The ATLAS Muon Spectrometer Offline software: achievements in 2011

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The offline software of the ATLAS [1] Muon Spectrometer [1] consists of the full chain of algorithms and service software components that is responsible for processing the data coming from the Muon Chambers, through the trigger/DAQ, to permanent storage in order to reconstruct tracks in the Muon Spectrometer (MS) system. The main steps in the chain are, data decoding and calibration, segment finding, track finding. During data decoding a raw level representation of the detector hits as seen from the Monitored Drift Tubes (MDT), Resistive Plate Chambers (RPC), Thin Gap Chambers (TGC) and Cathod Strip Chambers (CSC) readout systems is obtained out of the bynary files from the DAQ; this first step is referred as bytestream (BS) to Raw Data Objects (RDO) conversion. Then the raw hits are mapped onto the detector geometry and, hence, located in space to represent position measurements; at this level some corrections for hit-level calibration procedures are applied (like t_0 subtraction and time to distance conversion for the drift tubes of the MDT detectors). After decoding, the hits are organized in ordered collections (corresponding to the various physical muon chambers in the MS) in a form prepared for reconstruction. This data format is referred as PRD (prepared raw data) or RIO (reconstruction input objects). The segment finding algorithms use PRD as input, in addition to the geometry representation of the MS detector that allows to select combinations of hits compatible with the hypothesis of coming from a common track.

The complex structure of the Muon Spectrometer requires a high precision alignment system in order to exploit the precision tracking in the three layers of stations typically crossed by high p_T prompt muons. Moreover, in order to estimate the correction to nominal position and orientation of each drift tube, the deformations of the MDT chamber mechanics due to mechanical stresses and temperature variations must be monitored and corrected. Finally, the internal structure of the muon detectors, as defined at the chamber assembly stage must be controlled to an high level of precision. Generally the assembly procedures themselves were defined such to ensure the required accuracy, however in some cases corrections to the design chamber geometry, measured from data or from post-production monitoring procedures, are sizeable and therefore must be taken into account in order to avoid resolution degradation. Fig.1 shows the various contributions to the muon p_T resolution from intrinsic space resolution, alignment uncertainty (assuming design performance of the alignement system), multiple scattering and fluctuations in the energy loss as estimated by Monte Carlo simulations. The alignment is based on a system of optical sensors that monitor relative variations of the chamber positions and deformations and record them at time intervals (or the order of one hour). The output of optical sensor analysis is integrated with the resuts of a track-based absolute alignment procedure in order to provide alignment constants with very fine grained time granularity that, at design performance should be precise at the level of 30 μm in the barrel and 40 μm in the end-cap region.

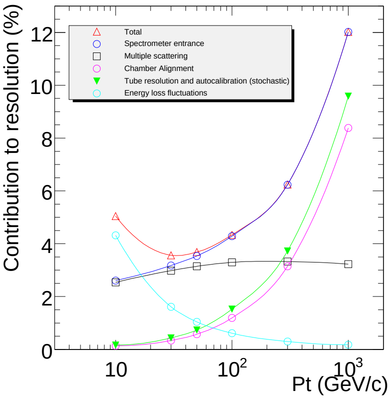

Figure 1. Contributions to the relative p_T resolution for muons reconstructed in the Muon Spectrometer as a function of the transverse momentum. The accuracy of the alignment is assumed to be 30μm.

One of the offline software components that are crucial for the achievement of the design resolution of the muon spectrometer is the service

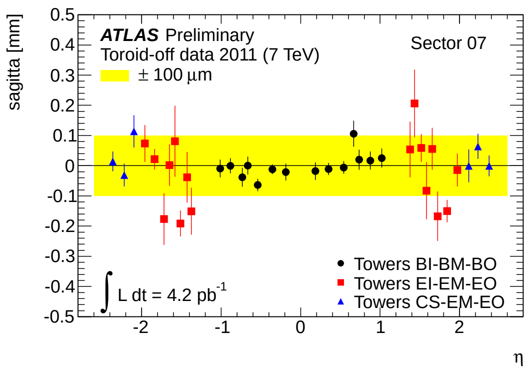

Figure 2. Sagitta mean value for the towers of sector07, observed in the 2011 toroid-o run reprocessed with Atlas offline softare release 17.

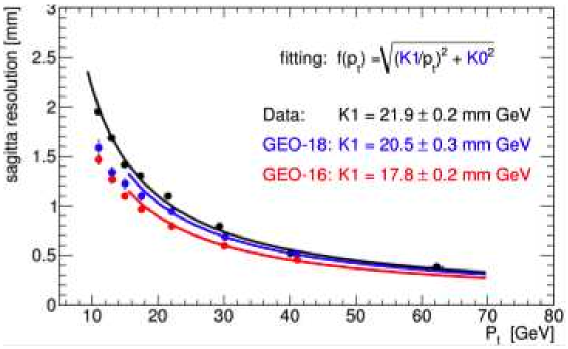

Figure 3. Sagitta resolution as a function of the transverse momentum measured in data and in the ATLAS simulation for 2010 and 2011 (MC10 and MC11) based on the software release 16 and 17 respectively. The plot refers to small sectors in the barrel of the ATLAS MS.

