



CERN SUMMER STUDENT PROGRAMME

Project Report

Upgrading Simulation Monitoring in Monet

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Abstract

During the 2025 CERN Summer Student Programme, the simulation monitoring of the LHCb Muon sub-detector was significantly upgraded within the MONET. A two-dimensional hit map was implemented for stations M2–M5 and added to the SimDQ chain alongside existing radial and time multiplicity histograms. Run-specific layouts were created for Run 1–2 and Run 3, reflecting detector configuration changes, and the correct reference ROOT files were identified and applied for validation. Monitoring was also extended to the Boole digitization step, completing the coverage of the simulation chain. The new pages and functionalities are now actively used by shifters and experts during simulation campaigns, improving their ability to identify anomalies quickly and assess detector performance. The new system made the monitoring workflow more robust and user-friendly, strengthening Muon simulation monitoring and improving consistency across all LHCb sub-detectors. It established a solid foundation for systematic validation in future production campaigns.

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1. Introduction

The LHCb Muon system, illustrated in Fig. 1, is a key component of the experiment, enabling both triggering and particle identification. Analyses involving muons in the final state rely on accurate detector simulation and on monitoring tools that validate the quality of simulated data. Simulation monitoring in LHCb is performed within MONET, a web-based interface for visualization and validation of detector and simulation data quality, through the Simulation Data Quality (SimDQ) chain, which before this project did not yet include the Muon system.

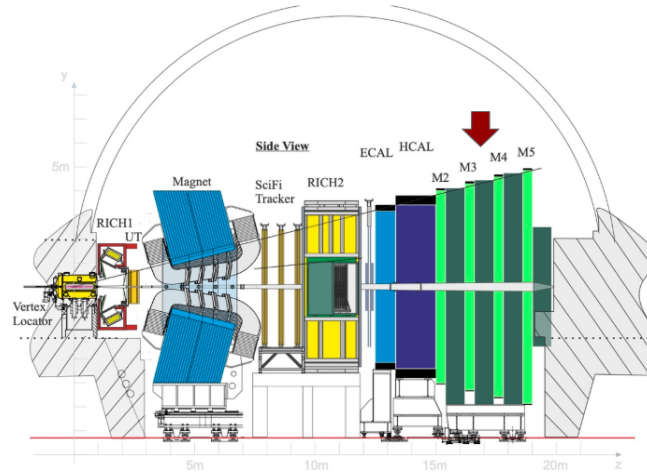


Figure 1: LHCb Detector (Muon System marked with arrow)

The LHCb simulation workflow is composed of multiple stages. The Gauss is responsible for particle generation, decay, and propagation through the detector geometry, while Boole performs the digitization step that converts simulated hits into electronic detector signals. Prior to this work, no Muon monitoring was implemented in SimDQ for Gauss, and Boole outputs were not represented in the system at all. As a result, Muon simulation quality could not be validated alongside other sub-detectors, and digitization monitoring remained unavailable.

The aim of this project was to integrate the Muon system into the SimDQ chain and to extend monitoring to include the Boole digitization stage, thereby establishing a framework consistent with that of other LHCb sub-detectors. The main objectives were to:

- Add the Muon system in SimDQ
- Create suitable layouts for different data-taking periods
- Find and configure reference plots
- Prepare monitoring for Boole (Digitization Step)

These developments strengthened the Muon simulation monitoring framework within MONET, aligned it with other LHCb sub-detectors, and established a reliable basis for future systematic validation of simulated data.

2. Methodology

2.1 Adding Muon System to SimDQ

The Muon sub-detector was integrated into the SimDQ chain to extend monitoring of simulated detector responses. The Muon system consists of four stations M2–M5 (Run3), each divided into four concentric regions (R1–R4) with finer granularity toward the beam axis. This geometry was accurately represented in the new monitoring setup through the addition of dedicated histograms and visualization layouts in MONET.

