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Performance of ATLAS RPC Level-1 muon trigger during the 2015 data taking

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Abstract: RPCs are used in the ATLAS experiment at the LHC for the muon trigger system in the barrel region, which corresponds to a pseudorapidity range of $|\eta| < 1.05$. The status of the system during the 2015 data taking is presented, including measurements of the RPC detector efficiencies and of the trigger performance. The RPC system has been active in more than 99.9% of the ATLAS data taking, showing very good reliability. The RPC detector efficiencies were close to Run 1 and to design values. The trigger efficiency for the high-p_T thresholds used in single-muon triggers has been approximately 4% lower than in Run 1, mostly because of chambers disconnected from HV due to gas leaks. Two minor upgrades have been performed in preparation of Run 2 by adding the so-called feet and elevator chambers to increase the system acceptance. The feet chambers have been commissioned during 2015 and are included in the trigger since the last 2015 runs. Part of the elevator chambers are still in a commissioning phase and will probably need a replacement at the end of 2016.

Keywords: Large detector systems for particle and astroparticle physics; Particle tracking detectors (Gaseous detectors); Trigger detectors

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Contents

1 Introduction

RPCs are used in the ATLAS experiment at the LHC for the first-level (L1) muon trigger in the barrel region, which corresponds to the pseudorapidity range of $|\eta| < 1.05$. The system has been operated successfully during the first LHC run in 2009–2012 (Run 1), in which protons have been collided at center-of-mass energies up to $\sqrt{s} = 8$ TeV, at instantaneous luminosity of up to 8×10^{33} cm^{-2}s^{-1} and with a typical time interval between colliding bunches of 50 ns [1, 2]. Run 2 started in 2015, providing *pp* collisions at $\sqrt{s} = 13$ TeV with an interval between colliding bunches of 25 ns. The expected maximum luminosity during Run 2 is about 10^{34}cm^{-2}s^{-1}. These new conditions are providing a more challenging environment to the RPC muon trigger. To prepare the system to Run 2, a consolidation campaign has been performed during the long shutdown 2013–2014, including small upgrades to increase the trigger acceptance. This note reports the system status and the performance measured during 2015, the first year of Run 2 operations. Section 2 describes the status of the system and the upgrades performed in preparation for Run 2, section 3 presents the status of the RPC detectors and section 4 describes the performance of the trigger system. Finally section 5 gives a summary of this report.

2 System status and Run 2 upgrades

The ATLAS RPC system consists of three layers of RPC doublets in which each gas volume is read out with two sets of orthogonal strips with a width of 23–35 mm that read the η and the ϕ (azimuthal) coordinates. The RPC electrodes are made of bakelite, with a gas gap of 2 mm and are operated in avalanche mode with a gas mixture of $C_2H_2F_4$: iso-C_4H_{10} : SF_6 in the proportion (94.7 : 5.0 : 0.3)% at 4.8 kV/mm. In ATLAS there are 3714 RPC gas volumes with a total surface of ≈4000 m^2. The RPCs are used for the L1 barrel muon trigger, for muon reconstruction to measure the azimuthal coordinate of tracks in the muon spectrometer [4], and to provide a time measurement useful to reject cosmic muons and to search for delayed signals from high-mass long-lived particles expected in certain extensions of the Standard Model [5].

