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The Compact Muon Solenoid Experiment

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First year of experience with the new operational monitoring tool for data taking in CMS during Run 3

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Abstract

The Online Monitoring System (OMS) at the Compact Muon Solenoid experiment at CERN aggregates and integrates different sources of information into a central place and allows users to view, compare and correlate information. It displays real-time and historical information. The tool is heavily used by run coordinators, trigger experts and shift crews, to ensure the quality and efficiency of data taking. It provides aggregated information for many use cases including data certification. OMS is the successor of Web Based Monitoring (WBM), which was in use during Run 1 and Run 2 of the LHC. WBM started as a small tool and grew substantially over the years so that maintenance became challenging. OMS was developed from scratch following several design ideas: to strictly separate the presentation layer from the data aggregation layer, to use a well-defined standard for the communication between presentation layer and aggregation layer, and to employ widely used frameworks from outside the HEP community. A report on the experience from the operation of OMS for the first year of data taking of Run 3 in 2022 is presented.

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First year of experience with the new operational monitoring tool for data taking in CMS during Run 3

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Abstract. The Online Monitoring System (OMS) at the Compact Muon Solenoid experiment at CERN aggregates and integrates different sources of information into a central place and allows users to view, compare and correlate information. It displays real-time and historical information. The tool is heavily used by run coordinators, trigger experts and shift crews, to ensure the quality and efficiency of data taking. It provides aggregated information for many use cases including data certification. OMS is the successor of Web Based Monitoring (WBM), which was in use during Run 1 and Run 2 of the LHC. WBM started as a small tool and grew substantially over the years so that maintenance became challenging. OMS was developed from scratch following several design ideas: to strictly separate the presentation layer from the data aggregation layer, to use a well-defined standard for the communication between presentation layer and aggregation layer, and to employ widely used frameworks from outside the HEP community. A report on the experience from the operation of OMS for the first year of data taking of Run 3 in 2022 is presented.

1 Introduction

The Compact Muon Solenoid (CMS) [1] is a multi-purpose detector operating at the Large Hadron Collider (LHC) [2] at CERN. Operating CMS involves managing a complex system of sensor channels, a wide supporting infrastructure, and sophisticated trigger and data acquisition (DAQ) systems. This setup handles an immense and diverse set of information, including details about detector and environmental conditions, DAQ status, run configuration, trigger rates, luminosity, and accelerator parameters. To ensure efficient and high-quality data

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collection, a comprehensive monitoring system is essential. The CMS collaboration extends its reach across the globe, encompassing more than 6000 contributors from over 247 institutions spanning across 57 countries. Given this extensive network of expertise and varied data sources in the CMS experiment, the need arises for a centralized monitoring system that can be accessed remotely. Seamless remote access to this data for experts proves invaluable, as it empowers them to effectively assist in diagnosing problems. This facilitates enhanced identification and resolution capability for any data-taking issue.

The CMS Online Monitoring System (OMS) is a comprehensive set of software designed to gather data from various online monitoring sources and present them through a web interface accessible to authenticated users worldwide. This software suite provides an overview of the activities currently ongoing in the experiment and offer convenient access to historical data. One of the main tasks of the OMS is to integrate information from various online sources, catering to the requirements of shift crew members, detector subsystem experts, operations coordinators, and researchers engaged in physics analyses. The primary objective of OMS is to offer an interactive suite of tools that support centralized data taking with ease of use, security, flexibility, and maintainability as key priorities. The OMS tools complement other data quality monitoring tools that rely on event data [3].

This paper describes the architecture of the project and the technologies employed for its development. Moreover, it aims at exploring the content pages of the OMS, providing a comprehensive overview of all available content categories. The paper also illustrates what was learned from using OMS during data taking, along with the prospects of upcoming new developments

2 OMS architecture and technologies

OMS has a predecessor known as the Web Based Monitoring (WBM) [6]. WBM was actively utilized during the CMS commissioning and in LHC Runs 1 and 2. Throughout the initial decade of CMS data taking, WBM evolved through the integration of new services and technologies, accumulating experience and tools that facilitated efficient detector monitoring.

