Muon forward reconstruction efficiencies with $Z \rightarrow \mu^+\mu^-$ with the ATLAS data from the LHC pp run at $\sqrt{s} = 13$ TeV

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1. Introduction

The ATLAS [1] muon spectrometer (MS) is designed to reconstruct muons, providing an independent measurement of momentum from their curvature in a toroidal magnetic field.

The MS is the outermost ATLAS sub-detector. It detects muons in the pseudorapidity [1] region up to $|\eta| = 2.7$ and determines momentum measurements with a relative resolution better than 3% over a wide p_T range and up to 10% at $p_T \approx 1$ TeV.

The MS consists of one barrel ($|\eta| < 1.05$) and two end-cap sections. A system of three large superconducting air-core toroidal magnets produce a magnetic field with a bending integral of approximately 2.5 Tm in the barrel and up to 6 Tm in the end-caps. A detailed description of the ATLAS detector can be found in Ref. [1]. Measurements from the Inner Detector (ID), the MS, and the calorimeters, is used to identify and precisely reconstruct muons produced at the Large Hadron Collider (LHC).

A tag-and-probe method, described in detail in Ref. [2,3], is employed to measure the reconstruction efficiencies of muons within the acceptance of the ID ($|\eta| < 2.5$). The measured efficiency in data is then used to correct the the residual mis-modeling of the detector response in simulation by applying data to Monte Carlo (MC) scale factors (SF) to the simulated samples.

The tag-and-probe method is sensitive to the ID reconstruction efficiency, and to the MS reconstruction efficiency together with the efficiency of combining the ID and MS measurements. The tag-and-probe analysis is based on the selection of a pure muon sample from $Z \rightarrow \mu^+\mu^-$ event requiring one leg of the decay (tag) identified as a Medium quality [3] muon and firing the trigger and the second leg (probe) reconstructed from an independent system with respect to the one that is measured.

The muon reconstruction efficiency measurement in the pseudo-rapidity region $|\eta| < 2.5$ is driven by the ID acceptance. Above $|\eta| \sim 2.5$ the muon standalone reconstruction provides the main contribution to the efficiency. It is therefore important for physics analyses, which need to exploit the full MS acceptance in order to increase their sensitivity, to estimate the reconstruction efficiency SF in the range $2.5 < |\eta| < 2.7$, hereafter called high-η.

2. The high-η SF extraction method

In order to extract the reconstruction efficiency SF for the high-η muons a typical tag-and-probe method cannot be applied since there is no acceptance from the ID to provide the probe track [3]. The reconstruction efficiency SF is instead calculated from the double ratio

$$SF = \left[\frac{N(data)}{N(MC)}\right]^{Z\rightarrow\mu\mu}_{|\eta|>2.5} \Big/ \left[\frac{N(data)}{N(MC)}\right]^{Z\rightarrow\mu\mu}_{2.2<|\eta|<2.5} . \tag{1}$$

In equation 1, the numerator is the ratio of $Z \rightarrow \mu\mu$ candidates in data over MC for which one of the muons is reconstructed in the high-η region, in this case called the *probe*, while the other leg of the Z decay can be anywhere below $|\eta| = 2.5$, called the *tag* muon. The denominator of equation 1 is the ratio of $Z \rightarrow \mu\mu$ candidates in data over MC with the probe muon in this case lying in region $2.2 < |\eta| < 2.5$,

[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r,φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln[\tan(\theta/2)]$. Transverse momentum and energy are defined as $p_{\mathrm{T}} = p\sin\theta$ and $E_{\mathrm{T}} = E\sin\theta$, respectively.

hereafter called control region. Again, the tag muon is allowed to be anywhere within the region $|\eta| < 2.5$. The backgrounds for the tag-and-probe selection, in both numerator and denominator of equation 1, are estimated with simulation and subtracted from the data.

3. Tag and Probe Selection

For the evaluation of both the numerator and denominator of equation 1, the selection the tag muon follows tight quality requirements to ensure a high purity sample of muons as described in Ref. [3]. Table 1 summarizes the selection requirements on the probe and the tag-probe system.

Reconstruction efficiency scale factors are applied for the tag muon and also for the probe muon in the control region. Event trigger scale factor and trigger matching is applied for the tag muon. In this manner is possible to remove from the double-ratio (equation 1) any residual bias due to the mis-modeling in MC of the probe and tag reconstruction efficiency as well as tag trigger efficiency.

Probe Selection requirements		
	p_T	> 20 GeV
High-η region	Quality	loose
	$\lvert\eta^{num}\rvert$	$2.5 - 2.7$
Control region	Quality	medium
	$\lvert\eta^{den}\rvert$	$2.2 - 2.5$
Tag-Probe Selection requirements		
	Opposite charge	
Invariant mass		$\lvert M_Z^{PDG} - M_{\mu\mu}\rvert < 10GeV$

Table 1
Probe muon selection criteria. Note that η^{num} corresponds to the η requirement of the numerator of equation 1 while η^{den} corresponds to the denominator as described in the text.