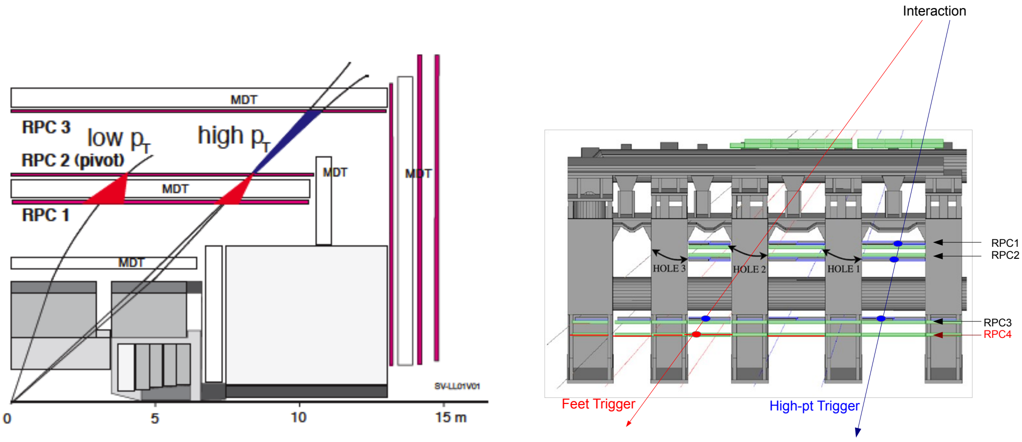

Figure 1. Schematic drawing of the ATLAS L1 Barrel muon trigger system. Left: standard sector with low-p_T and high-p_T triggers. Right: "feet" sector with acceptance holes due to support structures and, in red, the fourth RPC layer.

The main source of RPC failures during Run 1 has been the breaking of the gas inlets/outlets of the gas volumes. Approximately 400 inlets/outlets, out of ≈8000, have developed leaks during Run 1. In some cases the leaks implied that one or more gas volumes had to be disconnected from HV. During the long LHC shutdown 2013–2014 an intense repair campaign was conducted and at the end of the shutdown most of the leaks have been repaired except in approximately 60 cases. Currently the total gas flow in the system is approximatively 5000 l/h, with an inflow of fresh gas of 700 l/h that compensates leakages. To improve the detection of gas leaks, a new monitoring system based on sensitive flow meters placed at the outlet of each chamber has been developed. Six sectors out of 16 have been fully equipped with the new flow-meters. The installation of the new flow-meters in the remaining sectors will be completed in the winter break 2016–2017.

The ATLAS L1 barrel muon trigger is described in [3] and is shown in figure 1 (left). The trigger system consists of two halves (positive and negative η) each divided into 32 azimuthal sectors. Each sector is divided along η in projective towers. Two kinds of muon triggers are provided: low-p_T triggers that are based on a coincidence between the innermost two layers of RPCs and are used to select muons with p_T thresholds between 4 and 10 GeV, and high-p_T triggers that require an additional coincidence with the outer RPC layer and are used to select muons with p_T thresholds between 11 and 20 GeV. The high-p_T triggers are used to select events based on single-muon signatures, while low-p_T triggers are only used in coincidence with other trigger objects to select multi-object signatures, including muon pairs.

Two minor upgrades have been performed in preparation of Run 2. The geometrical acceptance of the L1 muon barrel trigger in Run 1 was limited to 78% for the high-p_T triggers. This was in part caused by acceptance limitations in the lower part of the ATLAS muon spectrometer that includes structures to support the weight of the ATLAS detector (the so-called feet) and two elevator shafts for the access to calorimeters and to the inner part of the muon system. To increase the geometrical acceptance, a fourth layer of RPC chambers has been installed in the "feet" region since the construction of ATLAS. As shown in figure 1 (right), thanks to the non-projective geometry of the support structures, these additional chambers allow to cover most of the holes caused by the feet structures with a coincidence between the third and the forth RPC layers, recovering approximately 2.8% of the barrel acceptance. These chambers were not equipped with services and electronics during ATLAS construction due to budget limitations and thus were not operational during Run 1. In the long shutdown 2013–2014 the feet chambers have been instrumented and included in the trigger system as new special trigger towers. To cover the ≈1% acceptance holes corresponding to two elevator shafts, new chambers have been installed: a special movable muon station (BME) with two layers of RPC detectors of new type, with 1 mm gas gaps, plus a further chamber (BOE), equipped with standard ATLAS RPCs, placed in the trench below ATLAS, have been installed. Feet and elevator chambers have been in commissioning phase during most of 2015. While the commissioning of the feet and of BOE chambers has been completed, the BME chambers have hardware problems and will need a refurbishment, currently foreseen for the 2016–2017 winter break.