To secure lasting support and reduce person-power and technical resources needed for CMS monitoring tools, a decision was made in 2015 to redesign the core functionality of the former WBM into the OMS project. Framework and initial content development occurred during 2016 and 2017, with the first beta version being announced in February 2018. The development of OMS continued during the LHC long shutdown 2, and transitioned into full production by the end of 2021.

2.1 Architecture

In accordance with best practices, OMS is designed with two distinct layers: an aggregation layer and a presentation layer. The first layer is the aggregation component, responsible for summarizing the monitoring information into the database, while the second layer is the visualization component tasked with displaying the OMS data.

Figure 1 illustrates the architecture of the OMS project. At the bottom of the diagram, there are two distinct types of data sources: those accessible at the database level, and some that are not directly available in the database. The CMS proxy DIP [7] and the BRIL eventing BUS [8] are two distinct sources that are not available in the database. For these sources, dedicated software has been developed within OMS to integrate their data into the database. The data warehouse stores aggregated non-event data collected from various sources, each with distinct data format and dynamic context. The aggregation REST API retrieves data from the database and exposes it through a REST API. The OMS presentation layer is responsible for displaying non-event data through a web browser interface, in addition other CMS projects can access the aggregation layer for both online and offline tasks.

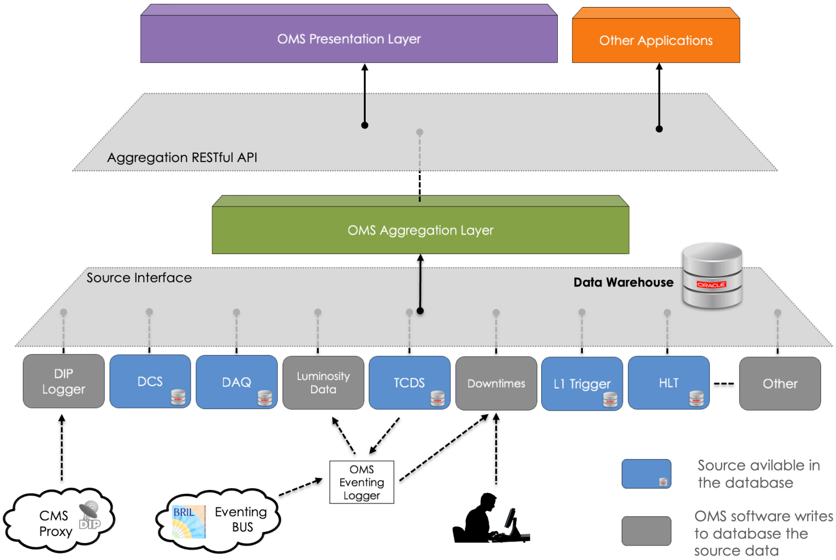


Figure 1. OMS architecture.

2.2 Data warehouse

The OMS data warehouse (DWH) serves as the central component of the OMS system, housing all non-event data within ORACLE databases. PL/SQL code is employed to aggregate and modify these data. A key objective of the DWH was to revamp the PL/SQL code inherited from the WBM project. This involved creating new aggregation tables and introducing various enhancements to the PL/SQL code, including better "name and code convention" practices, a more conducive development environment, and a workflow for continuous integration. The DWH comprises multiple Oracle schemas. A significant aspect of its design involved the utilization of external PL/SQL libraries. The CERN Beams Common4Oracle library [9] was chosen, as it offers a collection of common functionalities from different CERN Beams department databases.

2.3 Aggregation API

The REST aggregation API [10] is a Java-based web application that retrieves non-event data from the DWH. This data is made accessible through a REST API compliant with the JSON:API specification. The heart of the aggregation API lies in the QueryBuilder, a custom-developed library designed to dynamically generate SQL queries based on REST requests. The API demonstrates scalability through its utilization of request connection pools and database connection pools; it also supports multiple database instances. An accompanying Python REST client library is available for using the API within Python applications.