Initial work began by integrating existing Muon histograms, produced during the Gauss simulation step and available within the LHCbPR monitoring, such as radial multiplicity plots (Fig. 2) for individual stations and time multiplicity plots (Fig. 3) for detector regions. These histograms provided one-dimensional checks of hit counts and timing distributions in the Muon system.

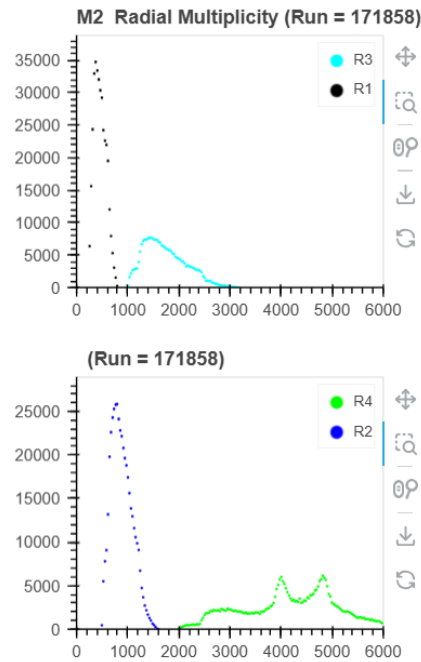


Figure 2: Radial multiplicity plots for the M2 station by region: R1 and R3 - top, R2 and R4 - bottom

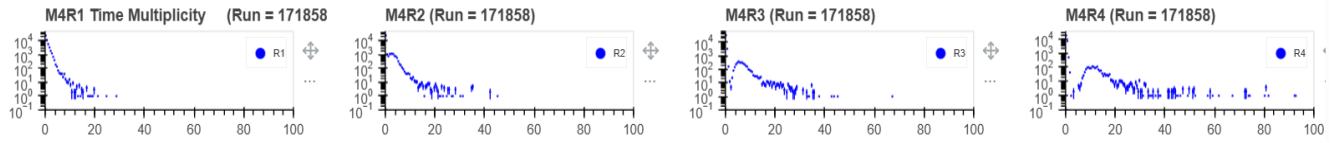


Figure 3: Time Multiplicity plots for M4 station per region

To complement these, a new two-dimensional hit map (Fig. 4) was implemented for Muon stations M2–M5. This required modifications in the Gauss simulation framework to enable the production of the necessary hit information for visualization. The 2D map provided spatial insight into hit distributions across the detector surface, allowing localized variations or irregularities to be identified — features that could not be observed in one-dimensional histograms alone. An example of such a hit map is shown in Figure 6, illustrating the distribution across the M2 station. The implementation and corresponding changes in Gauss were submitted through a dedicated Merge Request (https://gitlab.cern.ch/lhcb/Gauss/-/merge_requests/1197)

