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# DESIGN AND IMPLEMENTATION OF A WEB APPLICATION FOR CMS RPC STATE MONITORING [2]

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***Abstract:*** *This work presents the design and implementation of the RPC State Tracker, a web application for monitoring and analyzing the performance of the Resistive Plate Chambers (RPCs) of the CMS experiment at CERN. The application was developed to facilitate systematic exploration of RPC efficiency data and to support comparative analysis across different operational periods. It provides an intuitive, web-based interface for interactive visualization of efficiency maps and derived performance metrics. Implemented with a Python (Flask) backend and a JSROOT-based frontend, the system integrates ROOT data processing, statistical analysis, and dynamic visualization within a unified and modular framework. The application enables quantitative efficiency comparisons and incorporates statistical significance testing, including the Z-test and the Wilcoxon signed-rank test, allowing users to assess performance variations in a consistent and reproducible manner. The backend architecture is designed to ensure efficient data handling and on-demand execution of statistical computations, while the frontend focuses on usability and clarity of data presentation. By combining established scientific data formats with modern web technologies, the RPC State Tracker enhances accessibility to complex performance data and demonstrates the potential of lightweight, data-driven web applications for monitoring and analysis tasks in large-scale physics experiments.*

***Keywords:*** *RPC State Tracker, Resistive Plate Chambers (CMS), Performance Monitoring, Web Application, Data Visualization, Statistical Analysis, ROOT Data Processing.*

## INTRODUCTION

The Compact Muon Solenoid (CMS) (CMS Collaboration, 2008), a part of the Large Hadron Collider (LHC) at CERN, plays a critical role in exploring fundamental properties of matter. Among its key components are Resistive Plate Chambers (RPC), which are crucial for detecting and triggering of muons. However, RPCs may face challenges such as aging and efficiency degradation due to prolonged exposure to high radiation. The anticipated instantaneous luminosity increase (up to $5 – 7.5 \times 10^{34}$ $cm^{-2}$ $s^{-1}$) in the upcoming years underscores the need for innovative tools to monitor and address these issues proactively.

The RPC State Tracker was developed to complement existing monitoring solutions by providing a dedicated web-based application for assessing RPC efficiency, detecting aging, and enabling informed maintenance planning. By integrating statistical analysis with intuitive visualization, the application supports researchers in ensuring the smooth operation of the system.

## EXPOSITION

### Background and Existing Solutions

Current monitoring frameworks at CERN, including C2MON (Copy, B. et al., 2017) and

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WinCC OA (Arcidiacono, R., et al., 2005), focus on real-time data handling and operational control but lack comprehensive capabilities for aging analysis. The Detector Control System (DCS), a specialized solution for monitoring RPC parameters, is specialized in immediate operational metrics and lacks tools for long-term performance assessment and statistical analysis.

While these systems excel in ensuring the immediate functionality of detectors, they do not address the specific needs for analyzing efficiency trends or aging effects, that are a subject of in-depth offline analyses. The RPC State Tracker was designed to bridge these gaps by incorporating advanced statistical tools and user-friendly visualization features tailored to RPC performance monitoring.

**Datasets**

The RPC State Tracker was developed as a sophisticated solution to analyze and visualize efficiency maps (efficiency per 1 $cm^2$, obtained after muongraphy) of the RPC detectors (CMS Collaboration, 2010). Leveraging the ROOT data format – a specialized framework developed by CERN for handling large scientific datasets – the application processes and presents efficiency data in an accessible format. Efficiency data for 1020 RPCs from the barrel part of the system, obtained in 2018 and 2023, were preprocessed to eliminate edge effects, ensuring the accuracy and reliability of the analysis. This preprocessing step involved filtering out data from regions near the physical edges of the detectors, where measurements tend to be less precise due to geometric constraints.

The cleaned data was stored in ROOT files, as well as metrics such as absolute (actual) and relative efficiency differences, calculated on a per-square-centimeter basis. These metrics provide a granular view of the possible aging effects, allowing for precise assessments of performance degradation across individual RPC chambers. By structuring data in this format, researchers can efficiently retrieve, analyze, and visualize trends in detector performance over time.

**Methodology**

The architecture of the RPC State Tracker comprises three main components: a user-friendly frontend for data visualization, a Python-based backend for data processing and statistical analysis, and ROOT files (Brun, R., & Rademakers, F., 1997) for data storage (Fig. 1). The web interface, implemented using JSROOT, enables users to interact with the data intuitively (JSROOT, 2025).