providing the description of the detector geometry `MuonGeoModel`[2] both for data reconstruction and for the ATLAS simulation [3]. The baseline implementation of this service provides an accurate description of the nominal Muon Spectrometer layout. The alignment constants are available through a database and consist of chamber translations and rotations in addition to deformation parameters. A strategy [4] for accessing the database and applying run-time updates of the detector geometry representation at the occurrence of updates of the alignment constants must be implemented in the software in order to reach the required tracking precision. Fig.2 shows the sagitta resolution measured for tracks reconstructed in a run taken with the toroidal magnetic field of the MS off. In these conditions the muon tracks are stright line in the MS and any apparent curvature of the track as reconstructed from hits in the MS is purely a result of uncorrected misalignements of the projective chamber towers. The plot refers to the chamber towers in the 7th azimuthal sector of the spectrometer and the sagitta is measured as the distance between the track reconstructed with the two segments in the inner and other stations and the hits in the middle station whose position is given by `MuonGeoModel`. In the ATLAS offline release 16, used for the prompt reconstruction of 2011 ATLAS data, `MuonGeoModel` was missing the implementation of the MDT chamber deformations. In addition, during 2011 data taking, from the study of the CSC resolution in the data reprocessed with release 16 as a function of the chamber layer and of the distance of the track from the chamber center, correction to the nominal internal geometry of the CSC chambers have been derived. Amongst the major developments of the Muon Software between release 16 and release 17, which whas been used for the full reprocessing of the 2011 data, during Fall 2011, there are the implementation of CSC internal geometry corrections and of the MDT deformation parameters for the stations in the end-caps. This upgrade allowed to bring the sagitta measured on toroid off runs from the values $50 \pm 4\mu m$ (barrel), $113 \pm 10\mu m$ (endcap), $186 \pm 15\mu m$ (CSC region) obtained in release 16 to $54 \pm 4\mu m$ (barrel), $102 \pm 9\mu m$ (endcap), $59 \pm 8\mu m$ (CSC region) in release 17.

The special runs collected with the magnetic field off in the MS can be exploited to study the resolution on the measured apparent sagitta as a function of the muon transverse momentum. After correcting for the tower by tower residual misalignments, the contributions to the sagitta resolution are coming from the intrinsic space resolution achieved with the tracking detectors, which does not depend on the muon transverse momentum, and from the multiple Coulomb scattering that is expected to be proportional to the inverse of p_T. A good description in simulation of the resolution of the ATLAS MS is crucial for the physics program of the experiment, where muon identification and reconstruction play a very important role both in Standard Model measurements and in various searches for unexpected new phenomena. In the analysis model most often pursued, the Monte Carlo simulation is used to predict efficiencies, acceptance for the signal under investigation, resolution, misidentification probability, etc. All those quantities are then extracted from data with dedicated studies typically based on candle physics processes (like resonance production and decays in di-lepton final states) which, however, allow to sample the detector performance on a phase space not always matching the kinematic domain of the searches for new physics. Therefore corrective factors on the detector related performance are derived from the comparison the efficiencies and resolutions measured in data and MC on coherent samples; these corrections are then extrapolated and applied to MC predictions in other kinematic regimes. The systematic uncertainty on the derived measurement increases with the correction factors, i.e. with the disagreement between the MC and the data on control samples. During 2011 an important step forward in the accurate simulation of the Muon Spectrometer has been achieved by refining the description in the software used for data simulation and reconstruction of the materials related to services (cables, electronics boxes mounted on the chambers, detector support rails) which lead to an improved matching between data and MC in the multiple scattering contribution to the p_T resolution. The comparison between the previous Monte Carlo prediction (MC10) and the 2011 simulation is shown in terms of sagitta resolution for straight track runs in fig. 3 where the trend observed in data is in satisfactory agreement with the prediction of MC11.

The overal modeling of the p_T resolution directly impacts on the invariant mass resolution. A very usuful candle process at LHC is production of a Z boson. Its deay to $\mu^+\mu^-$ provides a large statistics for measuring from ATLAS data the performance of the muon identification and reconstruction. Fig. 4 shown how the di-muon invariant mass compares in data and MC using $Z \rightarrow \mu^+\mu^-$ decays. In the top plot the MC superimposed to the data includes the improvements in the inert matter description released in the MS software since ATLAS release 17. In spite of these refinements, the simulation the Z lineshape in MC is affected by a too optimistic resolution. Several studies have been pursued in order to track the subtle mismodeling of the detector performance that can cause such behavior. These studies allowed to identify a residual discrepancy between the emulation of the space resolution of MDT with respect to data which requires some tuning of the drift tube response. However, the most important effect has been shown to be due to the assumption of ideal alignment of the MS in the simulation. Particles produced by the event generators are propagated by Geant4 inside volumes describing the muon detectors that are located and orineted according to the design technical drawings. In addition, when simulated tracks are reconstructed with the same offline software used for offline data reconstruction, the geometry of the MS is again assumed to correspond to the nominal MS layout, without any smearing of the design positions. This situation is clearly different with respect to the real data processing case, where the real ATLAS MS geometry is corrected for shifts and titls of the chambers according to constants provided by the alignment system and determined with the uncertainties discussed earlier. When the MS layout used to reconstruct muons from simulated hits (generated in detectors at nominal positions) is randomly corrected to emulate the known level of undertainty of the alignment, the mass resolution at the Z peak becomes closer to the resolution in real data. The plot at the bottom of Fig. 4, showing the performance of MC12 where realistic alignment is assumed in MC reconstruction demonstrate the gain in data-MC agreement that, based on this study, has been achieved in the preparation of the Simulation for 2012.