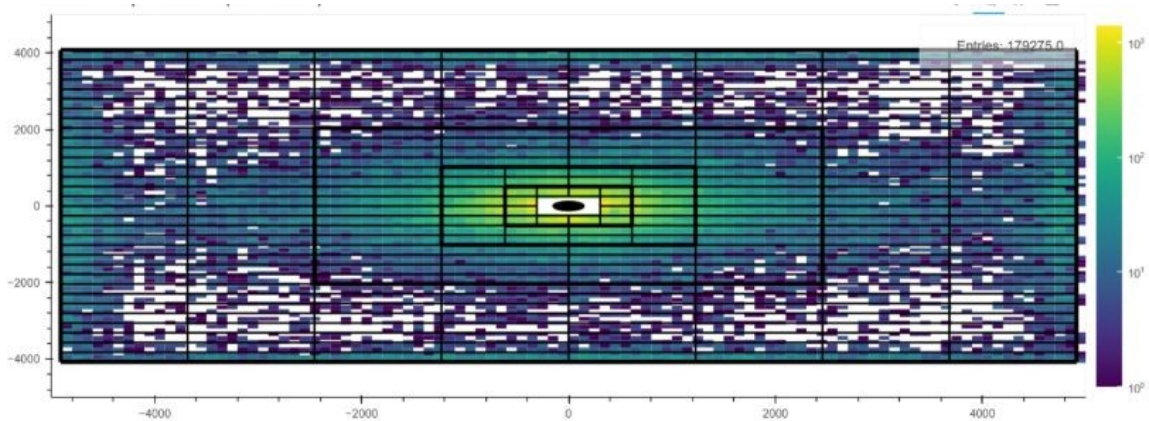


Figure 4: 2D Hitmap for M2 station

All newly implemented plots were validated against simulation outputs and then prepared for integration into the MONET visualization interface. The resulting pages, shown in Fig. 5, illustrate how the Muon system monitoring now appears within the SimDQ section, alongside other LHCb sub-detectors. These pages display the newly added Muon histograms, including the two-dimensional hit maps, radial multiplicity, and time multiplicity plots.

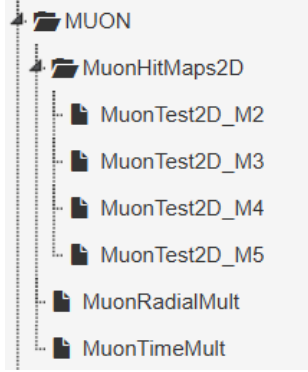


Figure 5: Muon system layout in Monet

2.2 Layouts for Different Data-Taking Periods

To ensure compatibility with different detector configurations, new run-specific layouts were created within the SimDQ structure for all sub-detectors, including the Muon system. Before this work, all Gauss histograms for the Muon system were collected under a single, flat layout (Fig. 6) corresponding only to Run 1–2 conditions. This structure made it difficult to distinguish between simulation campaigns belonging to different detector eras and data-taking campaigns

The SimDQ tree was therefore reorganized to include separate folders for Run 1–2 and Run 3 (Fig. 7), both under Gauss and Boole monitoring sections. Each layout was assigned the correct reference ROOT files and detector geometry, allowing simulation outputs to be validated against the appropriate baseline. As a result, Boole monitoring was also integrated into the structure for the first time, providing full coverage of both hit-level and digitized data.

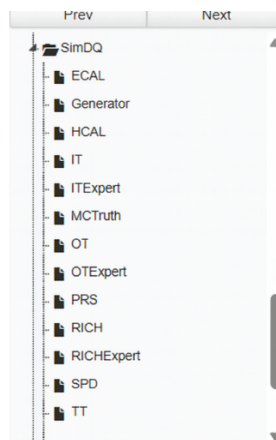


Figure 6: Before changes

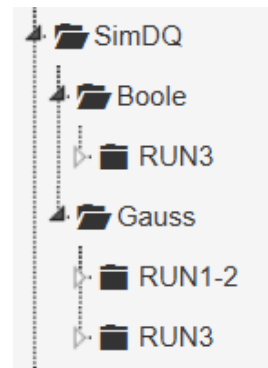


Figure 7: After changes

A validation mechanism was additionally implemented to check whether the Request ID corresponds to the correct run period (Fig. 8). When a mismatch occurs, the system prevents histogram display and issues an on-screen error message informing the user that the request belongs to a different data taking period. This feature protects experts from using incorrect references and significantly reduces time spent on debugging.

