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2020/12/28
Archive Hash: 85410b3-D
Archive Date: 2020/12/22

CMS paper template: 2011 LaTeX/PdfLaTeX version

The CMS Collaboration

Abstract

DQM Paper abstract here.

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PDFAuthor:	Kaori Maeshima
PDFTitle:	CMS DQM Paper
PDFSubject:	CMS
PDFKeywords:	CMS, DQM, Data Certification, Software

Please also verify that the abstract does not use any user defined symbols

1 Introduction

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1.1 subsection in the Introduction section

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector can be found in Ref. [1].

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. During the LHC running period 2010-2016, the silicon tracker consisted of 1440 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles of $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter. From 2017 onwards, the silicon tracker consisted of 1856 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles of $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 2.5$, the track resolutions are typically 1.5% in p_{T} and 20–75 μm in the transverse impact parameter.

The ECAL consists of 75 848 lead tungstate crystals, which provide coverage in pseudorapidity $|\eta| < 1.48$ in a barrel region (EB) and $1.48 < |\eta| < 3.0$ in two endcap regions (EE). Preshower detectors consisting of two planes of silicon sensors interleaved with a total of $3X_0$ of lead are located in front of each EE detector. In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted or late-converting photons that have energies in the range of tens of GeV. The remaining barrel photons have a resolution of about 1.3% up to a pseudorapidity of $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$. In the endcaps, the resolution of unconverted or late-converting photons is about 2.5%, while the remaining endcap photons have a resolution between 3 and 4%. When combining information from the entire detector, the jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV.

The forward hadron (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end, and together they provide coverage in the range $3.0 < |\eta| < 5.2$. They also serve as luminosity monitors. Each HF calorimeter consist of 432 readout towers, containing long and short quartz fibers running parallel to the beam. The long fibers run the entire depth of the HF calorimeter (165 cm, or approximately 10 interaction length), while the short fibers start at a depth of 22 cm from the front of the detector. By reading out the two sets of fibers separately, it is possible to distinguish showers generated by electrons and photons, which deposit a large fraction of their energy in the long-fiber calorimeter segment, from those generated by hadrons, which produce on average nearly equal signals in both calorimeter segments.

In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in pseudorapidity and 0.087 in azimuth (ϕ). In the η-ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 arrays of ECAL crystals to form calorimeter towers projecting radially outwards from close to the nominal interaction point. For $|\eta| > 1.74$, the coverage of the towers increases progressively to a maximum of 0.174 in $\Delta\eta$ and $\Delta\phi$. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies, which are subsequently used to provide the energies and directions of hadronic jets.

Three types of gas ionization chambers were chosen to make up the CMS muon system: drift tube chambers (DTs), cathode strip chambers (CSCs), and resistive plate chambers (RPCs). The DTs are segmented into drift cells; the position of the muon is determined by measuring the drift time to an anode wire of a cell with a shaped electric field. The CSCs operate as standard multi-wire proportional counters but add a finely segmented cathode strip readout, which yields an accurate measurement of the position of the bending plane ($R - \phi$) coordinate at which the muon crosses the gas volume. The RPCs are double-gap chambers operated in avalanche mode and are primarily designed to provide timing information for the muon trigger. The DT and CSC chambers are located in the regions $|\eta| < 1.2$ and $0.9 < |\eta| < 2.4$, respectively, and are complemented by RPCs in the range $|\eta| < 1.9$. We distinguish three regions, naturally defined by the cylindrical geometry of CMS, referred to as the barrel ($|\eta| < 0.9$), overlap ($0.9 < |\eta| < 1.2$), and endcap ($1.2 < |\eta| < 2.4$) regions. The chambers are arranged to maximize the coverage and to provide some overlap where possible.

Events of interest are selected using a two-tiered trigger system [2]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed time interval of about 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

3 DQM infrastructure and tools

The Data Quality Monitoring is a central infrastructure in the CMS experiment. It is used in the following key environments:

1. Online, for real-time detector monitoring;
2. Offline, for the prompt-offline-feedback and final fine-grained data quality analysis and certification;
3. Validation of all the reconstruction software production releases;
4. Validation in Monte-Carlo simulation productions .

The DQM system spans the entire CMS readout and reconstruction chain as can be seen in Figure 1.

