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CMS RPC performance and operation in LHC Run 3

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on behalf of the CMS Collaboration

Abstract

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CMS RPC performance and operation in LHC Run 3

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Abstract

The CMS experiment has collected more than 180 fb^{-1} of proton-proton collision data at a 13.6 TeV center-of-mass energy in Run 3 data taking (2022, 2023 and 2024). The CMS RPC system faces the challenge of the LHC delivered instantaneous luminosity of up to 2 x 10^{34} cm^{-2}s^{-1}, providing redundant information for robust muon triggering, reconstruction and identification. To ensure stable data taking, the CMS RPC collaboration has performed a series of detector operation, calibration and performance studies, including the development and maintenance of various software monitoring tools. The detector operation and overall performance at 13.6 TeV, as well as the encountered problems and their corresponding solutions are documented in this report.

Keywords: Resistive Plate Chambers, CMS Experiment, gaseous detectors

1. Introduction

Four different gaseous detector technologies are used to build up the Muon system [1] of the Compact Muon Solenoid (CMS) experiment [2], [3], ensuring its focus on delivering excellent muon triggering and identification, as well as charge and transverse momentum measurement. The central barrel region utilizes Drift Tubes (DT), covering pseudorapidity ($|\eta| < 1.2$), Cathode Strip Chambers (CSC) and Gas Electron Multipliers (GEM) constitute the endcap region ($0.9 < |\eta| < 2.4$) and ($1.5 < |\eta| < 2.2$) respectively, and Resistive Plate Chambers (RPC) are used in both regions, covering pseudorapidity up to ($|\eta| < 1.9$), as shown in Fig. 1

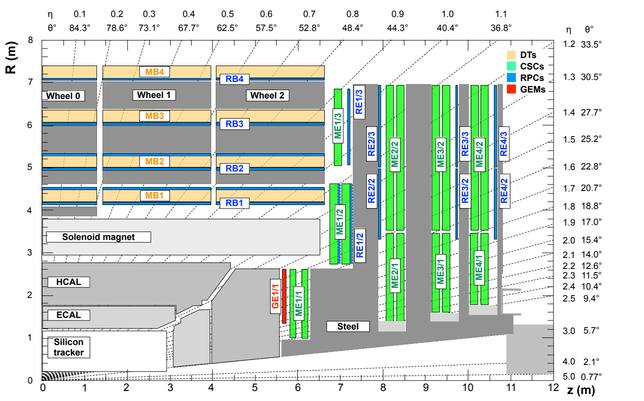


Figure 1: Schematic view in the *r*–*z* plane of a CMS detector quadrant at the start of Run 3 [3].

With a total number of 1056 double–gap chambers, covering an area of about 3950 m^2, the CMS RPC system is the largest muon detector in the experiment. Each chamber has a copper strips readout plane located between the top and the bottom gaps [1] and consists of 2 gaps with 2 mm gas gap width each. High-pressure laminate (HPL) with bulk resistivity in the range of 2–5 $\times 10^{10}$ $\Omega \cdot$ cm is used to build each of the detecting gaps, where the High Voltage (HV) is applied to graphite electrodes coated on it. In the barrel, the strips are rectangular in shape with a pitch width in the range between 2.28 and 4.10 cm, while in the endcaps they are trapezoidal with a pitch width between 1.74 and 3.63 cm [3].

To ensure the good and stable performance of the chambers, the RPC are operated in avalanche mode at 35–45% relative humidity with a 3-gas-component mixture – 95.2% Freon ($C_2H_2F_4$), to enhance the ionization caused by incident particles, 4.5% Isobutane (iC_4H_{10}), used to clean the signal, controlling the secondary ionization and 0.3% Sulfur hexafluoride (SF_6) used as a electronegative gas to reduce the streamer formation.

