

In-situ Determination of the ATLAS Muon Performance

D. López Mateos *on behalf of the ATLAS Collaboration*

*California Institute of Technology, Pasadena, CA 91125, USA
Columbia University, New York, NY 10027, USA*

Abstract. The ATLAS detector allows for the precise and efficient reconstruction of muons. Muon tracks are reconstructed with 97% efficiency with a momentum resolution of approximately 2-3% over most of the kinematic range and better than 10% for transverse momenta up to 1 TeV and $|\eta| < 2.7$. We present methods to measure the performance of the muon identification during the operation of the ATLAS detector using muons from Z and J/ψ decays.

Keywords: LHC, ATLAS, muon spectrometer, reconstruction, muons, tracking, in-situ, Z-boson

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INTRODUCTION

Muons produced in proton-proton collisions at the LHC traverse the ATLAS inner detector and calorimeters before reaching the muon spectrometer[1]. The *stand-alone* muon reconstruction uses the measurement of the muon kinematics provided by the spectrometer. This measurement is corrected for the energy loss in the calorimeters and magnetic field bending to obtain the muon kinematics at the perigee. When possible, this measurement is combined with that of a track reconstructed in the inner detector (*combined* reconstruction). Here, we discuss the performance of the stand-alone reconstruction as obtained with Monte Carlo, and demonstrate how it can be characterized using data[2].

MUON SPECTROMETER PERFORMANCE FROM MONTE CARLO AND DATA

Three variables are studied to benchmark muon performance: efficiency, and momentum scale and resolution. A muon in the Monte Carlo is considered as reconstructed successfully if a reconstructed muon is found within a radius in $\eta \times \phi$ space of 0.05. The momentum scale and resolution are defined as the mean and width of a Gaussian fit to the ρ distribution:

$$\rho = \frac{1/p_{T,\text{rec}} - 1/p_{T,\text{truth}}}{1/p_{T,\text{truth}}}, \quad (1)$$

where $p_{T,\text{rec}}$ ($p_{T,\text{truth}}$) is the p_T of the reconstructed (Monte Carlo generated) muon. Gaussian fluctuations of the spectrometer measurement of the bending in the muon trajectory (*sagitta*) give rise to a Gaussian ρ distribution. However, η and ϕ non-uniformities as well as energy losses lead to tails in the distribution. The influence of

these tails on the fit is minimized by limiting the fit range to 2σ above and below the mean. This fit is repeated recursively until the fit parameters have converged.

Figure 1 shows the efficiency of the spectrometer as a function of muon p_T (left), η and ϕ (center), and its resolution for central muons (right). The efficiency is flat above

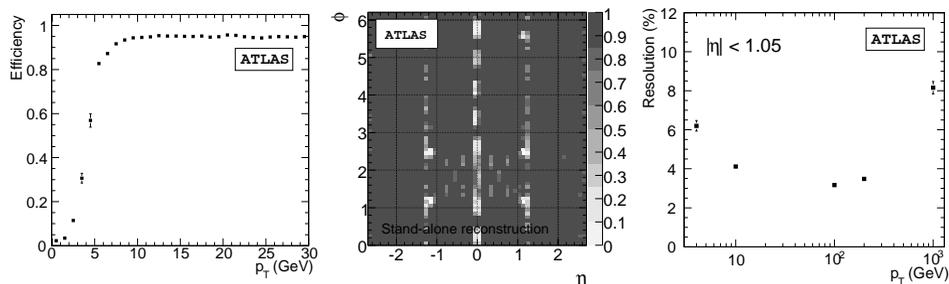


FIGURE 1. Left (center): Muon spectrometer efficiency as a function of p_T integrated over the full geometrical acceptance. Center: Muon spectrometer efficiency as a function of η , ϕ for muons of $p_T = 50$ GeV. Right: Muon spectrometer resolution as a function of p_T for central muons.

$p_T \approx 10$ GeV. Below this p_T , muons do not always cross enough muon chambers for efficient track fitting. The (η, ϕ) efficiency map shows the service gap at $\eta \approx 0$, and the support and service structures at $\phi \approx 1.4$ and 2.4 rad. A reduced number of chambers causes the drop in efficiency at $|\eta| \approx 1.2$. The resolution is dominated by fluctuations of the energy loss in the calorimeters at low- p_T ($\lesssim 10$ GeV), multiple scattering in the muon chambers at mid- p_T (≈ 10 -200 GeV) and chamber resolution at high- p_T .