Though the basic structure of the Run1 DQM system[3, 4] remained the same for Run2[5–7], between the Run1 and Run2 periods, the DQM system underwent substantial upgrades in many areas[8], not only to adapt to the surrounding infrastructure changes, but also to provide improvements to meet the growing needs of the collaboration with an emphasis on more sophisticated methods for evaluating data quality. It was needed to cope with the higher-energy and -luminosity proton-proton collision data, as well as the data from various special runs, such as Heavy Ion runs.

This section describes the current DQM software, structure and workflow in the different environments.

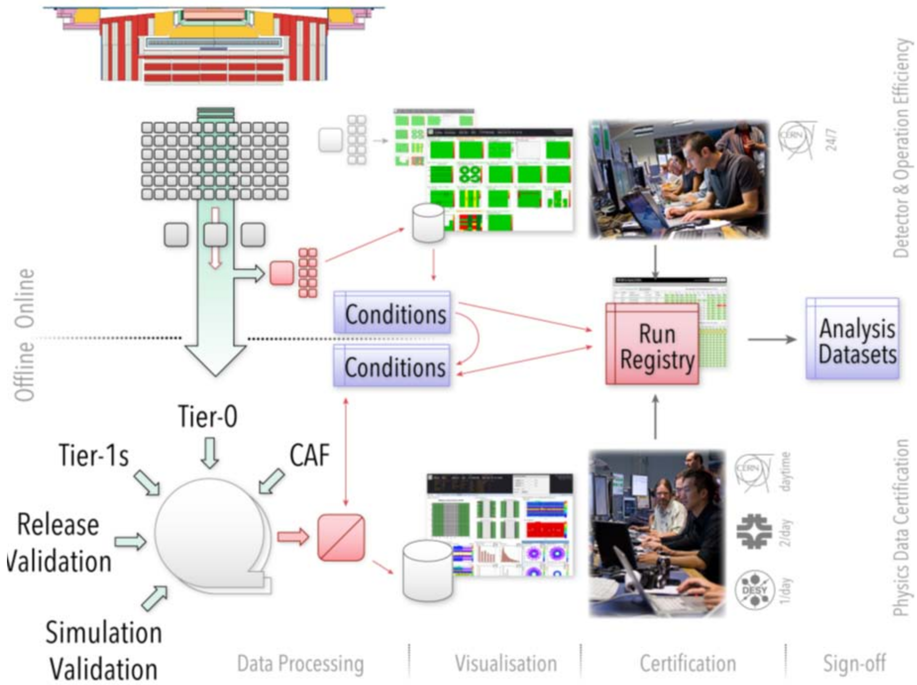

Figure 1: Usage of the DQM framework in the CMS experiment.

3.1 DQM system and usage

In the CMS experiment, the DQM group serves three related, but subtly different purposes:

1. it provides monitoring, that means it raises alarms when some part of the detector malfunctions;
2. it provides data certification, that means it records for which fractions of taken data parts of the detector were faulty;
3. it aids debugging, by providing detailed information that helps experts to find the cause of spotted issues.

The output for each of these tasks is very different: for the first two, it can be reduced to a single bit indicating the data quality as *good* or *bad*. The difference between monitoring and certification is that for monitoring the results have to be available in real time, while some false positive and even false negative rate can be tolerated. Instead for certification, the error rate should be as low as possible, while a delay of several days is acceptable. In contrast, as a debugging tool, the output of DQM consists of a large amount of plots called monitor elements (MEs). Usually, these are histograms in ROOT [9] format of some quantity derived from event data for a subpartition of the detector and some window of time. Detector experts can browse these MEs to understand what is happening in the detector.

The DQM group cooperates with each of the CMS subsystems to collect data about the subsystem and display it in an useful way. Subsystems are usually the different detectors in CMS, but also groups that are not directly represented in the CMS detector, such as the trigger systems and also DQM itself.

The DQM system consists of modules in the CMS data processing software (CMSSW) [10] as well as independent applications (see Section 3.2), which are run on hardware infrastructure dedicated to DQM. This software can roughly be decomposed into a data collection step, which consumes CMS event data and produces MEs, which are no longer connected to individual events; a visualization part, which makes the MEs browsable in a convenient form; and tools to handle metadata, including the final certification results. Each of these parts also has a user interface (UI): the data collection software is provided by subsystem experts, which are users of DQM; therefore the application programming interfaces (APIs) in this part of the DQM software are a part of the user interface.