The barrel region of CMS RPC system is divided in the direction along the beam axis into 5 separate wheels (W0, W±1 and W±2), covering the pseudorapidity up to ($|\eta| < 1.2$), while each endcap region has a total number of 4 stations (RE±1, RE±2, RE±3, RE±4), covering the pseudorapidity range ($0.9 < |\eta| < 1.2$) [1]. Each barrel wheel has 12 sectors in azimuthal angle ϕ and 4 stations (RB1, RB2, RB3, RB4), while every endcap station has 36 sectors. Due to requirements in the trigger logic, the chambers are divided into two or three pseudorapidity (η) partitions, called rolls. In most of the barrel detectors, there are two rolls: forward and backward. Only 60 barrel chambers are divided into three rolls, 1 per each azimuthal sector in every wheel (RB2in in W±1 and W0 and RB2out in W±2), called forward, middle and backward (stations RB1 and RB2 have two chambers per sector called IN and OUT, the IN chamber is closer to the center and the OUT chamber is farther away). The endcap RPC detectors are divided into three rolls: A, B, and C, where roll C is the one located towards the center [3], [4], [5].

The specific design of the CMS RPC system, combined with the well calibrated operating conditions, allows the chambers to cope with high background rates and ensures an excellent time resolution of about 2 ns. It also contributes to the lower absolute number of adjacent fired strips in a single muon hit (called cluster size) of less than 3. These are important parameters that directly impact the muon bunch crossing (BX) assignment (particles in the Large Hadron Collider (LHC) travel in bunches, colliding every 25 ns), ensuring precise and fast muon detection and identification [3].

During the ongoing LHC Run 3 data taking, for the period from 2022 to 2024, the CMS detector recorded ~180 fb^{-1} and the RPC system contributed very efficiently with its stable performance during the entire period.

2. CMS RPC Operation in Run 3

2.1. RPC Calibration

To ensure the stable operation for the RPC system, the high voltage (HV), applied to each chamber, is controlled in a way, which allows the effective high voltage to be constant, even when environmental conditions change during the data taking. The optimal operating voltage for every chamber, called Working point (WP), is determined after a series of high voltage scans [6], regularly performed once or twice per year, typically in low and high luminosity conditions.

The HV scan is taken at effective, equidistant voltages within the working range of 8600 to 9800 V. The RPC hit efficiency is obtained using the Segment Extrapolation Method [4], where the RPC efficiency is measured as the ratio between the number of detected and the number of expected hits. Segments (DT in the barrel and CSC in the endcap) that belong to a standalone muon track with timing corresponding to the time of the RPC readout windows (called bunch crossing - BX) are selected and extrapolated to the plane of a given RPC. The detector unit is considered efficient if an RPC reconstructed hit is found within ± 4 strips from the position extrapolated from the DT/CSC segment.

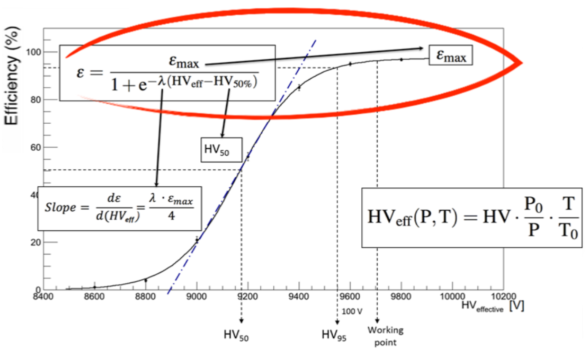


Figure 2: RPC HV scan Sigmoid fit of the efficiency data points, taken at effective voltage (corrected for pressure variations). The efficiency for every single RPC eta partition (roll) is calculated and fitted for each calibration HV scan run [6]

A sigmoid function is used to fit the efficiency data points, taken at effective voltage, as shown on Fig. 2, where the maximum efficiency is ϵ_{max}, the effective high voltage is HV_{eff}, the voltage at which the fit efficiency is 50% of its maximum value is $HV_{50\%}$, and λ represents the slope of the sigmoid function at HV_{50} [7]. The HV WP is defined as the voltage at 95% efficiency, also known as Knee (before the plateau) of the efficiency curve, plus 100 V for barrel and 120 V for endcap [7]. A few differences in the assembly parameters of the chambers (geometry, size, layout, electronics) define the small difference in HV between barrel and endcap detectors [3].