The performance of the muon spectrometer can be degraded by many effects such as an imperfect knowledge of the magnetic field, chamber calibration and alignment. Some of these effects can be minimized through targeted algorithms. However, residual effects may remain and they need to be measured and, if possible, corrected using data.

The tag and probe method can be used to measure the efficiency of the muon spectrometer. The tag muon reveals the presence of another muon in the event (the probe) that is used to measure the efficiency. The tag muon and the probe candidate are selected to enhance di-muon events and suppress backgrounds. Below we show results using $Z \rightarrow \mu\mu$ events corresponding to 100 pb^{-1} at $\sqrt{s} = 14$ TeV. $J/\psi \rightarrow \mu\mu$ events can be used to measure the efficiency at lower p_T , but this is not explored here.

The tag muon is required to pass the single-muon 20 GeV trigger, be reconstructed in both muon spectrometer and inner detector with $p_T > 20$ GeV, and pass tight calorimeter and tracking isolation cuts. The probe muon is required to be reconstructed in the inner detector, pass the same kinematic and isolation cuts and be away from a reconstructed electron. Both tracks are required to have an invariant mass within 10 GeV of the Z mass, opposite charge and $\Delta\phi > 2$ rad. A cut-flow diagram showing the background suppression as different selection cuts are applied on the probe muon is shown in Figure 2 (left). These cuts leave only 0.02% of selected events originating from background processes.

The efficiency is calculated in the selected sample as the fraction of probe muons reconstructed in the spectrometer: $\varepsilon(\eta, \phi, p_T) = n_{\text{probe}}^{MS}(\eta, \phi, p_T)/n_{\text{tag}}$. Figure 2 shows the efficiency calculated from the tag and probe method and from the Monte Carlo. Both calculations agree within uncertainties. For this study, the spectrometer acceptance was

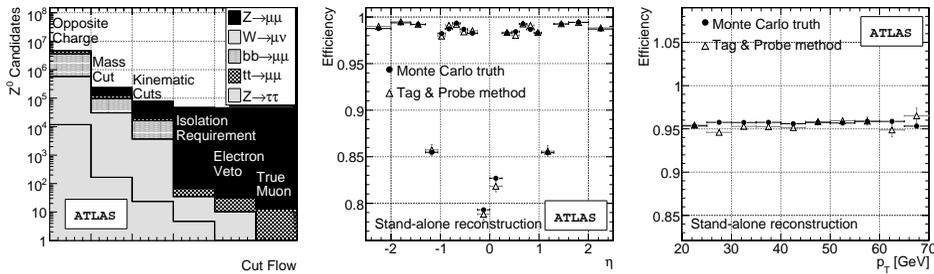


FIGURE 2. Left: Events from background and signal samples surviving the selection cuts on the probe muon. The last cut shows events that contain a true muon matched to the probe muon. Center (right): Efficiency as a function of η (p_T) estimated using the tag and probe method and Monte Carlo truth.

divided in 320 regions. A statistical uncertainty in the efficiency measurement of $\approx 2\%$ can be achieved in each of these regions with an integrated luminosity of 100 pb^{-1} , corresponding to a 0.08% statistical uncertainty on the overall efficiency measurement. The systematic uncertainty of 1% in the overall measurement is dominated by differences between the efficiency obtained with the tag and probe method and the Monte Carlo truth and by uncertainties on the background.

Figure 3 (left, center) shows the performance degradation in momentum resolution and in the reconstruction of the Z peak when large misalignments are added to the simulation. The misalignments considered are prior to the determination of the alignment

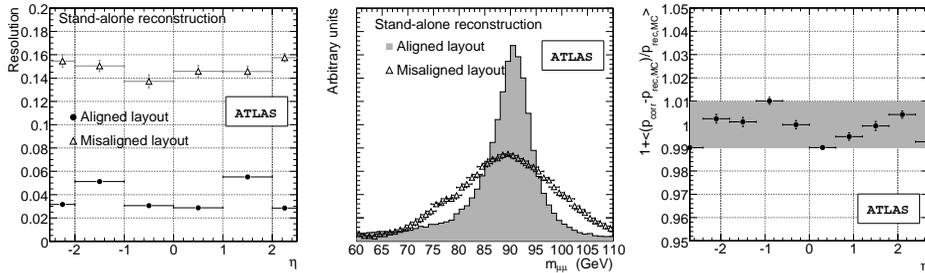


FIGURE 3. Resolution as a function of η for muons of $p_T = 50 \text{ GeV}$ (left) and invariant mass of Z candidates (center) for the ideal and misaligned layouts. Right: Scale dependence of reconstructed muons in the misaligned layout after applying a scale correction calculated from 50 pb^{-1} of simulated data.