The visualization of MEs is part of the user interface provided for debugging, but also used internally by the monitoring and certification team. This team then uses tools to record their findings, which are presented to the collaboration on another set of interfaces and user-facing APIs. This user interaction turned out to be one of the biggest challenges in DQM.

3.1.1 DQM software

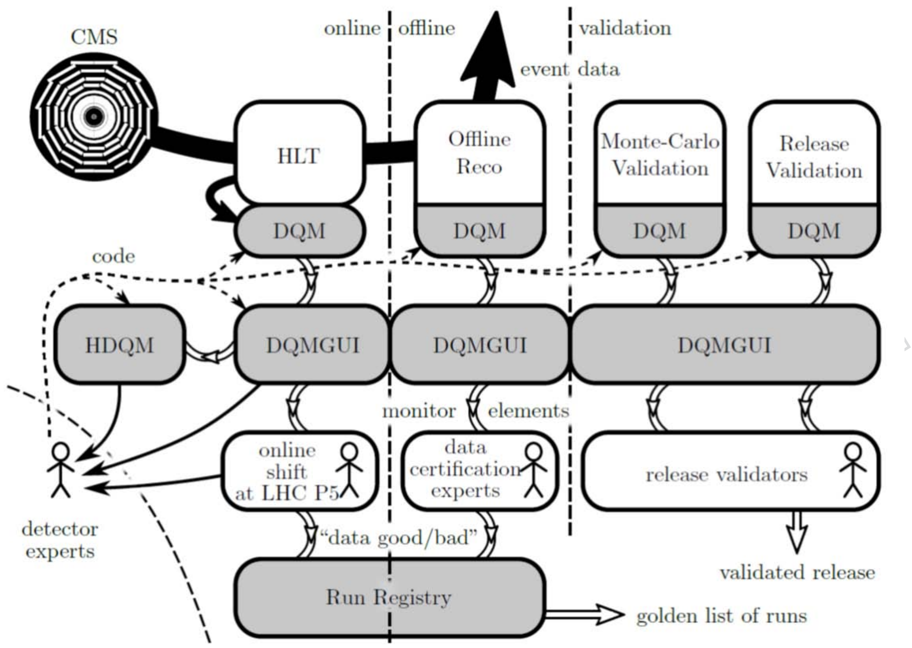

Figure 2: Schematic overview of the DQM system.

CMS event data is processed by CMSSW, using the event data model (EDM) framework specifically built for this purpose. This EDM framework allows to decompose the processing into small plugins, which are connected into sequences that event data is piped through.

The DQM system spans the entire CMS readout and reconstruction chain. Figure 2 shows a schematic overview of most of the components of DQM, with the software parts of the DQM system highlighted in gray.

DQM code runs as part of CMSSW for most places where CMSSW is used: in the High Level Trigger (DQM at HLT), in the dedicated online DQM machines, in the data reconstruction jobs in the CMS computing centers, and in the simulation and reconstruction jobs used for release validation and Monte-Carlo production. The MEs produced by all these jobs are aggregated in the DQM Graphical User Interfaces (DQMGUIs),which archive the data and provide a web-based interface to browse and view the DQM output. The DQMGUIs are then queried by the DQM shifters, certification and validation teams and subdetector experts, sometimes using additional tools. Most of these tools are summaried in Section 3.2.

The DQM plugins are developed by subsystem experts, using a framework provided by DQM. This DQM framework touches some corner cases of the EDM framework, since it consumes machines, in the data reconstruction jobs in the CMS computing centers, and simulated or event data but stores and outputs non-event data.

Since the functionality of the DQM framework within CMSSW to produce and save non-event data is also useful for other applications, there are a few plugins which use DQM infrastructure, even though they are not within the scope of DQM as outlined previously. Primarily such plugins are used by the Alignment and Calibration group to save data required to update the detector conditions, while providing the detector conditions to all CMSSW plugins handled by CMSSW EDM directly.

3.2 DQM tools

Several independent applications have been developed around the DQM system as shown on Figure 2, including the Run Registry (RR), the Graphical User Interface (DQMGUI), the Historic Data Quality Monitor (HDQM) and the DQM^2 tool. All these tools were built and maintained by DQM team and deal with CMS event data. However, detector information as well as LHC running conditions were monitored by the Web Based Monitoring (WBM) and Online Monitoring Systems (OMS). The following sections describe briefly the functionality of all these tools.