3 RPC detector operation and performance

During the 2015 data-taking period, ATLAS collected an integrated luminosity of 3.9 fb^{-1} of pp collision data at a center-of-mass energy of 13 TeV. Most of the data have been collected with a time interval of 25 ns between crossings of colliding proton bunches, to be compared to the 50 ns of Run 1. The maximum luminosity was 5.0×10^{33} $\text{cm}^{-2}\text{s}^{-1}$. The RPC system has been active in more than 99.9% of the ATLAS data taking, showing very good reliability.

Different tools have been developed to monitor the detector performance. Most basic quantities, such as hit maps, checks of consistency in the readout, etc., are performed by the online data quality system that continuously samples RPC data. A more detailed monitoring is run offline, after full event reconstruction, to provide detector and trigger efficiencies, detailed timing information etc. A dedicated data set is used to obtain an unbiased sample of muons to be used as a probe to measure the RPC response. It contains events selected by non-muonic triggers in which a muon has been identified using information from the inner detector and from precision muon chambers.

Figure 2 shows the distribution in $\eta - \phi$ in the middle RPC plane of hits associated to a high-p_{T} trigger. The acceptance holes related to the feet/elevator regions at $-1 < \phi < -2$ are visible. Regions within the RPC coverage with low counts may indicate inefficient detectors. This is seen more quantitatively in the distribution of the number of strips that are not providing signals (dead strips) within each strip panel shown in figure 3 (left). A strip panel is the set of η or ϕ strips that reads a particular gas volume. The total fraction of dead channels is 3.5%. The peak at zero shows panels in which all strips are operational, while the peak at one shows whole panels that are not providing signals, which are approximately 2% of the total. Most dead panels are caused by gas volumes that have been disconnected due to gas leakages or HV problems. Approximately 0.25% of panels are accounted as dead because of failures of the readout electronics. The panels with a fraction of dead strips between 0 and 1 are related to readout problems or to strips that have been masked because of high noise levels, typically related to grounding problems.

The RPC detector efficiency has been measured using reconstructed muon tracks, extrapolating them to the RPC measurement plane, and checking if hits associated to the track are found. Figure 3 (right) shows the distribution of the efficiency for each gas volume. Two kinds of efficiency are shown, one is called “gap efficiency” and is defined as the probability that a hit is found in at

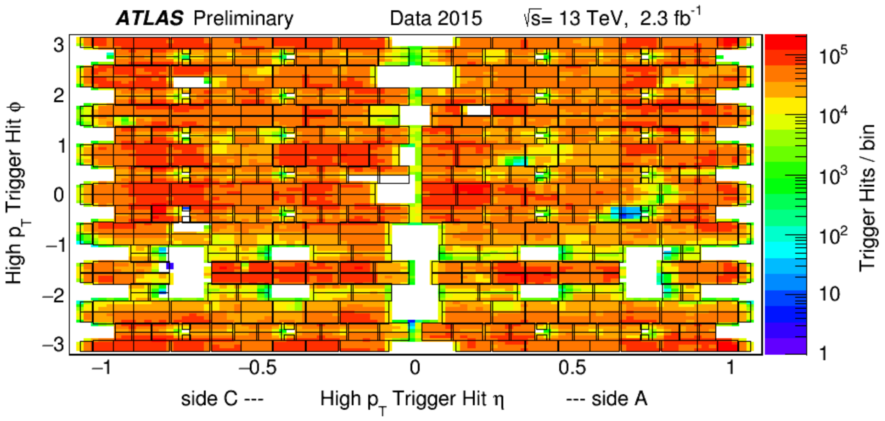

Figure 2. RPC trigger coverage. Distribution of RPC trigger hits in the pivot layer associated with a high-p_T trigger, shown in terms of the η and ϕ strip coordinates. The black lines indicate the contours of individual RPC chambers. Data from *pp* collisions collected in 2015 with 25 ns colliding bunch spacing [6].