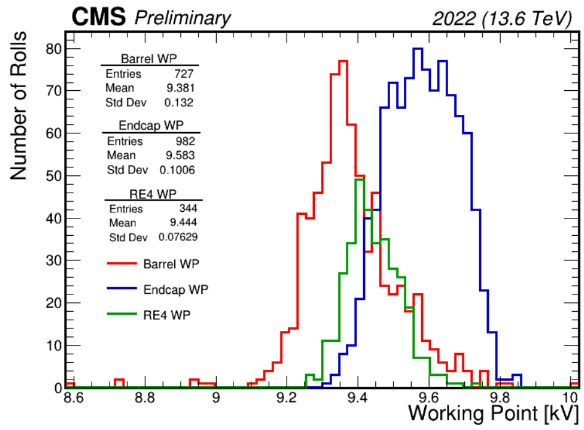


Figure 3: RPC HV Scan Working Point (WP) distribution for 2022 [8].

Figure 3 presents the HV WP distribution for the different parts of the RPC system, as obtained with 2022 data. All sigmoid fits which have failed to fit the data are excluded from the sample, therefore the underflows and the overflows of the distribution are zeros. The clean sample (without the excluded rolls), containing approximately 75% of the rolls, is quite representative. What causes fits to fail may vary between missing extrapolations from other muon detectors and hardware problems like chambers OFF, chambers in single-gap operation mode or rolls with higher number of inactive (masked) electronic channels (strips). In 2024, a new machine learning approach was used to analyze RPC HV scan data with the aim of minimizing the number of failed fits [9].

RPC HV scans are used also to study the stability of the HV working points in time, as well as the efficiency at WP. Figure 4 shows the evolution of the efficiency as a function of time, as determined from the HV scan data, evaluated at the WP and at HV at 50% efficiency during the LHC Run 1, Run 2 and Run 3. Despite the changes in the environmental and luminosity conditions, the different calibrations implemented in the detector allowed the system to keep the efficiency stable.

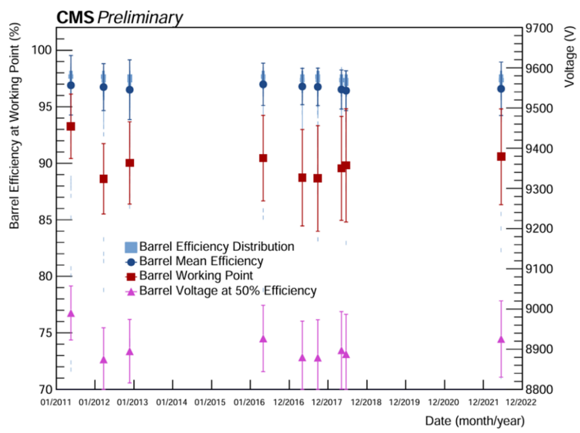


Figure 4: Temporal evolution of efficiencies determined from HV scan data at the WP and at HV at 50 %, for the barrel [8].

In addition to all WP validation scans, the good and stable operation and performance of the RPC system is regulated by special HV and low voltage (LV) maintenance procedures, following regulated access time slots, called technical stops (TS), during the data taking. The HV maintenance aims to identify all problematic channels and parts of the HV power system and fix them in the best feasible way. This allows the recovery of HV lines and change of the detector operation mode from a single-gap to a double-gap one, resulting in better performance of the detectors. The LV maintenance aims to ensure flawless operation along the communication buses, precise functionality of the LV power boards, as well as proper operation and configuration of the on-detector electronics, including the Front-end Boards (FEBs) and the LV distribution boards (LVDB).