3.2.1 Run Registry

The CMS Run Registry (RR) [11] was a tool for tracking the quality of data taking runs for the experiment. This information was used to determine which data taking runs are used by various physics analyses. The RR consisted of a suite of applications deployed in the Web Based Monitoring(see Section 3.2.5) servers. The Online RR provided a user interface and tools for shift personnel to provide the initial quality assessment as runs are taken. The Offline RR provided a user interface and tools for offline shift personnel further evaluating data quality information for runs, this is shown in Figure 3. The User RR application provided a user interface and API for end users to browse, query, and export certification results for use in physics data analysis or other uses.

The RR was extensevely and sucessfully used during Run1 and Run2 data taking periods, and it was developed with the best existing technology of 2010-2012. In 2018 it was decided that a new upgraded version which made use of the latest programming and web technologies was needed. The 2018 version of RR was built up from the previous version and although some functionality was copied to function in the same way, the complexity was reduced by creating a same database for both Offline and Online content. An "event sourcing" schema design was selected on top of a regular SQL (Postgres) database: actions are saved in an SQL table. Several new features were also added including history tracking, since database is now immutable; bookmarkability, i.e. shareability of filtered runs; fields to store Machine Learning certification results in the future; linkability to OMS (see Section 3.2.5) and to DQM GUI and HDQM (see Section 3.2.3) applications.

2018 RR is divided into two parts, online and offline: online being the part of the web application used to record data monitoring results, run by run, by an online DQM shifter at Point 5. Offline being the part later used by shifters and data certification experts to certify the datasets from the runs that passed through online. Both -online and offline- are integrated into one web application (only one link is needed). It uses e-groups for authentication and a Python API client was created to access and modify data by other applications. Figure 4 shows a snapshot of the current RR. RR has being extensively commisioned during LS2 cosmic data taking and Run2 data reprocessing and certification and will be used from Run3 onwards.

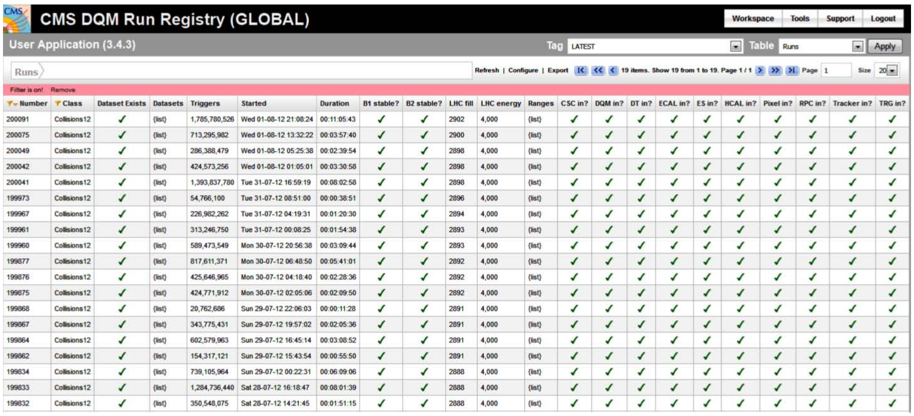

Figure 3: A snapshot of the Run2 Run Registry.

