Muon identification and performance in the ATLAS experiment

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Muon reconstruction and identification play a fundamental role in many analyses of central importance in the LHC run-2 Physics programme. The reconstruction and identification of muons with transverse momentum from a few GeV to the TeV scale at ATLAS, is presented. The performances are measured in data based on the decays of Z and J/ψ to pairs of muons, that provide a large statistics calibration sample. Reconstruction and identification efficiencies are evaluated, as well as momentum scales and resolutions, and the results are used to derive precise MC simulation corrections. Reconstruction efficiency also in presence of high pileup is presented.

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1. Introduction

During the 2013-2015 shutdown the LHC was upgraded to increase the centre-of-mass energy from 8 to 13 TeV. The ATLAS detector was upgraded, too, and the muon reconstruction software was improved. We present the performances of the ATLAS muon identification and reconstruction using the LHC dataset recorded at $\sqrt{s} = 13$ TeV.
A detailed description of the ATLAS detector can be found in Ref.[1]. In order to identify and reconstruct muons produced in pp collisions in ATLAS we use information from the Inner Detector (ID) and muon spectrometer (MS), supplemented by information from the calorimeters. The ID consists of three subdetectors: the silicon pixels (Pixel) and the semiconductor tracker (SCT) with a pseudorapidity coverage up to $|\eta| = 2.5$, and the transition radiation tracker (TRT) with a pseudorapidity coverage up to $|\eta| = 2.0$. The ID measures the muon track close to the interaction point, providing accurate measurements of the track parameters inside an axial magnetic field of 2 T. The MS is the outermost ATLAS subdetector. It is designed to detect muons in the pseudorapidity region up to $|\eta| = 2.7$, and to provide momentum measurements with a relative resolution better than 3% over a wide p_T range and up to 10% at $p_T \simeq 1$ TeV . The MS consists of one barrel ($|\eta| < 1.5$) and two endcap sections ($1.05 < |\eta| < 2.7$). A system of three large superconducting air-core toroidal magnets, each with eight coils, provides a magnetic field with a bending integral of about 2.5 Tm in the barrel and up to 6 Tm in the endcaps. Resistive plate chambers (RPC, three doublet layers for $|\eta| < 1.05$) and thin gap chambers (TGC, one triplet layer followed by two doublets for $1.0 < |\eta| < 2.4$) provide triggering capability to the detector as well as (η, ϕ) position measurements with typical spatial resolution of $5 - 10$ mm. A precise momentum measurement for muons with pseudorapidity up to $|\eta| = 2.7$ is provided by three layers of monitored drift tube chambers (MDT), with each chamber providing six to eight η measurements along the muon trajectory. For $|\eta| > 2.0$, the inner layer is instrumented with a quadruplet of cathode strip chambers (CSC) instead of MDTs. The single-hit resolution in the bending plane for the MDT and the CSC is about 80 and 60 μm, respectively. The muon chambers are aligned with a precision between 30 and 60 μm. During the shutdown preceding the LHC Run 2, the MS was completed to its initial design [2] by adding the last missing chambers in the transition region between the barrel and the endcaps ($1.0 < |\eta| < 1.4$). Four RPC-equipped MDT chambers were also installed inside two elevator shafts to improve the acceptance in that region compared to Run 1. Some of the new MDT chambers are made of tubes with a smaller radius compared to the ones used in the rest of the detector, allowing the detector to cope with higher rates.

2. Reconstruction and Muon Identification

Muon reconstruction is first performed independently in the ID and MS and then the information are combined to form the muon tracks for physics analyses.

Four muon types are defined depending on which and how subdetectors are used in the reconstruction: 1. *Combined*, muon tracks are reconstructed in the MS and are associated to ID tracks; 2. *Segment-tagged*, ID track is extrapolated to the MS; 3. *Calo-tagged*, ID tracks associated with an energy deposit in the calorimeter; 4. *Stand-alone*, muon tracks are reconstructed only in the MS.

Four muon identification selections are provided to address specific needs of different physics analysis: 1. *Loose*, maximizes reconstruction efficiency; 2. *Medium*, minimizes systematic uncertainties; 3. *Tight*, maximizes the purity of muons at the cost of $3-4\%$ loss in efficiency; 4. *High-p_T*, maximizes momentum resolution for $p_T > 100$ GeV. A new selection, Low-p_T, has been implemented for muon identification below 5 GeV [3] .