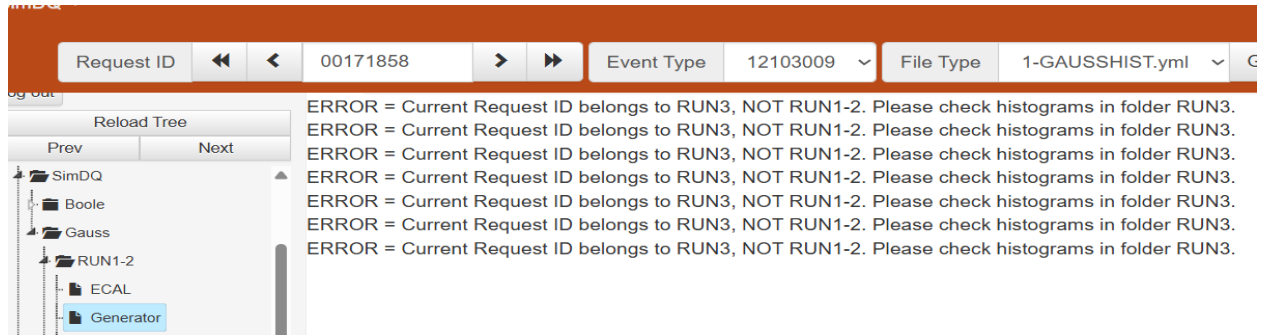


Figure 8: Error messages based on Runs

2.3 References

Simulation histograms must be compared with validated reference samples to detect potential deviations and anomalies. Correct references are essential for ensuring that simulation outputs correspond to the correct detector configuration and software version.

During this work, the appropriate reference ROOT files were collected and identified for each simulation dataset. Matching was based on key metadata fields such as “*SimCondition*” and “*Event Type*”, which uniquely define the simulation configuration. This matching process ensured that histograms generated from a given simulation run were compared against the correct reference, preventing false discrepancies arising from incompatible versions.

To automate and standardize this process, an existing script within the SimDQ framework — [simdqdata/scripts/update_reference_samples.py](#) — was updated. The function responsible for determining reference keys was improved to handle different simulation versions and event types, thereby increasing reliability across various configurations.

The updated logic automatically associates each histogram with its corresponding reference file during validation, as illustrated in Fig. 9. The resulting plots display overlaid distributions of simulation outputs and their respective references, making any deviations immediately visible. This functionality provides a consistent and efficient quality-control mechanism for the monitoring of all sub-detectors.

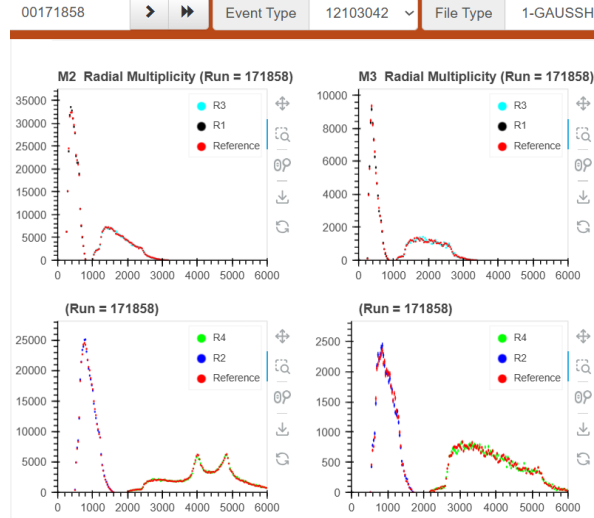


Figure 9: Example result for References (M2 and M3)

2.4 Monitoring for Boole (Digitization Step)

The monitoring coverage of SimDQ was extended to include the Boole digitization step, enabling validation of digitized detector signals in addition to hit-level simulation outputs. Dedicated pages were created in MONET for Boole (Fig. 10), providing visualization of histograms such as digits multiplicity, radial distribution, and time distribution for each Muon station. In parallel, pages were also prepared for all other sub-detectors to ensure uniform monitoring coverage across the experiment. This integration allowed both simulated and digitized data to be examined within a consistent and coherent monitoring environment.