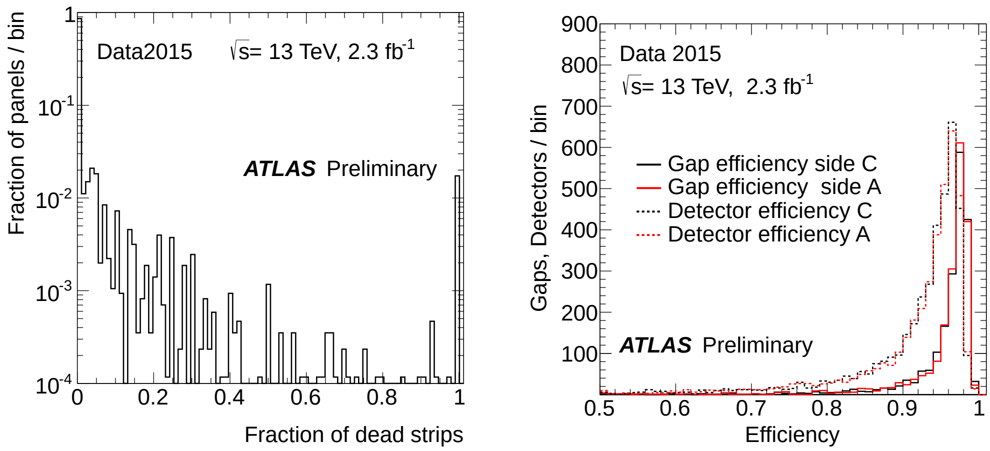

Figure 3. Left: distribution of the fraction of "dead" strips per readout panel for both views. Right: distribution of the measured RPC "gap efficiency" of each gas volume, defined by the presence of hits on at least one of the two strip panels (η and ϕ), and of the "detector efficiency" for each strip panel, defined by the presence of hits in the strip panel. Data from *pp* collisions collected in 2015 with 25 ns colliding bunch spacing [6].

least one of the two readout panels (η or ϕ) facing the gas volume. The other is called "detector efficiency" and is evaluated independently for each panel (η, ϕ) as the probability to find a hit in the panel. Being a logical OR of the two panels, the gap efficiency is insensitive, to first order, to inefficiencies due to the readout electronics of the panels. Thus the gap efficiency is always larger than the detector efficiency and is expected to be close to the intrinsic RPC detector efficiency. The distribution of the gap efficiency peaks at 98%. The inefficiency due to the RPC gap spacer is expected to account for 1% of the observed inefficiency.

Other RPC operational parameters are constantly monitored, for example the cluster size. Figure 4 shows the distribution of the cluster size and the average cluster size per panel in 2015. For clusters with less than nine strips, the average cluster size is 1.64 strips, consistent with the Run 1 result.

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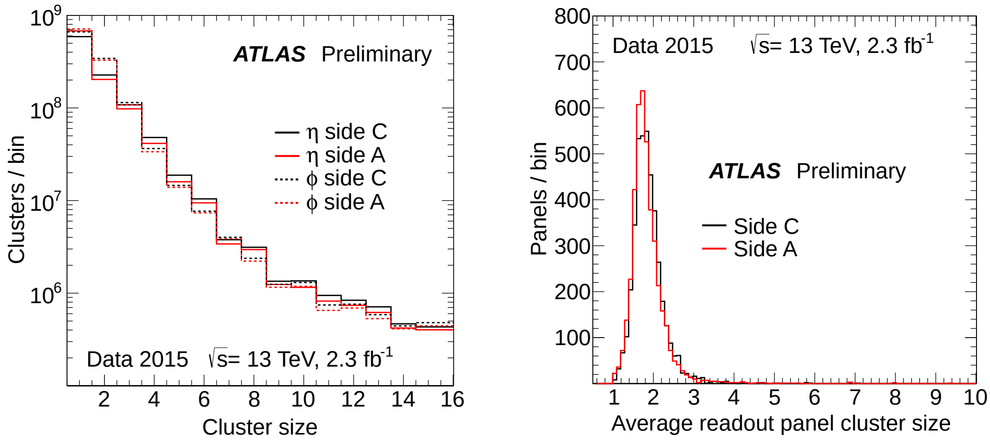

Figure 4. Left: distribution of RPC cluster size separately for the η and ϕ strips and for the two ATLAS sides ($\eta < 0$ for side C and $\eta > 0$ for side A). Right: distribution of average RPC cluster size for each readout panel. Data from pp collisions collected in 2015 with 25 ns colliding bunch spacing [6].