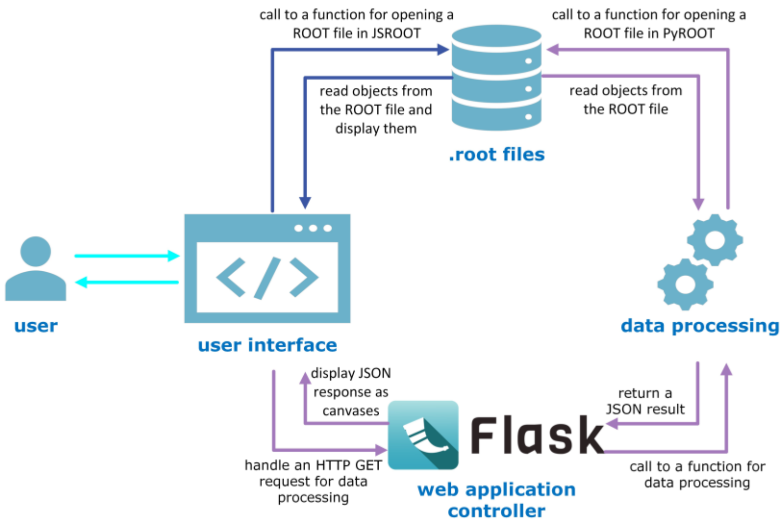


Fig. 1. Architecture of RPC State Tracker

Researchers can select specific RPC chambers and visualize efficiency histograms for different years, gaining insights into performance changes (Fig. 2). The backend, built using the Flask web framework, processes user requests, executes statistical tests, and returns results in real time. This integration of frontend and backend components ensures seamless interaction and efficient data handling, allowing researchers to focus on analysis rather than technical complexities. Additionally, the use of Python and its robust ecosystem of libraries facilitates the implementation of advanced analytical techniques, enhancing the application's functionality.

Statistical methods implemented in the application include the Z-test and the Wilcoxon signed-rank test. These tests are integral to quantifying the significance of observed efficiency changes between 2018 and 2023. The Z-test evaluates changes in the mean efficiency (Montgomery, D. C., & Runger, G. C., 2010), providing a measure of whether the observed variations are likely to be due to random fluctuations or represent genuine trends. In our implementation, it compares the differences for each square centimeter of the chamber to the mean difference.