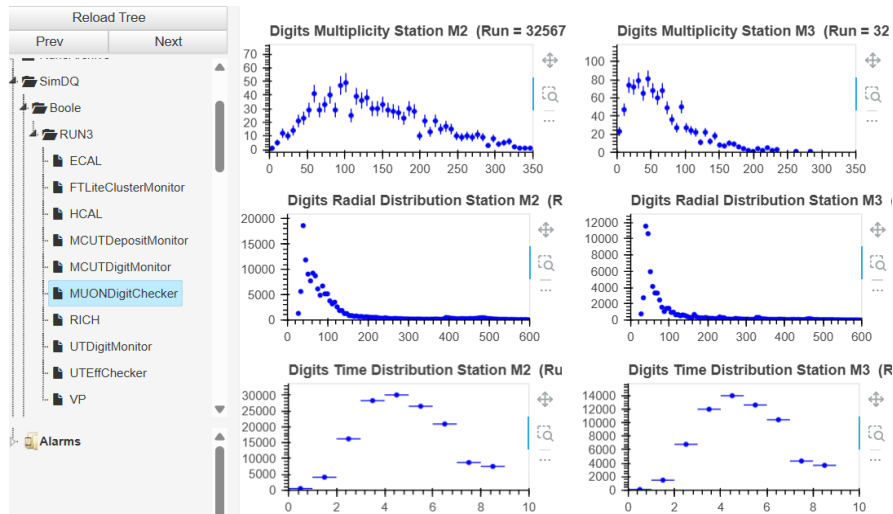


Figure 10: Example page of histograms from Boole

To improve reliability, error-handling functionality was implemented directly in the MONET source code and integrated with the SimDQ backend. When a file not corresponding to the Boole type is selected, the system now displays a clear on-screen error message instructing the user to switch to the appropriate histogram category, as shown in Fig. 11. This mechanism prevents confusion between Gauss and Boole outputs and minimizes the risk of using incorrect files during validation. The code was updated to automatically check the expected file type before rendering histograms, ensuring that only valid Boole or Gauss inputs are processed.

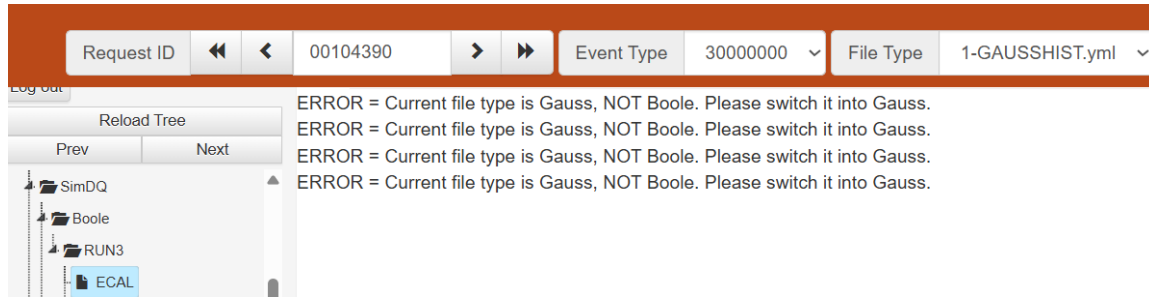


Figure 11: Error messages based on File Type

3. Results

As a result of this work, the Muon simulation now has fully functional monitoring pages in MONET under SimDQ. Experts can now inspect all relevant statistics and distributions, including the newly implemented hit maps, directly from the simulation output. This improvement enables efficient validation and troubleshooting of Muon simulations within the existing LHCb monitoring framework.

The monitoring and quality-control process has become more robust and user-friendly. The reference-handling logic was modernized to correctly distinguish between Run 1–2 and Run 3 datasets, ensuring that comparisons are always made against the correct detector configuration.

Furthermore, the extended framework establishes a foundation for future Boole-stage monitoring for all LHCb sub-detectors. The outcome represents a significant step toward a unified and automated simulation validation infrastructure.

4. Conclusion

The project successfully introduced the Muon sub-detector into the LHCb SimDQ framework, providing its first dedicated simulation monitoring within MONET. The implementation included new histograms, run-specific layouts, reference configuration, and Boole digitization monitoring. Modifications to the Gauss simulation and MONET source code ensured proper functionality and integration at each stage.

The resulting monitoring chain now enables systematic validation of Muon simulation outputs and strengthens the overall simulation quality control across all LHCb sub-detectors. These developments contribute to a more unified and reliable monitoring environment within MONET. Future improvements may further refine automation for reference management and validation workflows, extending the framework's capabilities to additional detector components.

References :

- [1] R. Aaij *et al.* (LHCb Collaboration), *Performance of the LHCb Muon System*, *Journal of Instrumentation* **8** (2013) P10020. doi:10.1088/1748-0221/8/10/P10020.
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