4 Trigger performance

One important requirement of the L1 trigger system is the association of the triggering muon to the correct collision bunch crossing (BC). This is of particular importance in Run 2 because of the reduced interval between colliding BCs with respect to Run 1. Figure 5 (left) shows the time distribution of the trigger hits associated to reconstructed muons, compared to the interval corresponding to the collision BC. The fraction of reconstructed muons with $p_T > 10$ GeV associated to the correct BC is 99.7%. The width of the trigger time distribution is $\sigma = 2.9$ ns and is dominated by the propagation of signal along the strips and by imperfection of the online calibration used in the trigger hardware. These effects can be corrected offline to provide a time resolution at reconstruction level of ≈ 2 ns [7].

The new feet trigger towers have been commissioned during the 2015 data taking. All the towers have been finally included in the trigger at the end of 2015, during the special runs taken at a reduced center of mass energy of 5 TeV. The fraction of triggers associated to the correct BC is shown in figure 5 (right) for all the L1 Muon Barrel trigger towers. The areas marked with a red contour correspond to the new feet towers. All the feet towers were operational, but not all were correctly calibrated to give a good BC identification.[1] The figure also shows two holes corresponding to the towers associated to the BME elevator chambers that were still in commissioning at the end of 2015.

Another important requirement of the trigger system is to keep the trigger rate at an acceptable level. The ATLAS L1 trigger has to reduce the input event rate of 40 MHz to less than 100 kHz of events to be passed to the software-based higher-level trigger that applies a more refined selection. During 2015, approximately 10 kHz of the ATLAS L1 trigger output have been allocated to single-muon triggers, and a larger fraction to dimuon triggers. The lowest p_T threshold for single muons was kept at 15 GeV (MU15) and a threshold of 4 GeV was used for muon pairs. The barrel system has a very good purity, with about 90% of the MU15 triggers that correspond to

[1]The timing calibration of the feet towers has been completed with the first 2016 data.

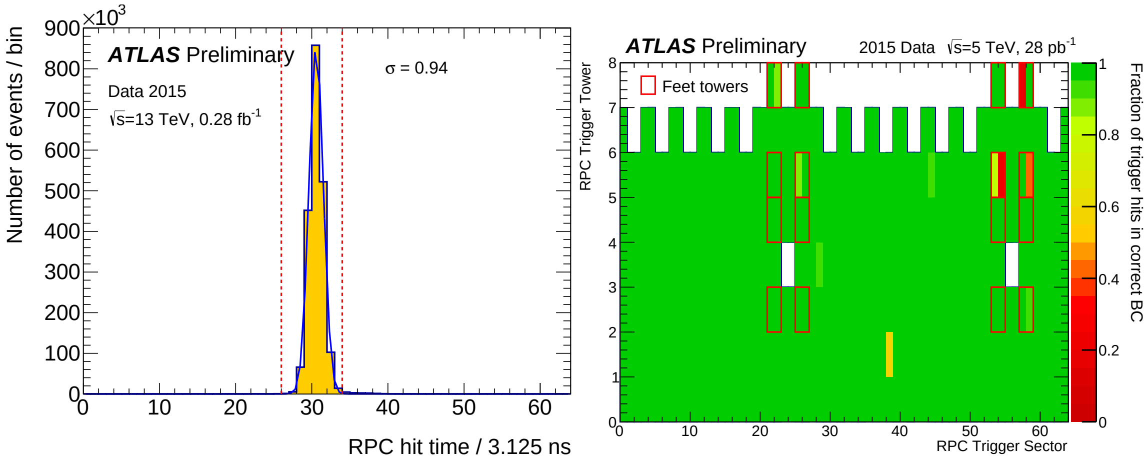

Figure 5. Left: RPC hit time distribution for trigger hits, measured from readout data (yellow histogram), and its gaussian fit (blue line). The red dotted lines identify the collision Bunch Crossing (BC). One time unit on the horizontal axis is 1/8 of a BC (3.125 ns). The horizontal axis covers the readout window in which data are collected that corresponds to 8 BCs. Data from a *pp* run at $\sqrt{s}$ = 13 TeV. Right: fraction of RPC trigger hits associated correctly to the collision BC for each of the 428 Barrel Muon trigger towers. The red contours show the new trigger towers of the feet chambers. One tower with hardware problems (Tower=2, Sector=38) is visible as an orange area. The two white areas (Tower=3, Sector=23, 24, 55, 56) correspond to the "elevator" chambers, not yet commissioned in 2015. Data from *pp* runs at $\sqrt{s}$ = 5 TeV, integrated luminosity L=28 pb^{-1} [6].