2.4 Presentation layer

The presentation layer [11] consists of three parts: the web application, metadata API, and the presentation database. The web application serves as a web browser interface designed to be user-friendly, interactive, responsive, and easily customizable. The main technologies employed here are React, Redux, and MaterialUI. The metadata API enables the web application to access portal metadata information, such as content organization, page layout, portlet type, size, and position, as well as user privileges, using a REST API compliant with the JSON:API specification. The main technologies utilized within this API are Python, Flask, and SQLAlchemy. The presentation database stores all portal metadata and configurations.

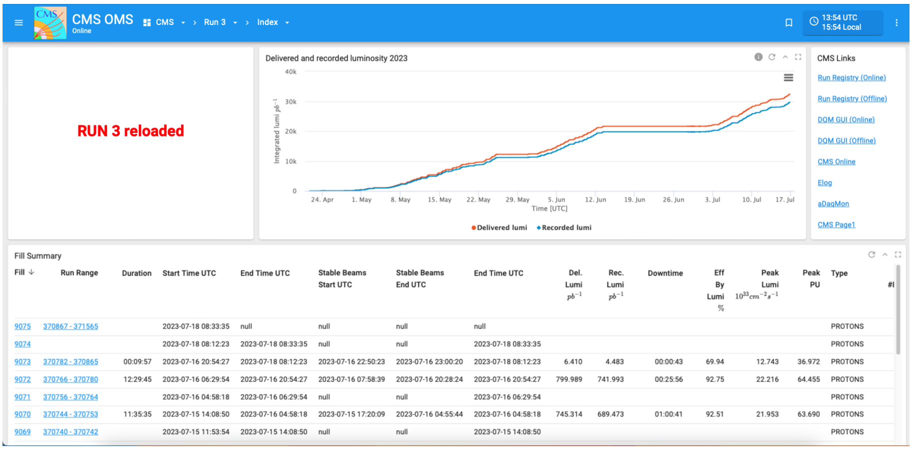
2.5 Infrastructure

Another crucial aspect of the OMS project involves its infrastructure, which includes virtual machines, and proxies deployed across multiple locations: the CMS experiment site (P5) and CERN IT facilities. This infrastructure was initially designed for the WBM project and has since become stable and well-established.

The primary OMS services are running at P5. Users connect to OMS based on their location: through the internet using the CERN IT OMS proxy, via the CERN network using the CMS OMS proxy, or directly from P5 without the need for proxies. OMS web pages are accessed through a single sign-on authentication based on OAUTH2. The operating system employed is CentOS 7.9, currently undergoing an upgrade to RHEL 8. The technology stack includes Java 8, Python 3, and ES6 JavaScript. All the source software code is stored in GitLab repositories and software deployment is facilitated through dropbox [12] functionality and Puppet [13] at P5.

3 OMS content

The user interface for OMS is accessed through a web browser, as depicted in figure 2, illustrating the initial OMS landing page. Content within OMS is systematically structured across various tiers (highlighted by the top blue bar). The foremost tier is the workspace, serving as a container for organizational units or sub-detectors, such as "CMS General Information". The second tier takes the form of folders containing contextually grouped pages. The third and final tier consists of individual pages, each including one or more portlets. An optional component referred to as a controller may be present on a page, allowing users to fine-tune search results. Portlets are essential elements of OMS pages, serving as fundamental components that efficiently combine the content of the pages and functionality.