4. Systematic Uncertainties

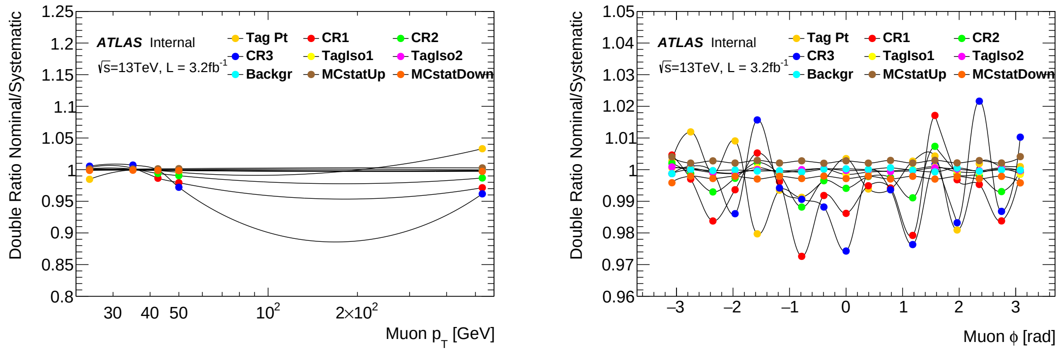
The main source of systematic uncertainties considered in the SF measurement are derived from the variation of properties of the tag muon and the control region which is selected for the denominator of the double ratio. For the tag muon the p_T and isolation requirements are variated from their nominal values.

A systematic due to the control region definition is also extracted. Three additional control regions are used to act as the denominator in the double ratio formula. These are denoted as CR1, CR2, and CR3 and correspond to the cases where the probe muon is in the η range [2.0,2.2], [2.0,2.5] and [-2.5,2.5] respectively. The control region showing the largest difference from the nominal value of the double-ratio is considered as the systematic uncertainty due the control region selection.

The uncertainty due to the background subtraction is estimated by assuming 100% uncertainty on the MC estimation for all considered backgrounds. The uncertainty due to the MC statistics is estimated by varying up and down the MC yield in the double ratio by its statistical uncertainty and taking the difference from the nominal; the total uncertainty due to MC statistics is then taken as the average of the up and down variations.

The systematic uncertainty from the MC modeling of the $Z \to \mu\mu$ process is obtained from the strategy adopted in the Run-1 measurement [3]. The overall uncertainty due to this source is of the order of $\sim 0.5\%$.

Figure 1 show the effect of the different sources of systematic uncertainties described above on the high-η muon SF with respect to the nominal SF value, as a function of the probe p_T and ϕ respectively.



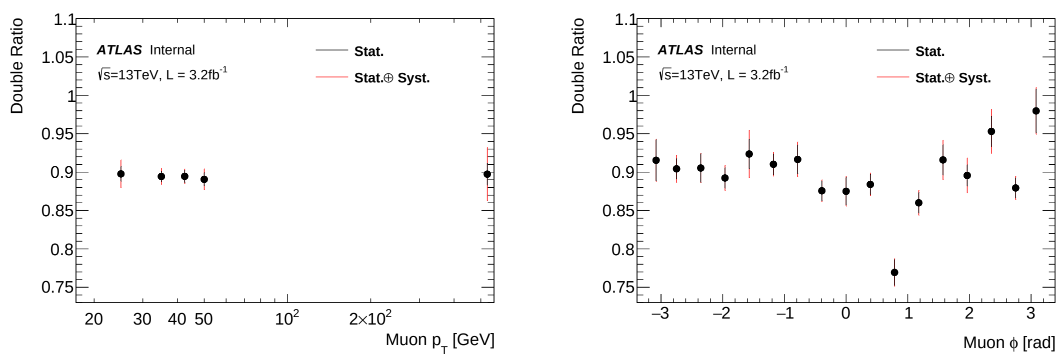
(a) (b)

Figure 1. Summary of the effect of different sources of systematic uncertainties (see text) on the high-η muon SF with respect to the nominal SF value, as a function of the probe $p_T$and ϕ.

5. Results

The reconstruction efficiency SF for high-η muons is computed according to equation 1 and provided as a function of the probe p_T and ϕ. Results are illustrated in Figure 2 (a) and (b) for p_T and ϕ respectively. The systematic uncertainties are considered to be uncorrelated and are added in quadrature to obtain the total systematic uncertainty shown on the plots of Figure 2 (a) and (b).

In most of the bins the SF measurements deviates from one by about 10%. The dependence of the double ratio on the probe p_T is flat while the dependence on ϕ exhibits fluctuations. The precision of the measurement is of about 2-3% in all the p_T and ϕ bins.



(a) (b)

Figure 2. Reconstruction efficiency scale factor as a function of the probe muon p_T and ϕ. Black error bars correspond to the statistical uncertainty while the red error bars correspond to the statistical and systematic uncertainty added in quadrature.

REFERENCES

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