2.2. RPC Gas System and green-house emission strategy

The standard CMS RPC gas mixture is composed mainly of fluorine composed gases (F-gases) with high global warming potential (GWP) of about 1400. In accordance with CERN wide emission reduction policy, RPC were obliged to reduce Green House Gases (GHG) emissions. In order to achieve this goal a newly developed "freon (R134a) recuperation system" developed by CERN EP-DT group (Cern gas group) was implemented in Run 3 (2023) [10]. RPC group defined a strategy to reduce overall gas loss of the system by disconnecting the leaking channels (each gas channel provides gas to 2 RPC chambers) in order to have gas in the exhaust and to operate the freon recuperation system in most efficient way. The freon recovered from the recuperation system was further reinjected into RPC gas system.

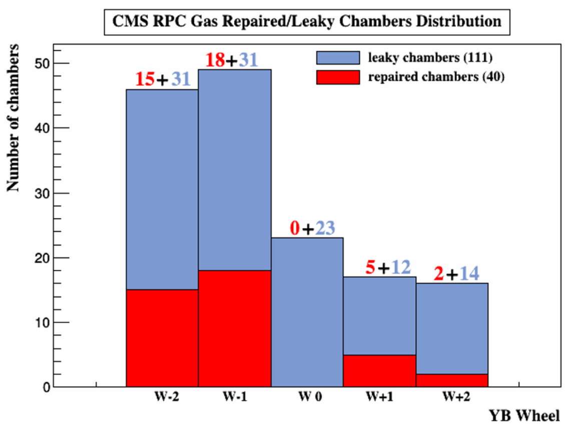
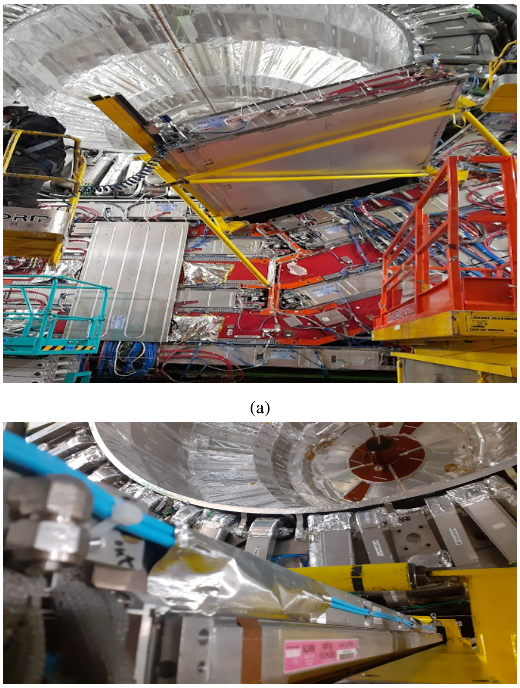


Figure 5: Distribution of leaking and recovered gas chambers per wheel: the gas status of CMS RPC barrel chambers as of March 2024.

The RPC gas system is a 13 m^3 closed-loop volume with recirculation of 7.3 m^3/h nominal mixture flow: 5 m^3/h for the barrel and 2.3 m^3/h for the endcaps. The increase in the leak rate of the system can be caused by a combination of factors including bad quality components (gas tubes and connectors) and operation (abnormal gas stops). In addition, switching from freon to Nytrogen (N_2) and back to freon during technical stops, as well as environmental conditions in the experimental cavern, such as humidity and temperature, can accelerate the degradation process of the different components of the system.

The main cause for development of gas leaks in the CMS RPC system are the low-density polyethylene pipes that deteriorate in time becoming brittle or cut due to time aging, as well as the T-shaped or L-shaped polycarbonate gas connectors that break due to stress applied through the gas pipes [3].