Fill Summary

Fill ↓	Run Range	Duration	Start Time UTC	End Time UTC	Stable Beams Start UTC	Stable Beams End UTC	End Time UTC	Del. Lumi pb^{-1}	Rec. Lumi pb^{-1}	Downtime	Eff By Lumi %	Peak Lumi $10^{33}cm^{-2}s^{-1}$	Peak PU	Type
9075	370867 - 371565		2023-07-18 08:33:35	null	null	null	null							PROTONS
9074			2023-07-18 08:12:23	2023-07-18 08:33:35	null	null	2023-07-18 08:33:35							PROTONS
9073	370782 - 370865	00:09:57	2023-07-16 20:54:27	2023-07-18 08:12:23	2023-07-16 22:50:23	2023-07-16 23:00:20	2023-07-18 08:12:23	6.410	4.483	00:00:43	69.94	12.743	36.972	PROTONS
9072	370766 - 370780	12:29:45	2023-07-16 06:29:54	2023-07-16 20:54:27	2023-07-16 07:58:39	2023-07-16 20:28:24	2023-07-16 20:54:27	799.989	741.993	00:25:56	92.75	22.216	64.455	PROTONS
9071	370756 - 370764		2023-07-16 04:58:18	2023-07-16 06:29:54	null	null	2023-07-16 06:29:54							PROTONS
9070	370744 - 370753	11:35:35	2023-07-15 14:08:50	2023-07-16 04:58:18	2023-07-15 17:20:09	2023-07-16 04:55:44	2023-07-16 04:58:18	745.314	689.473	01:00:41	92.51	21.953	63.690	PROTONS
9069	370740 - 370742		2023-07-15 11:53:54	2023-07-15 14:08:50	null	null	2023-07-15 14:08:50							PROTONS

Figure 2. The OMS first page.

On the initial page of the OMS in figure 2, there are four distinct portlets. Positioned in the upper left is the first portlet, which serves as a reminder that CMS is currently engaged in LHC run 3. The second portlet, situated in the upper middle section, displays the recorded and delivered luminosity data for the year 2023. Moving to the upper right, the third portlet contains a collection of valuable CMS links, tailored for OMS users. Positioned at the bottom, the fourth portlet provides a comprehensive summary of the latest LHC fills, containing pertinent details. OMS covers eight main content categories, each of which is presented in the subsequent sub-sections.

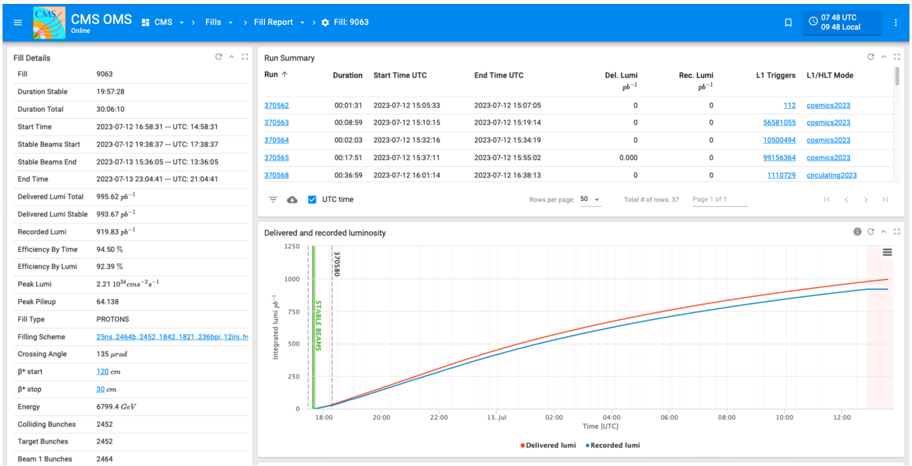
3.1 LHC – general information and status

The general LHC category includes pages related to LHC information, starting with the status of the LHC and details regarding general parameters of the LHC.

The LHC status diagram page indicates the current operational state of the LHC, consisting of modes such as "Stable Beams," "Ramp," or "Beam Dump," within the realm of potential statuses. Further pages exhibit the up-to-the-moment delivered and recorded luminosity in CMS, status of LHC clock, the CMS instantaneous luminosity and β^*. β^* is a parameter related to the size of the beams at the interaction point in a particle accelerator.