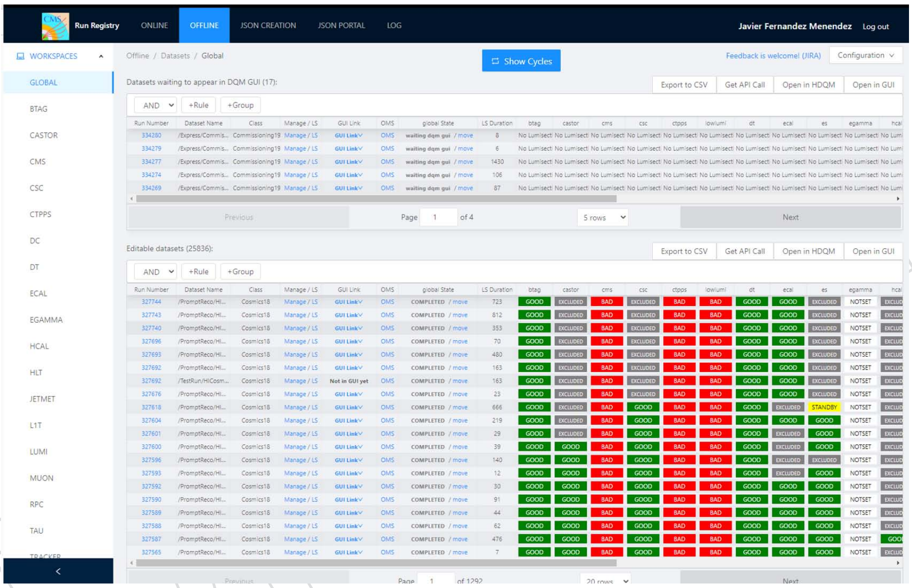

Figure 4: A snapshot of the 2018 Run Registry.

3.2.2 The Graphical User Interface

The monitor elements produced by CMSSW jobs are uploaded to the DQMGUI [3] for browsing and distribution. There are three main instances of the DQMGUI software, each running on dedicated hardware:

- the online DQMGUI, which displays data from the online system and is physically located in the datacenter at LHC Point 5;
- the offline DQMGUI, which holds the DQM output from offline reconstruction and has the largest volume of data;
- the RelVal DQMGUI, which holds the DQM output for release and MC validation.

Each DQMGUI consists of a web server hosting the web-based user interface (Figure 5), HTTP-based APIs to access DQM data, and a custom-built database called the index, which holds the actual monitor element data and can be queried via the APIs. Data enters the DQMGUIs as ROOT files containing the monitor elements. As a special case, the online DQMGUI also receives monitor elements from the online system over a custom network protocol: these live mode monitor elements are immediately shown in the web interface.

The detector experts contribute code to the DQMGUIs in the form of render plugins, which determine how monitor elements should be displayed, as well as layouts, which provide useful overviews tailored to specific use cases.

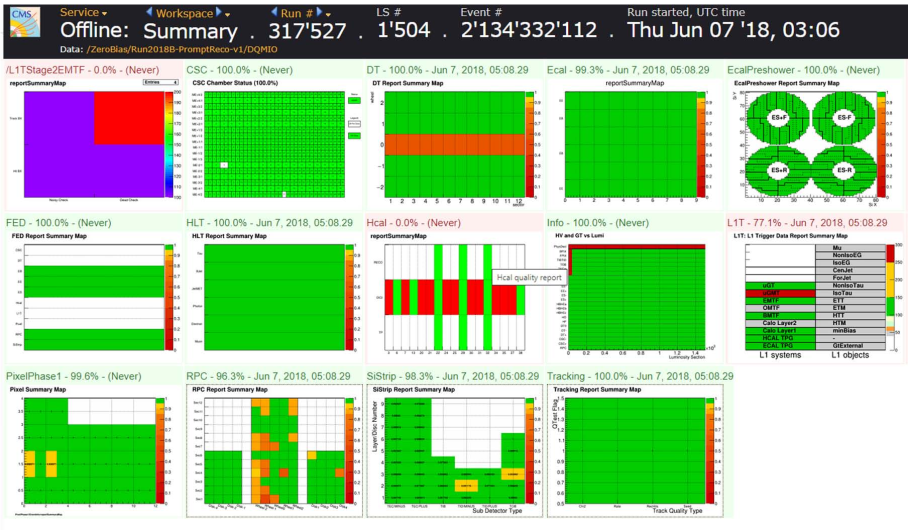

Figure 5: Example from the DQM Graphical User Interface.

The DQMGUI was used sucessfully during the Run1 and Run2; in the year 2020 it was redesigned making use of modern technologies which would allow for better maintainability as well as an ability to add more complex features, which would improve the user experience. The redesign was made in both the frontend and the backend, keeping them as independent projects. The new GUI frontend is now a statically generated site with access to the backend via ajax http requests, in comparison to the old one which was server rendered on every page change. The new DQMGUI backend was designated with the latest ProtoBuf technologies, so that now DQM ROOT files can be directly read from disk (EOS) [12] instead of the previous uploads to the server which produced some problems like corruption of database index or failing uploads.

This architecture allows three advantages:

- Performance: every time there is a page change, there is no need to go to the server and re-render everything.
- Maintainability: backend and frontend are decoupled and thus can even be developed by separate teams.
- Deployment: frontend can be deployed everywhere as it just consists of static html, css and js files.