The distribution of the gas leak repairs and the number of leaks in all five barrel wheels as of March 2024 is shown in Fig. 5. A total number of 111 gas leaking chambers, caused by cracked or broken pipes are identified in the RPC system barrel region. The number of gas disconnected chambers is 145 – 110 gas leaking chambers and 35 chambers (not leaking, but sharing a gas channel with leaking chamber), which can be recovered and put back in operation in case of available access during any of the LHC Year "End" Technical Stops (YETS).



(a)

(b)

Figure 6: Representation of the new full extraction gas leak reparation protocol: extracted chamber for leak repairs in W−2 during YETS 23/24 (a) and repaired chamber with external (blue) pipes (b).

Following the CMS GHG reduction strategy, resulted in disconnecting ∼14% of the RPC system in the barrel. In order to recover this large fraction of disconnected chambers, a new gas leak reparation protocol was validated during the YETS 23/24. A full DT/RPC barrel station (two RPC chambers with a DT chamber in between) was fully extracted, as shown in Fig. 6 (a), which allows access for improvement of all weak points, relevant for leak development - replacement of all polyethylene pipes and T-shaped and L-shaped connectors inside the RPC detectors.

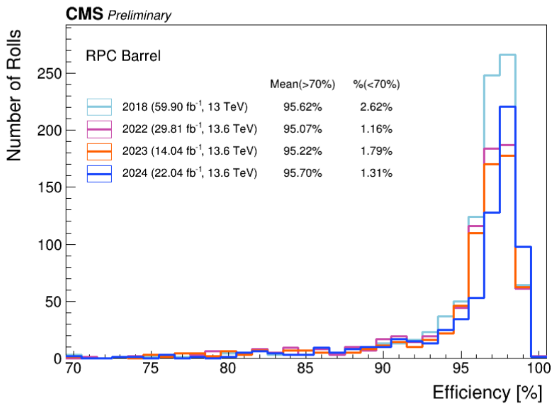
During YETS 23/24, two DT/RPC stations in W−2 were fully extracted and all four RPC detectors (2 leaking chambers + 2 connected to them) got new pipes attached outside the chamber and new robust connectors, as shown in Fig. 6 (b). The chambers with gas leak were fully recovered and operational during the data taking in 2024.

The already tested procedure of gas leak repair using full extraction is a permanent solution to the gas leak problem in barrel RPC chambers and could be applied thoroughly. No leak is observed in the repaired chambers almost 1 year after reparation. Therefore a massive lifesaving leak repair campaign must be addressed in upcoming YETS or Long Shutdown (LS3) period.

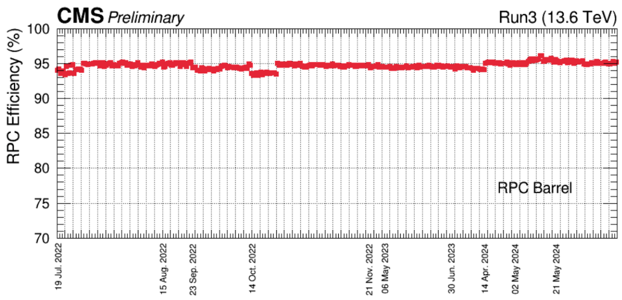
3. CMS RPC performance in Run 3 collisions

LHC Run 3 data taking started with reaching the 13.6 TeV record value of the center-of-mass energy in proton-proton collisions. The CMS experiment started the new data taking period with stable performance, ready to collect good quality data on all possible new phenomena [3].

To validate the RPC system operation after the extensive preparation for Run 3 [11], the CMS RPC system performance has been closely monitored, while a special comparison study on the main RPC detector working parameters has been carried out.