3.2 LHC fill

The fill category includes pages related to LHC fill information, beginning with comprehensive details such as the delivered and recorded luminosity for the LHC fill itself. The fill report page displays information regarding the ongoing LHC fill or previous fills. This report shows tables and plots detailing luminosity, backgrounds, accelerator parameters, trigger rates, and more. It also provides a list of runs taken during the fill, complete with hyperlinks for accessing further information about each of them. Examples of these can be found in figures 3 and 4. Additionally, a database service is available to send email or SMS notifications to subscribed users. These notifications inform users about the start and conclusion of stable beams in a fill, also supplying valuable extra information such as the accumulated integrated luminosity. The fill report page is of great value to both run coordinators and the shift crew, functioning as a crucial tool for supervising and addressing current and recent operational issues within the experiment.



Fill Details

Fill	9063
Duration Stable	19:57:28
Duration Total	30:06:10
Start Time	2023-07-12 16:58:31 --- UTC: 14:58:31
Stable Beams Start	2023-07-12 19:38:37 --- UTC: 17:38:37
Stable Beams End	2023-07-13 15:36:05 --- UTC: 13:36:05
End Time	2023-07-13 23:04:41 --- UTC: 21:04:41
Delivered Lumi Total	995.62 pb^{-1}
Delivered Lumi Stable	993.67 pb^{-1}
Recorded Lumi	919.83 pb^{-1}
Efficiency By Time	94.50 %
Efficiency By Lumi	92.39 %
Peak Lumi	2.21 $10^{34} cms^{-2} s^{-1}$
Peak Pileup	64.138
Fill Type	PROTONS
Filling Scheme	25ns_2464b_2452_1842_1821_236bpi_12inj_h
Crossing Angle	135 μrad
β* start	120 cm
β* stop	30 cm
Energy	6799.4 GeV
Colliding Bunches	2452
Target Bunches	2452
Beam 1 Bunches	2464

Run Summary

Run ↑	Duration	Start Time UTC	End Time UTC	Del. Lumi pb^{-1}	Rec. Lumi pb^{-1}	L1 Triggers	L1/HLT Mode
370562	00:01:31	2023-07-12 15:05:33	2023-07-12 15:07:05	0	0	112	cosmics2023
370563	00:08:59	2023-07-12 15:10:15	2023-07-12 15:19:14	0	0	56581055	cosmics2023
370564	00:02:03	2023-07-12 15:32:16	2023-07-12 15:34:19	0	0	10500494	cosmics2023
370565	00:17:51	2023-07-12 15:37:11	2023-07-12 15:55:02	0.000	0	99156364	cosmics2023
370568	00:36:59	2023-07-12 16:01:14	2023-07-12 16:38:13	0	0	1110729	circulating2023

Figure 3. The fill report page.

The bunch info page gives a visual representation of the bunch patterns that populate the LHC accelerator rings. Both charts and tables are accessible for the ongoing collision period, providing a dynamic, real-time presentation, or for past operational periods.

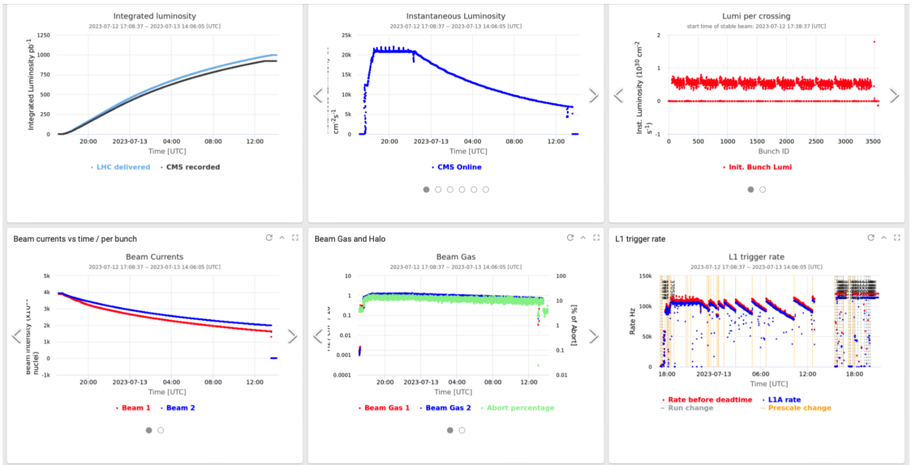


Figure 4. A subset of summary plots displayed on the fill report page.