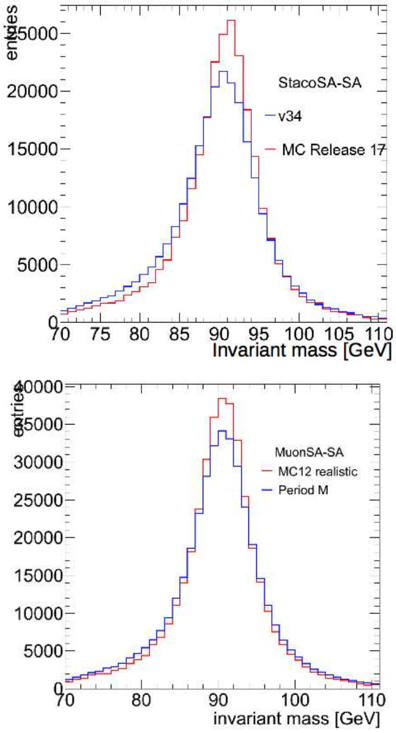

Figure 4. Invariant mass of the $\mu^+\mu^-$ system at the Z pole in 2011 ATLAS data compared with MC11 (top plot) and MC12 (bottom plot). The muon kinematic is measured using the muon tracks reconstructed in the Muon Spectrometer only and extrapolated to the interaction point correcting for energy loss in the calorimeters and the other materials on the muon paths.

Nowadays, most of the effort in the ATLAS software is going into reproducing realistically the detector conditions and tracking them. The main mechanism allowing to follow the time varying conditions is the access to the Conditions database where most of the external conditions affecting the detector performance are stored and can be accessed in data reconstrcutuion in order to understand deviations from the expected behavior. One of the hardware conditions that can lead to a non optimal performace is the occurrence of readout electronics or DAQ errors that prevent the recording of some fragments of the data for a given detector or can lead to a corrupted data format. The consistency of the data coming from the DAQ with the format expected is strictly necessary in order to allow data decoding. Mismatches with respect to the expectations, usually referred as bytestream errors, can be detected while decoding data and allow to flag detector segments that mishaved from the DAQ point of view. The bytestream error detection can be performed online for monitoring purposes; in the offline software the flagging of corrupted events might allow a high level of data quality check preventing use for physics of events with data inconsistencies which might potentially lead to spurious patterns. Recently some development has been done in the context of the MS software for the detection and output in ESD (Event Summary Data) format of the bytestream errors in the RPC system. The RPC data fragment consists of a collection of sixteen Read-Out-Drivers (ROD) for side A and sixteen for side C which are read independently and in sequence during data decoding. An RPC ROD collects data from a pair of adjacent semi-sectors and the two corresponding data fragments are referred as RX. Each RX holds up to eight PAD fragments, which are the data blocks corresponding to the trigger towers belonging to the sector and located in a sequence along the beam direction; they correspond to physical electronic boards implementing readout and LVL1 trigger capability. The PAD consists of 8 Coincidence Matrices, described in the data format by one CM frame each. ROD, RX, PAD, CM data fragments have headers where indices allowing to locate the data block in the system are stored and they are followed by footers, sometime embedding data validity codes issued by the readout electronics. The presence of all expected data markers, like headers, subheaders and footers, and the consistency of the sequence of the data fragments with the official format guarantees the quality of the event and the absence of DAQ errors. A C++ class, following the standard of the ATLAS Event Data Model, has been developed for recording the container of RPC bytestream errors detected per event. All the features necessary in order to represent it in the pool/root format, adopted by ATLAS as persistency model are implemented, thus allowing to stream to disk and read back the container. It consists of a vector of pairs. In the pair a component represent a the key corresponding to the offline PAD identifier hash, which allows to identify in an unambiguous way the PAD within the full RPC system; the second componnet is the associated error code, i.e. an integer number whose values are defined conventionally in such a way to uniquely identify an error condition (examples are missing CM, missing PAD footer, CM with a data transmission error, etc). The vector is filled only with entries corresponding to pads with errors, therefore the size of the error container is very small both in memory and on disk when written in ESD. The identification of errors and filling of the error container is done at the level of BS to RDO ocnversion, in the early stage of the offline event processing. The RPC ROD decoder is responsible for filling the data collection while scanning the bytestream and therefore it's the natural place where the knowledge of the expected data structure can be used to detect anf record in memory error conditions. The error container written in the event store is later available to reconstruction, through a BS-error service that will be able to interpret the information stored in the error container and allow to identify regions of the detector where data are not safely thrustable due to format inconsistencies.

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