a good muon reconstructed offline and originating from the interaction region. Figure 6 (left) shows the distribution in η of the L1 single muon triggers. The barrel region $|\eta| < 1.05$ accounts approximately 20% of the total single muon rate. The larger fraction of triggers in the end-caps ($|\eta| > 1.05$) is partly due to the contamination of fake triggers that don't correspond to real muons. Since most of the triggers in the barrel correspond to real muons, the main handles to reduce the rate are the value and the sharpness of the p_{T} thresholds. Figure 6 (right) shows the efficiency turn-on curve as a function of p_{T} for the MU15 threshold, compared with the threshold of $p_{\mathrm{T}} = 20$ GeV applied in the software higher-level trigger which applies full tracking using the information from the precision chambers in addition to the RPCs.

The other important parameter for the trigger system is its efficiency. The trigger efficiency × acceptance is monitored run-by-run using reconstructed muons from events selected by independent triggers. Figure 7 shows the L1 efficiency × acceptance for muons with $p_{\mathrm{T}} > 15$ GeV and $|\eta| < 1.05$ in a run taken during 13 TeV collisions, when the feet towers were not yet commissioned, as a function of ϕ and η of the muon. Measurements are shown for a low-p_{T} (MU10) and for a high-p_{T} (MU11) threshold. The periodic structures seen as a function of ϕ are caused by the acceptance limitations in the odd sectors due to the support structures of the toroid magnet coils, while the two dips at ϕ around -2 and -1 correspond to the feet structures. The dips as a function of η also correspond to the support structures of the magnet. The average efficiency × acceptance is 76/68% for MU10/MU11, to be compared to 78/72% at the end of 2012. To better understand the source of the trigger inefficiency, the data are compared to a special MC simulation that includes a realistic description of the dead or inefficient RPC panels, taken from the measurements described in section 3. The simulation gives a satisfactory description of the trigger efficiency measured in

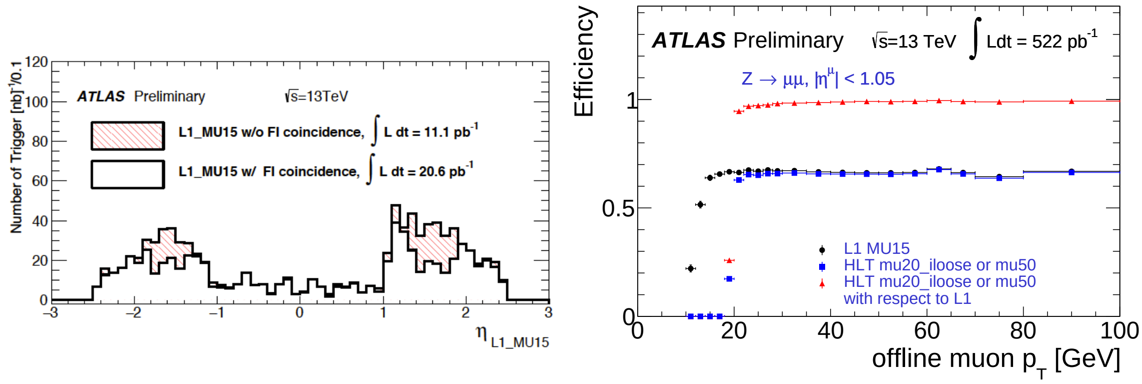

Figure 6. Left: η distribution of the ATLAS L1 muon triggers with a p_T threshold of 15 GeV (MU15). The region with $|\eta| < 1.05$ corresponds to the barrel RPC trigger. The empty/dashed histograms show the distribution for runs with or without an additional coincidence with the inner forward layer (FI), applied to reduce the trigger rate in the "endcap" region $1 < |\eta| < 2$ [8]. Right: efficiency × acceptance of the L1 threshold MU15 in the barrel as a function of the transverse momentum of the reconstructed muon, as measured from $Z \to \mu\mu$ decays. The efficiency of the software higher-level trigger (HLT_mu20iloose or mu50) is also shown as well as its efficiency with respect to L1 [9].