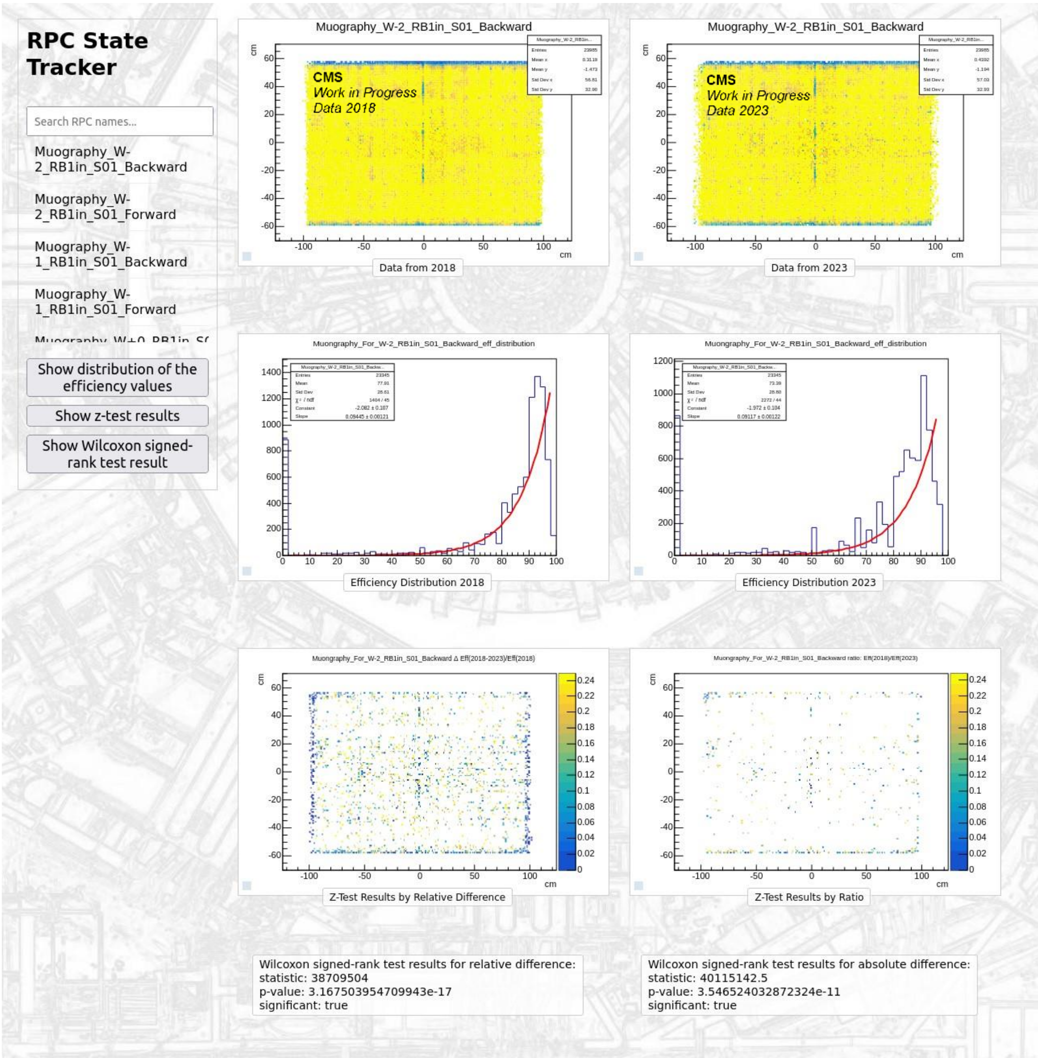


Fig. 2. User interface of the RPC State Tracker

The Wilcoxon signed-rank test, a non-parametric method, is particularly useful for evaluating distributions that deviate from normality (Rey, D., & Neuhäuser, M., 2011), as is often the case with efficiency data. By accommodating the non-normality observed in the data, the Wilcoxon test ensures robust and reliable results. We use the Wilcoxon signed-rank test to assess the overall distribution changes. Both statistical tests yield p-values that help determine whether performance variations are statistically significant, offering actionable insights for detector maintenance and operational planning.

We apply both statistical significance tests on the already calculated absolute and relative differences and ratios of the efficiencies per square centimetre of each RPC chamber, thus having the following hypotheses (Table 1):

Table 1. Statistical hypotheses used in RPC State Tracker

| № | Null Hypothesis ($H_0$) | Alternative Hypothesis ($H_1$) |
|---|---|---|
| 1 | $\frac{\Delta \text{Eff}\ (2018-2023)}{\text{Eff}\ (2018)} = 0$ | $\frac{\Delta \text{Eff}\ (2018-2023)}{\text{Eff}\ (2018)} > 0$ |
| 2 | $\frac{\text{Eff}\ (2018)}{\text{Eff}\ (2023)} = 1$ | $\frac{\text{Eff}(2018)}{\text{Eff}(2023)} > 1$ |
| 3 | $\Delta \text{Eff}\ (2018-2023) = 0$ | $\Delta \text{Eff}\ (2018-2023) > 0$ |

For the Z-test we use hypotheses 1 and 2, and for the Wilcoxon signed-rank test – hypotheses 1 and 3.

**Experimental Results**

Experimental results highlight the utility of the RPC State Tracker in identifying performance variations across 1020 RPCs in the CMS barrel part. Efficiency histograms, generated for each chamber, revealed that some regions of certain chambers show lower efficiency over the analyzed period while the performance of others remains unchanged. These visualizations provided a clear depiction of efficiency trends, enabling researchers to pinpoint areas requiring attention. The comparative analysis of efficiency between 2018 and 2023 demonstrated possible performance declines in specific regions of the detector. Such patterns underscored the importance of targeted interventions to address potential aging effects.

The statistical tests conducted further validated the observations. For instance, the Wilcoxon signed-rank test revealed some statistically significant differences in efficiency distributions across the years. The Z-test results complemented these findings by highlighting efficiency drops in specific areas of particular chambers. Collectively, these results provided a robust foundation for actionable insights into chambers performance.

The application's interactive interface proved invaluable in facilitating data exploration, allowing researchers to navigate and analyze the dataset with ease. By offering intuitive tools to visualize efficiency distributions, compare performance metrics, and run statistical analyses, the RPC State Tracker streamlined the process of identifying critical areas of concern. Additionally, researchers could generate detailed reports summarizing the findings for each chamber, further aiding in documentation and decision-making processes.

One of the most notable outcomes of this analysis was the identification of subtle trends in the detector performance data that could help reveal biased changes for further evaluation by detector experts. This finding underscores the potential for integrating environmental monitoring data with performance metrics in future iterations of the application. By doing so, researchers can gain a more comprehensive understanding of the factors influencing detector performance, ultimately enabling even more precise interventions.

**CONCLUSION**

The RPC State Tracker achieves its objectives by delivering a robust, accessible platform for monitoring the performance of the RPC system at CMS. Its seamless integration of ROOT data processing, advanced statistical analysis, and interactive visualization makes it a valuable tool for researchers in high-energy physics. By enabling the identification and quantification of aging effects, the application contributes to proactive maintenance planning and enhances the long-term operational efficiency of the detector system. The insights gained through the RPC State Tracker not only support the immediate needs of the detector experts but also provide a

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framework for developing similar monitoring solutions for other high energy physics experiments that involve RPC chambers.

Looking ahead, future enhancements to the RPC State Tracker include integrating real-time data streams to monitor RPC performance continuously and incorporating predictive analytics for early identification of potential failures. Real-time monitoring capabilities would enable researchers to respond promptly to emerging issues, minimizing downtime and optimizing detector performance. Predictive analytics, powered by machine learning algorithms, could further enhance the application by identifying patterns indicative of impending failures, allowing for preemptive maintenance. These developments would position the RPC State Tracker as an indispensable tool for ensuring the reliability and efficiency of detectors in high-energy physics experiments.

In conclusion, the RPC State Tracker represents a significant advancement in the monitoring and analysis of RPC performance within the CMS experiment. By addressing the challenges associated with detector aging and providing researchers with powerful analytical tools, the application supports the continued success of high-energy physics research at CERN. Its user-friendly design and comprehensive functionality set a benchmark for future monitoring solutions, reinforcing the importance of proactive maintenance and operational optimization in large-scale scientific experiments.

## ACKNOWLEDGEMENTS

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