3. Reconstruction Efficiency

Muon reconstruction is performed independently in the ID and MS detectors, using different methodology and then we combine the two; we measure the efficiency to resonstruct an MS track and combine it with an ID track. Reconstruction efficiency is measured using the tag-and-probe method [4] applied to the $Z \to \mu\mu$ and $J/\Psi \to \mu\mu$ events

- $Z \to \mu\mu$ decays provide a sample of probes with $p_T > 15$ GeV
- $J/\Psi \to \mu\mu$ decays provide a sample of probes with $2.5 < p_T < 20$ GeV

Muon efficiencies are extracted separately from simulation and data as a function of probe p_T and as a function of η. In Figure 1 (left) reconstruction efficiency, for the Medium muon selection as a function of the p_T of the muon, is shown in the region $0.1 < |\eta| < 2.5$, as obtained with $Z \to \mu\mu$ and $J/\Psi \to \mu\mu$ events. The error bars on the efficiencies indicate the statistical uncertainty. The

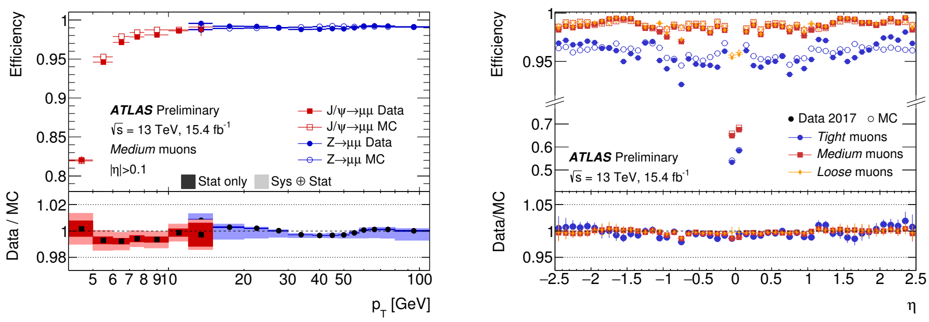

Figure 1: Left: Reconstruction efficiency for the Medium muon selection as a function of the muon p_T, in the region $0.1 < |\eta| < 2.5$. The bottom panel shows the ratio of the measured to predicted efficiencies, with statistical and systematic uncertainties; Right: Muon reconstruction efficiencies for the Loose/Medium/Tight identification algorithms measured in $Z \to \mu\mu$ events as a function of the muon pseudorapidity for muons with $p_T > 10$ GeV. The bottom panel shows the ratio between expected and observed efficiencies, the efficiency scale factor. The results in both figures are based on 15.4fb^{-1} of data collected in 2017 [5].

ratio of the measured to predicted efficiencies, with statistical and systematic uncertainties is also reported in the panel at the bottom of the plot. This ratio provides scale factors, which are close to unity. Efficiency is reduced in the MS crack region, i.e.$|\eta| < 0.1$, on account of gaps between muon chambers for ID and calorimeter services. The results are based on 15.4 fb^{-1} of data collected in 2017. Effect of multiple pp interations in one bunch crossing (pile-up, $<\mu>$) on the reconstruction efficiency has been study up to $<\mu>= 60$. In Figure 2 the muon reconstruction efficiency for the Medium identification algorithm measured in $Z \to \mu\mu$ events as a function of $<\mu>$ for muons

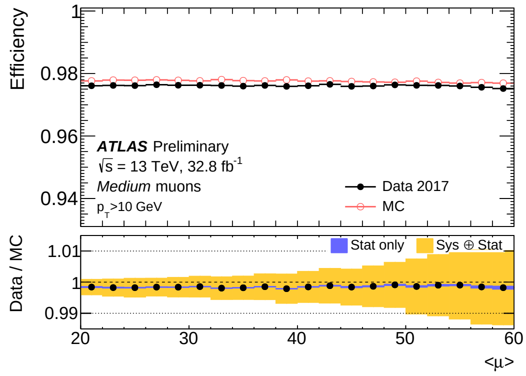

Figure 2: Muon reconstruction efficiencies for the Medium identification algorithm measured in $Z \to \mu\mu$ events as a function of the pileup for muons with $p_T > 10$ GeV [6].

with $p_T > 10$ GeV, is shown, comparing detector simulation with observation in collision data. The bottom panel shows the efficiency scale factor. Blue band shows the statistical error; orange band the quadratic sum of statistical and systematic uncertainty.