Several new features were added to the DQMGUI:

- Java Script ROOT plots overlay
- Plots with per lumisection granularity (offline GUI only) instead of run by run
- Clear indication of errors, updates and loading
- Live mode plots updates are based on files, but not streamed directly by clients
- Different ways of plot comparison with up to 8 histograms

The technologies used for the frontend were the following:

- React.js - A library for building user interfaces
- TypeScript - the main benefit of Typescript is that it offers the ability to add static types to Javascript code.
- Next.js - web application framework, based on React.
- Ant design - React UI library.
- Styled Components - a tool for overwrite component styles (in this case Ant Design component css).

The Figure 6 shows a snapshot of the new DQMGUI with a comparison of up to 8 different versions of the same ME. The new DQMGUI has entered its commisioning state during the LS2 and is expected to be fully operative during year 2021 in time for the Run3 data taking.

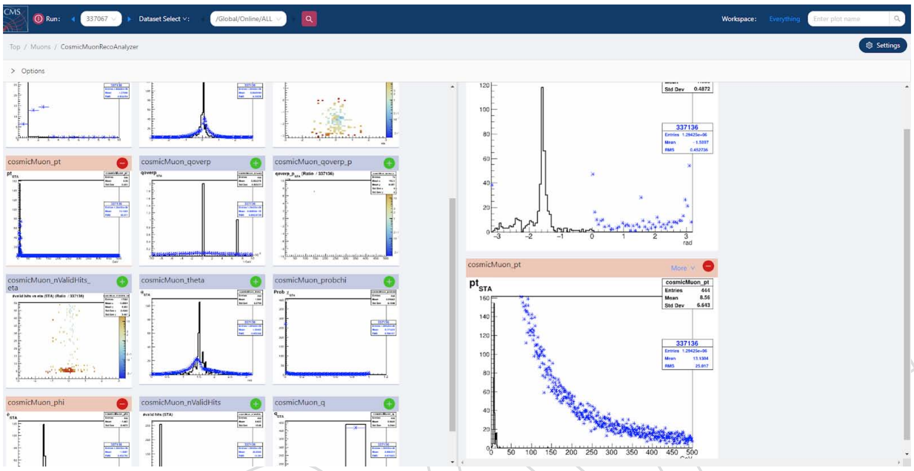

Figure 6: Example from the new DQM Graphical User Interface.

3.2.3 The Historic Data Quality Monitor

Monitoring the time evolution of data related observables is important for the successful operation of the LHC experiments. It permits keeping control on data quality during LHC running and also effectively checking the influence on data of any detector calibration performed during the year. The Historic Data Quality Monitor (HDQM) of the CMS experiment is a framework originally developed by the Tracker group of the CMS collaboration[13] that permits a web-based monitoring of the time evolution of interesting quantities (i.e. signal to noise ratio and cluster size) in the Tracker Silicon micro-strip and pixel.

During LS2, the HDQM was extended to other subsystems from CMS and upgraded with numerous extra functionalities like time trends of relevant DQM quantities as a function of the run number, over long periods of data taking. Also 2D correlation plots, where each point represents a single run, can be easily obtained accesing DQM information from ROOT files directly stored in EOS. Information from OMS data is linked for each run and an API was added to ease the interaction. At present, this central CMS tool is being used by almost all the subsystems and subdetectors. Figure 7 shows an example from the HDQM Front End displaying several trends versus run number for different Tracker observables

3.2.4 The DQM^2 interface

The DQM^2 tool is a web based interface which allows to monitor in real time the processing of the Online DQM streams, including magnitudes such as:

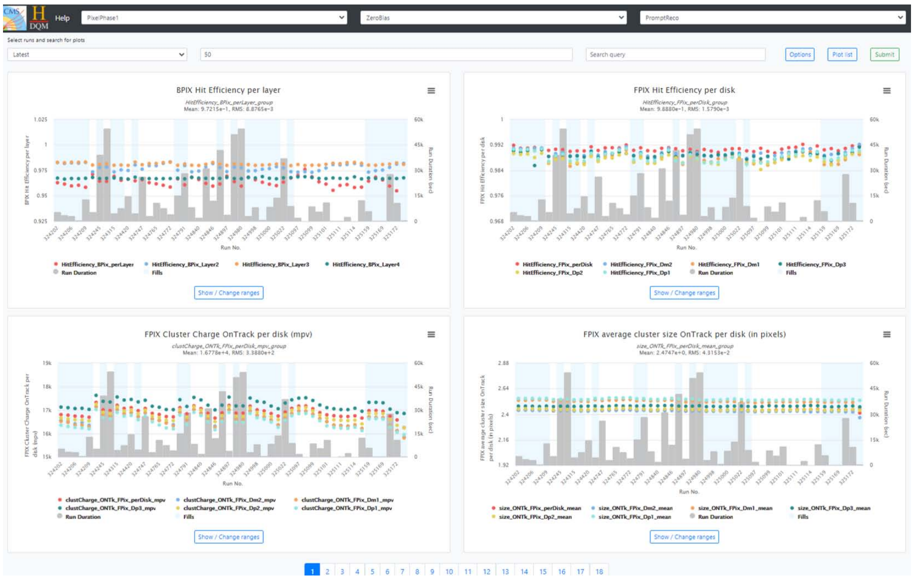

Figure 7: Example from the HDQM Front End displaying several trends versus run number for different Tracker observables.

- the delay (in seconds) of files delivered by the DAQ system on the DQM cluster, per LumiSection.
- the amount of events per file delivered by the DAQ system on the DQM cluster, per LumiSection.
- the list of running applications: this shows a list of all the configurations that were/are run for the run in question, including full logs

3.2.5 Web Based and Online Monitoring System

The DQM framework shows event data but needs accurate detector status information in order to provide hardware answers to possible data defects but also to collect information about LHC conditions at CMS and fill and run durations of data taking.

Efficient operation of the detector requires widespread and timely access to a broad range of monitoring and status information. To that end the Web Based Monitoring (WBM)[14] system was developed to present data to users located anywhere from many underlying heterogeneous sources, from real time messaging systems to relational databases. This system provided the power to combine and correlate data in both graphical and tabular formats of interest to the experimenters, including data such as beam conditions, luminosity, trigger rates, detector conditions, and many others, allowing for flexibility on the user's side.

The goal of the CMS WBM system is to provide collaborators a way to monitor the operational status of the detector and diagnose problems from any location via a web browser. The WBM is a set of hardware and software that acquires data from diverse online monitoring sources and makes them available to a set of web based applications accessible to any authenticated user anywhere.

These applications gave access to a summary of the current status of the experiment as well as convenient access to historical data. A single application can easily include information from different major online systems and the LHC accelerator. These applications are used by shift crew members, detector subsystem experts, operation coordinators, and those performing physics analyses. The tools have become important in managing data taking operations for the

CMS detector. This monitoring was complementary to the DQM tools that are based on event data.

Status of the trigger and DAQ systems is provided via the monitoring system of the online data acquisition framework XDAQ[15]. XDAQ is a software platform designed at CMS specifically for the development of distributed data acquisition systems. In addition to obtaining general status information, the Scaler server examines rate-counter information to note starts and stops in data taking and writes this information to the database. This information is used by WBM services that account for operational down time. Trigger scaler data is also recorded in the database. The Scaler server is a frontend in the data acquisition system, and contains hardware interfaces allowing it to insert some data it acquires into the raw data stream. This data includes the beam position, luminosity, bunch number, scalers, and subsystem status and other information required by the High Level Trigger and DQM systems. Online luminosity information measured by CMS subdetectors is obtained from the luminosity subsystem via a Data Interchange Protocol (DIP) [16] and also logged to the database. This information is used to mark blocks of delivered luminosity, approximately 23 seconds in duration, called Luminosity Sections (LSs). The detector subsystem status as well as scalers and other run time information is recorded in the database for each of these sections. The LSs where some part of the detector is not functioning properly may be excluded from some offline physics analyses. These sections are long enough to allow a precise determination of the luminosity but short enough so that data loss is minimized when the detector is not fully functional.

