in one of the endcaps of the inner detector, which has already been improved at the time of writing.
4.3. Validation of muon energy deposits in the calorimeters

Muons inside jets tend to be produced by hadron decays, therefore a powerful tool for selecting prompt muons is the requirement that the muon is isolated. The isolation can be performed in two ways: by applying an upper limit on the energy deposited in a cone around the muon (subtracting the energy deposited by the muon itself), or by cutting on the sum of the transverse momentum of the tracks in a cone around the muon. The size of the cone is typically $0.2 \leq \Delta R \leq 0.4$. The left plot of Figure 4 shows the distribution of the transverse energy deposited in a cone of size $\Delta R = 0.3$ around the muon normalized to the transverse muon momentum for muons with $p_T > 6$ GeV. One can see that muons inside jets have much larger
energy deposits around them. The right plot shows the sum of the transverse momentum of the tracks in a cone of $\Delta R = 0.3$ around the jet for both data and Monte-Carlo. An excellent agreement between the measured and the simulated distributions is achieved.

5. First physics results with muons at 7 TeV collisions

The W and Z bosons are produced abundantly at the LHC, and for the first time in proton-proton collisions. The well known properties of these bosons provide significant constraints in the determination of the ATLAS detector performance, powerful tools to constrain the Parton Density Function (PDF) inside the proton and understanding of these processes as backgrounds to new physics ones. At the time of the conference, the ATLAS experiment had observed 40 $W \rightarrow \mu\nu$ and 2 $Z \rightarrow \mu\mu$ candidates [9], from a total integrated luminosity of approximately 6.4 $nb^{-1}$ and 7.9 $nb^{-1}$ respectively.

5.1. Observation of W production

First of all, collision candidate events are selected by requiring a muon trigger and a primary vertex with at least three tracks. In addition, the muons are required to have $p_T > 20$ GeV, the $E_T^{miss}$ is required to be above 25 GeV and the transverse mass of the W candidate events is required to be $m_T = \sqrt{2p_T^{l}p_T^{\nu}(1 - \cos(\phi^{\nu} - \phi^{l}))} > 40$ GeV. The $m_T$ distribution in the selected events is shown in Figure 5 before and after the $E_T^{miss}$ cut. All events beyond $m_T > 40$ GeV are finally selected as W candidate events. The data are compared to expectations based on Monte-Carlo simulations and both distributions agree quite well. In Table 1, the number of observed data events and the Monte-Carlo predictions are summarized giving the statistical, systematic and luminosity uncertainty in the number of expected signal and background events. The QCD component of the background is estimated from data, while the electroweak component is obtained from Monte-Carlo.

5.2. Observation of Z production

For the Z boson search, candidates are required to contain two isolated muons of opposite charge and $p_T > 15$ GeV. The invariant mass is required to be $80 < m_Z < 100$ GeV. With an integrated luminosity of 7.9 $nb^{-1}$, two Z boson candidates with invariant masses of 80.2 GeV and 87.6 GeV have been observed in the muon channel.

6. Conclusions

The performance of the muon reconstruction algorithms in ATLAS has been studied with the first data available: cosmic rays and first proton-proton collisions at $\sqrt{s} = 7$ TeV. The ATLAS detector has delivered high quality results covering a wide spectrum of physics processes. With
the integrated luminosity collected at the time of the conference, ATLAS has scrutinized the detector performance and reconstructed stable objects. Data and Monte-Carlo comparisons have been performed and have allowed to validate the simulations. The measured track parameters and resolutions and the energy deposition in the calorimeters are well predicted by the Monte-Carlo simulation. In addition, the production of W and Z bosons has been observed.

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