constants (from tracks or the optical alignment system) and correspond to $\sim 1 \text{ mm}$ displacements and $\sim 1 \text{ mrad}$ rotations. The current alignment constants tested with cosmic muons already achieve a much better alignment than that assumed for this simulation.

The change in the Z peak shown in Figure 3 suggests that it can be used to detect shifts in the spectrometer scale and changes in resolution. Two important potential sources of performance degradation have been studied: residual misalignments and uncertainties in the energy loss in the calorimeters. These effects are studied individually here, but the methods described may be combined if both effects show similar importance in data.

To study the characterization of the spectrometer performance in the presence of

residual misalignments, a 100 pb^{-1} sample is split in half. Half the sample is used as the Monte Carlo sample, and the remaining half constitutes the ‘data’ sample. The ‘data’ sample is simulated with both an ideal layout and the misaligned layout used in Figure 3. The Monte Carlo sample is simulated with the ideal layout. A smearing, σ , and a scale factor, α are added to the Monte Carlo so that it matches the results obtained with the ‘data’ sample. The scale factor is calculated for two different regions, barrel and end-cap. The fitted smearing and scale factors are consistent with 0, when the ‘data’ sample is simulated with the ideal layout, and are as expected when it is simulated with the misaligned layout (Table 1). Figure 3 (right) shows the residual η dependence of the

TABLE 1. Scale factor and smearing added to the Monte Carlo sample in order to match the ‘data’ sample.

Layout	$1 - \alpha_{\text{barrel}}$	$1 - \alpha_{\text{end-cap}}$	σ
Ideal	$(4 \pm 14) \times 10^{-4}$	$(1 \pm 13) \times 10^{-4}$	-
Misaligned	$(6 \pm 2) \times 10^{-3}$	$(5 \pm 2) \times 10^{-3}$	$(11.6 \pm 0.3)\%$

muon scale after the scale factor is applied, demonstrating that this procedure determines the muon momentum scale to within $\approx 1\%$ with 50 pb^{-1} .

For muons below 100 GeV, 5% of additional material results in a 150-MeV shift in the momentum scale. This bias can be identified by fitting a change in energy loss in $Z \rightarrow \mu\mu$ events. The corrected muon momentum serves as input to the fit χ^2 function:

$$\chi^2 = \sum_{\mu^+\mu^- \text{ pair } k} \frac{(p_{+,k}^{\text{corr}} + p_{-,k}^{\text{corr}})^2 - M_Z^2}{\sigma_k}, \quad (2)$$

where $p_{\pm}^{\text{corr}} = p_{\pm} + \delta E_{\text{loss}}$ are the corrected values of the muon momenta, δE_{loss} is the fitted energy loss difference between data and Monte Carlo, and σ is the expected resolution of the invariant mass measurement. This fit is performed in simulated data using 320 δE_{loss} variables corresponding to the different detector regions used in the tag and probe study. A 100 MeV statistical uncertainty in the fit variables is achieved with 100 pb^{-1} . This demonstrates that the energy loss correction can be measured to within $\sim 5\%$ using this method.

CONCLUSION

Techniques to measure the performance of the ATLAS muon spectrometer with collision data have been developed. The techniques have been tested with Monte Carlo samples corresponding to $50\text{-}100 \text{ pb}^{-1}$ integrated luminosity at $\sqrt{s} = 14 \text{ TeV}$. An accuracy of better than 1% in the overall reconstruction efficiency can be achieved. Biases in the energy loss correction above 100 MeV can be detected and corrected. Momentum scale biases above 1% arising from residual misalignments can also be detected and corrected.

REFERENCES

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2. G. Add *et al.* (ATLAS Collaboration), Expected Performance of the ATLAS Experiment: Detector, Trigger and Physics, CERN, Geneva (2008), CERN-OPEN-2008-020, arXiv:0901.0512