the data. Residual difference between data and MC simulation are ascribed to inefficiencies of the trigger electronics (1%) and to localized areas in which the RPC efficiency measurement was not available. The decrease in efficiency with respect to Run 1 can be ascribed mostly to RPCs disconnected from HV.

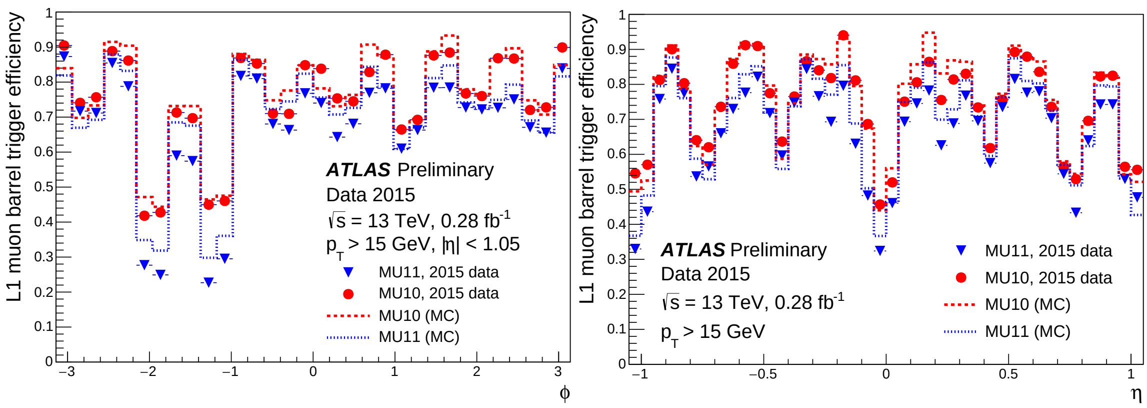

Figure 7. Efficiency of the barrel muon trigger for reconstructed muons with $p_T > 15$ GeV and $|\eta| < 1.05$. Left: efficiency as a function of ϕ for two thresholds: MU10 ($p_T > 10$ GeV, selected with a coincidence of the two inner RPC stations) and MU11 ($p_T > 10$ GeV selected with a further coincidence with the outer RPC stations). The dashed histograms show the results from a special MC simulation which includes measured efficiencies of the RPC chambers. Right: efficiency as a function of η. Results from a MC simulation including realistic RPC inefficiencies are also shown [6].

5 Summary and outlook

The RPC-based ATLAS muon trigger has been operating reliably during 2015. The performance of the RPC detectors has been monitored continuously. Detector efficiencies are stable and similar to

Run 1 and to design values. The fraction of dead strips is 3.5%, dominated by disconnected gas gaps due to gas inlet breaks. The L1 barrel trigger has been running with a lowest-p_T threshold for single muons of 15 GeV with very low rate. The trigger efficiency has been approximately 4% lower than in Run 1, mostly because of chambers disconnected from HV due to gas leaks. Two minor upgrades have been performed in preparation of Run 2 by adding the so-called feet and elevator chambers. The feet chambers have been commissioned during 2015 and have been part of the standard trigger since the last 2015 runs. Part of the elevator chambers are still in commissioning phase and will probably need a refurbishment at the end of 2016.

Run 2 will continue with the present RPC system until 2018. In 2019 new chambers (BIS78), equipped with triplets of new generation RPCs with 1 mm gaps, will be installed to improve the endcap trigger in the region $1.05 < |\eta| < 1.3$. For the High-Luminosity LHC phase, that is planned to start in 2026, the ATLAS RPC community is proposing a major upgrade of the barrel trigger, by adding a new internal layer of RPC triplets that will increase the geometrical coverage of the system and improve its robustness [10].

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