4. Momentum Scale and Resolution

The data-driven calibration of the simulated muon momentum resolution and scale is obtained using a simultaneous template fit to $Z \to \mu\mu$ and $J/\Psi \to \mu\mu$ events. The momentum scale is known to per-mill level and the resolution to a few per-cent [4]. In order to obtain such level of agreement between data and simulation, a set of corrections is applied: p_T and η distributions of the Z and J/Ψ resonances in simulation are reweighted to the distributions observed in data. Figure 3 shows the dimuon mass ($m_{\mu\mu}$) resolution as a function of pseudorapidity (η) obtained from reconstructed $Z \to \mu\mu$, on the left, $J/\Psi \to \mu\mu$ candidates on the right. The data are compared to simulation.

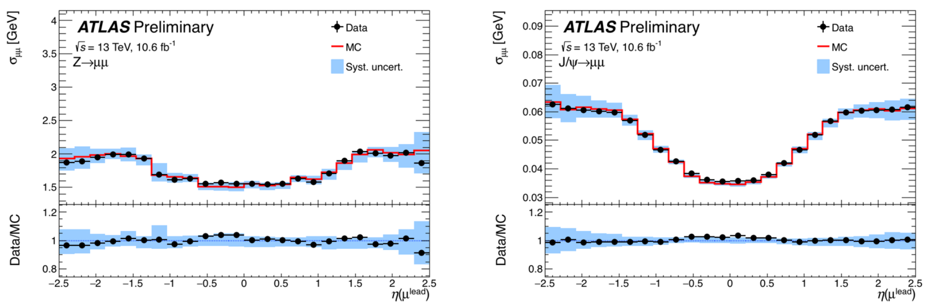

Figure 3: Left: Dimuon mass ($m_{\mu\mu}$) resolution as a function of pseudorapidity (η) obtained from reconstructed $Z \to \mu\mu$, on the left, $J/\Psi \to \mu\mu$ candidates on the right. The data are compared to simulation [7].

Figure 4 shows the transverse momentum (p_T) scale as a function of pseudorapidity (η) obtained from reconstructed $Z \to \mu\mu$ (figure on the left), $J/\Psi \to \mu\mu$ (figure on the right) candidates.

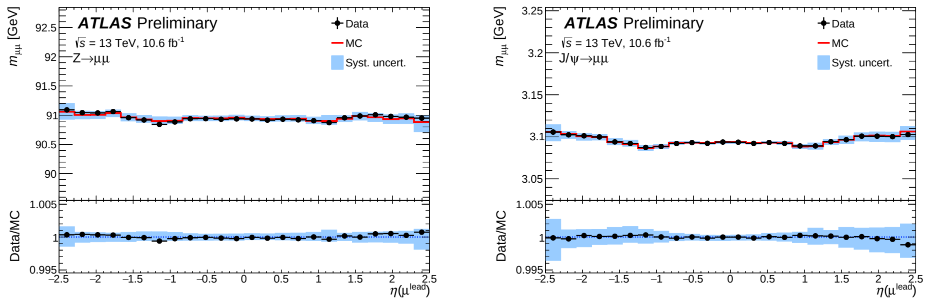

Figure 4: Transverse momentum (p_T) scale as a function of pseudorapidity (η) obtained from reconstructed $Z \to \mu\mu$ (left), $J/\Psi \to \mu\mu$ (right) candidates. The dataset, consisting of 10.6 pb^{-1} of proton-proton collision data collected in 2016 by the ATLAS detector at a centre-of-mass energy of $\sqrt{s} = 13$ TeV (filled markers), is compared to prompt Z (left)/J/Ψ (right) simulation (continuous line). The continuous line corresponds to the simulation with the momentum corrections applied. The band represents the effect of the systematic uncertainties on the momentum corrections. Simulations are normalised to data [7].

5. Conclusion

The performance of the ATLAS muon reconstruction has been measured using data from pp collisions at $\sqrt{s} = 13$ TeV recorded during the run at the LHC in 2017. A large calibration sample consisting of $Z \to \mu\mu$ decays and $J/\Psi \to \mu\mu$ decays allows for a precise measuremenre of the reconstruction and isolation efficiency as well as of the momentum resolution and scale over a wide p_T range. The muon reconstruction efficiency is close to 99% over most of the pseudorapidity range of $|\eta| < 2.5$ for $p_T > 5$ GeV. The muon momentum scale and resolution have been studied in detail using the two samples to correct the simulation and improve the agreement with data and to minimise systematic uncertainties in physics analyses.

References

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[7] https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/MUON-2016-004/index.html