3.3 CMS runs

The runs category contains pages focused on CMS runs, offering detailed information about each run and CMS Run Control information parameters.

The run report page presents information about CMS data-taking runs, covering details about the detector and trigger configuration, as well as the collected data. The run report page can be searched and provides links to more OMS pages with detailed information about the progression over time of the run. Examples of useful links include pages that offer detailed Level-1 trigger (L1T) and High Level Trigger (HLT) information and interactive plots showing trigger rates.

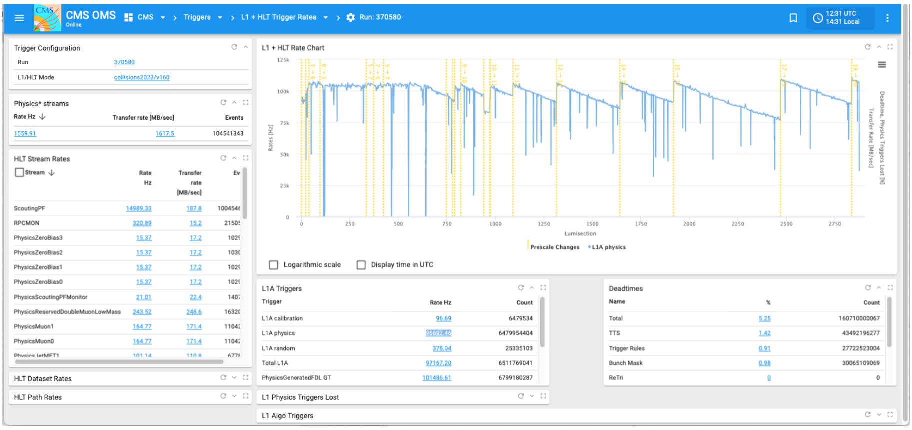
Another example involves monitoring the dead time of the system, providing insights into the detector parts responsible for its occurrence. Dead time arises when data buffers in specific subsystems reach full capacity, leading to the inhibition of new triggers.

3.4 CMS L1T/HLT

This category includes pages that focus on data related to L1T and HLT within CMS runs. The trigger rates pages display trigger counts, rates, and configurations, either in real time for the current run, or historically from the database, and include check boxes to select which trigger rates are plotted. The plots allow interactive zooming and display numerical values when the mouse is over a data point. For example, Figure 5 shows the L1T/HLT rates page for a specific run.

3.5 Detector control system: CMS and sub-systems

This category includes pages that provide information concerning the CMS Detector Control System (DCS) [4, 5], including details about CMS magnet parameters and the status of DCS sub-systems, among other things. Different modules within the OMS software subscribe to both LHC and CMS DIP information branches [7], enabling them to supervise, log, and display this data.



Trigger Configuration

Run	370580
L1/HLT Mode	collisions2023/v160

Physics* streams

Rate Hz	Transfer rate [MB/sec]	Events
1559.91	1617.5	104541343

HLT Stream Rates

☐ Stream	Rate Hz	Transfer rate [MB/sec]	Ev
ScoutingPF	14989.33	187.8	100454
RPCMON	320.89	15.2	21505
PhysicsZeroBias3	15.37	17.2	1029
PhysicsZeroBias2	15.37	17.2	1030
PhysicsZeroBias1	15.37	17.2	1029
PhysicsZeroBias0	15.37	17.2	1029
PhysicsScoutingPFMonitor	21.01	22.4	1407
PhysicsReservedDoubleMuonLowMass	243.52	248.6	16320
PhysicsMuon1	164.77	171.4	11042
PhysicsMuon0	164.77	171.4	11042
PhysicsJetMET1	101.14	110.8	677