(a)

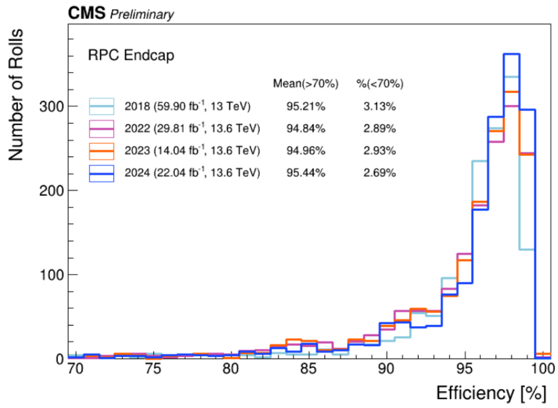


(b)

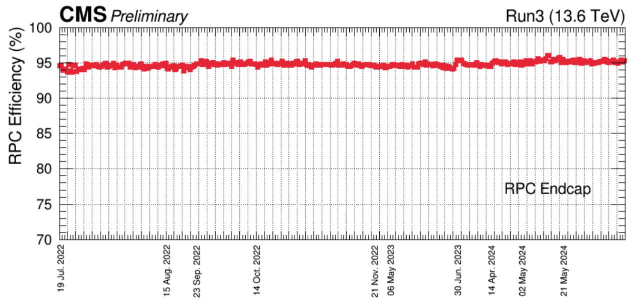
Figure 7: RPC overall efficiency distribution comparison for the barrel, obtained using 2018, 2022, 2023 and 2024 proton-proton collisions data (a) and RPC barrel average efficiency vs time, obtained using Run 3 proton-proton collisions data (b) [5].

The RPC overall efficiency distribution for the barrel and the endcap regions is shown in Fig. 7 (a) and 8 (a), respectively. The RPC hit efficiency is obtained using the Segment Extrapolation Method [4], described in Section 2.

For correct estimation on the performance of the RPC system configuration during the different years of data taking, all RPC chambers with known hardware problems or switched off due to the CMS gas leak reduction policy are excluded. The underflow entries in the efficiency distributions for both the barrel and the endcap regions are coming from detector units with efficiency lower than 70%, caused by known hardware problems, e.g. chambers working in single gap operation mode. The numbers given on the plots show the average efficiency for the well performing, as well as the fraction of the problematic RPC detector units.



(a)



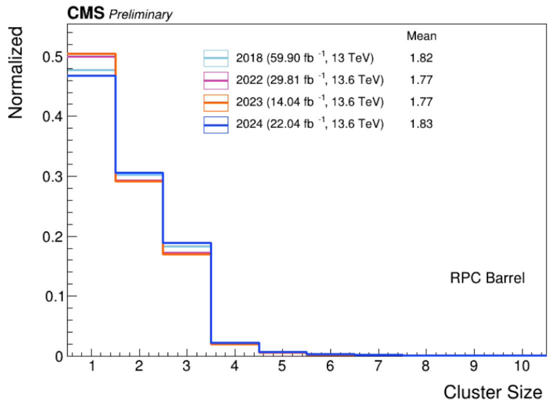
(b)

Figure 8: RPC overall efficiency distribution comparison for the endcap regions, obtained using 2018, 2022, 2023 and 2024 proton-proton collisions data (a) and RPC endcap average efficiency vs time, obtained using Run 3 proton-proton collisions data (b) [5].

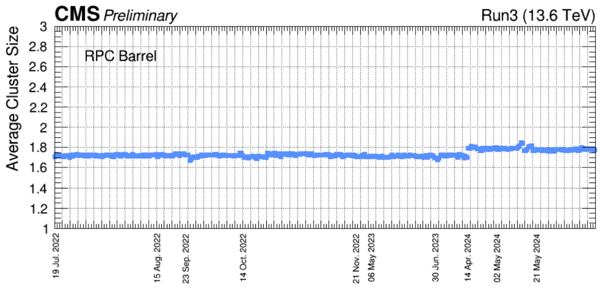
Figure 7 (b) and Fig. 8 (b) show the RPC efficiency history for the barrel and endcap regions respectively. The drops in the efficiency, appearing for different periods in time, are due to known hardware problems, which were successfully fixed.

Comparing the RPC system efficiency with previous measurements and the CMS requirements to keep the efficiency $\sim$ 95 % [1], the RPC efficiency measured in Run 3 (up to 2024) is stable and in agreement with the expectations. The stable fraction of detector units operating at lower efficiency (shown in Fig.7 (a) and Fig. 8 (a)) demonstrates the success of the HV, LV and gas system maintenance during the data taking period.

Another important RPC working parameter, which affects the RPC spacial resolution, is the cluster size – number of adjacent fired strips in a single muon hit. One of the most important prerequisites in the correct operation of the RPC system is keeping the cluster size stable over time, which guarantees the stability of the system. The comparison of the cluster size distribution of RPC hits associated with muons in the barrel and the endcap are shown in Fig. 9 (a) and Fig. 10 (a), while the average cluster size history is presented in Fig. 9 (b) for the barrel and Fig. 10 (b) for the endcap regions.



(a)



(b)

Figure 9: RPC cluster size distribution comparison for the barrel, obtained using 2018, 2022, 2023 and 2024 proton-proton collisions data (a) and RPC barrel average cluster size vs time, obtained using Run 3 proton-proton collisions data (b) [5].

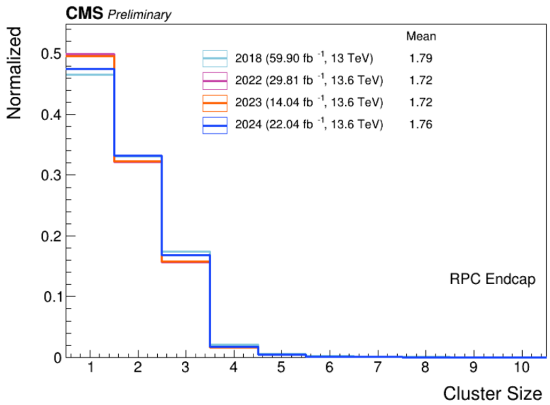
Even though, with respect to the distance to the beam pipe, the RPC readout strips pitch width varies from 1.7 cm in the innermost stations to 4.1 cm for the outermost stations [3], resulting in possible larger cluster size number for the different detector parts, the RPC system mean cluster size measured in Run 3 is below 2, which is comparable and in agreement with the expectations.

4. Conclusion

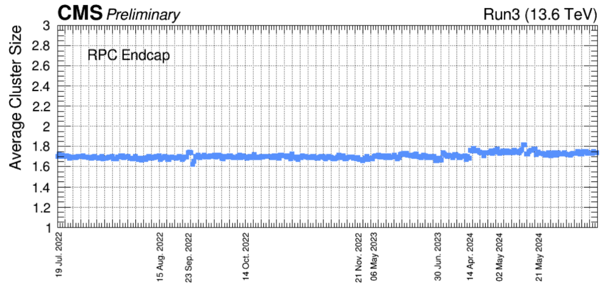
The CMS RPC system kept its stable performance during the ongoing Run 3 data taking. The RPC group performed a series of calibration studies and scans on the HV working parameters, gas leaks and LV to ensure the optimal operation conditions.

Following the CMS experiment aim to minimize the environmental impact of the RPC operational gas mixture, a new policy to disconnect all leaking chambers from the gas distribution was established. This allowed the successful validation and calibration of the new freon recuperation system.

In addition, a new gas leak reparation procedure was successfully tested and validated at the CMS experiment site to keep



(a)



(b)

Figure 10: RPC cluster size distribution comparison for the endcap regions, obtained using 2018, 2022, 2023 and 2024 proton-proton collisions data (a) and RPC endcap average cluster size vs time, obtained using Run 3 proton-proton collisions data (b) [5].

the number of gas disconnected detectors to minimum and ensure the repaired chambers are fully operational with no side effects from the reparation and no observed gas leak.

The results from the Run3 data analysis show stable performance of the RPC system, with average efficiency of $\sim$ 95% and average cluster size below 2. Results obtained from the Run 3 data analysis confirm the success and importance of all calibration activities performed during the data taking period, resulting in the RPC system optimal and smooth operation.

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