L1A Triggers

Trigger	Rate Hz	Count
L1A calibration	96.69	6479534
L1A physics	96692.46	6479954404
L1A random	378.04	25335103
Total L1A	97167.20	6511769041
PhysicsGeneratedFDL GT	101486.61	6799180287

Deadtimes

Name	%	Count
Total	5.25	160710000067
TTS	1.42	43492196277
Trigger Rules	0.91	27722523004
Bunch Mask	0.98	30065109069
ReTri	0	0

Figure 5. The L1T/HLT rates page.

3.6 Downtimes bookkeeping and reports

This section aggregates pages pertaining to the downtime bookkeeping and reporting, covering analyses such as runtime, dead time, and downtime assessments.

The main objective of the downtimes bookkeeping and report pages is to enhance the efficiency of CMS data taking. This is accomplished through the real-time and historical reporting of operational efficiency details, which are intended for use by the shift crew, operations group, detector experts, and run coordination management. In addition to monitoring downtimes, live time, and luminosity, they also record the causes of downtimes, enabling users to pinpoint the primary sources of downtime that affect DAQ.

3.7 Luminosity data summary

This category includes pages associated with CMS luminosity data summaries. These pages feature plots and tables illustrating luminosity and efficiency data grouped by day, week, month, and year, as well as performance records spanning different time intervals. The summaries page presents concise summaries and graphical representations of delivered and recorded luminosity, peak luminosity, and data-taking efficiency. These summaries are generated on a daily, weekly, monthly, or yearly basis. By default, the service displays information for the most recent time period, but it also allows retrieving earlier periods. The overview summaries page provides a comprehensive view of LHC runs 1, 2, and 3, along with links to more granular information through weekly summary pages.

3.8 Sub-system specific information

Apart from the previously described general OMS pages, OMS also provides dedicated pages for individual subsystems within the CMS detector. OMS can integrate the sub-system data with data-taking information, offering aggregated reports. Additionally, certain subsystems provide detector configuration data through OMS. Subsystem personnel are tasked with creating these pages and services. They develop their services for subsystem data and utilize the OMS framework to construct their pages instead of creating a web application from scratch.

4 First year of experience

During the first year of data taking in LHC Run 3, the OMS tools played a pivotal role in the CMS data collection activities and were utilized extensively, even by upper-level managers, to generate reports on data taking achievements, records, and efficiency.

OMS ran stably and reliably with only short downtimes when deploying new releases. The chosen technologies have proven to be adequate and performant. Especially the DWH was essential to improve the user experience by allowing faster access to pre-aggregated data from several database tables. Thanks to the flexible GUI configuration options, evolving user requirements driven by changes in data taking conditions could be easily handled.

5 Conclusions and future developments

In response to the monitoring needs in the CMS experiment, the OMS project offers a comprehensive set of tools to relay diverse information about detector operations from multiple sources. The OMS pages are accessible both locally and remotely, effectively addressing the demands of a widespread global collaboration. OMS emerged as an indispensable asset in efficiently managing data taking operations for the CMS detector. It functioned as a universal tool accessible to all CMS members, enabling them to inspect non-event data from Run 3, as well as from previous Run 1 and 2.

The CMS detector is planned to undergo important upgrades in view of the High Luminosity LHC. This involves not only significant changes in the sub-detectors but also upgrades to the L1T, DAQ, and HLT systems. Various enhancements and adjustments will be implemented, involving modifications to timing, DAQ system, trigger systems, and specific detector subsystems. A feasibility study will be conducted to explore new web technologies and determine the optimal choices for the upcoming OMS development, with the aim of streamlining the process by adopting a unified software language.

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