Since the inception of CMS, the WBM activity was the one that provided tools for run-time and retrospective monitoring of the detector. During the first decade of data taking (Run1+Run2), the WBM has accumulated experience and tools that provided efficient detector monitoring. In order to ensure longterm support of the manpower and technical resources for the monitoring tools required for CMS, in 2015 it was decided to re-designed the core functionality of former WBM into the CMS Online Monitoring System (OMS)[17] by mean of two layers: one for the aggregation layer and another for presentation. Framework and initial content development took place throughout the year 2017 and the first production version was announced in February 2018. It is planned that OMS will have a full functionality starting in Run 3 (2021, fully replacing WBM) while active development has converged during 2019

The OMS is an upgrade and successor to the WBM system, which is an essential tool for shift crew members, detector subsystem experts, operations coordinators, and those performing physics analyses. The CMS OMS is divided into aggregation and presentation layers. Communication between layers uses RESTful JSON:API compliant requests. The aggregation layer is responsible for collecting data from heterogeneous sources, storage of transformed and pre-calculated (aggregated) values and exposure of data via the RESTful API.

The presentation layer displays detector information via a modern, user-friendly and customizable web interface. The CMS OMS user interface is composed of a set of cutting-edge software frameworks and tools to display non-event data to any authenticated CMS user worldwide. The web interface tree-like component structure comprises (top-down): workspaces, folders, pages, controllers and portlets. A clear hierarchy gives the required flexibility and control for content organization. Each bottom element instantiates a portlet and is a reusable component that displays a single aspect of data, like a table, a plot, an article. Figure 8 shows a reduced view of the OMS user interface.

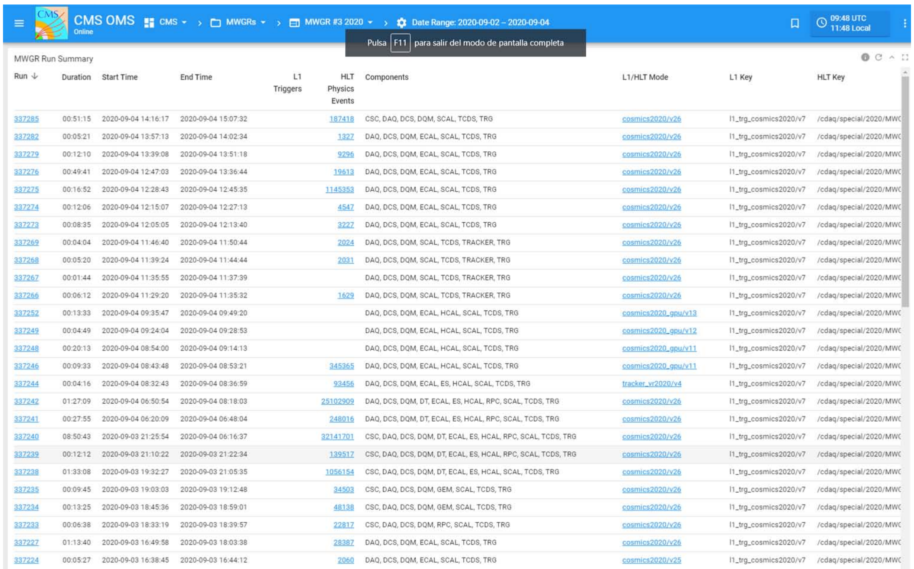

Figure 8: A view of the Online Monitoring System (OMS) user interface.

4 DQM and Data Certification operation and performance

4.1 Online data quality monitoring

4.1.1 Online DQM system and operation

4.1.2 DQM shift operation

4.2 Data Certification

4.2.1 Data certification workflow

4.2.2 Data certification results

5 Summary

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: the Austrian Federal Ministry of Education, Science and Research and the Austrian Science Fund; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport, and the Croatian Science Foundation; the Research and Innovation Foundation, Cyprus; the Secretariat for Higher Education, Science, Technology and Innovation, Ecuador; the Ministry of Education and Research, Estonian Research Council via PRG780, PRG803 and PRG445 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and

Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l'Énergie Atomique et aux Énergies Alternatives / CEA, France; the Bundesministerium für Bildung und Forschung, the Deutsche Forschungsgemeinschaft (DFG) under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Research, Development and Innovation Fund, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Ministry of Science, ICT and Future Planning, and National Research Foundation (NRF), Republic of Korea; the Ministry of Education and Science of the Republic of Latvia; the Lithuanian Academy of Sciences; the Ministry of Education, and University of Malaya (Malaysia); the Ministry of Science of Montenegro; the Mexican Funding Agencies (BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI); the Ministry of Business, Innovation and Employment, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR, Dubna; the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, the Russian Foundation for Basic Research, and the National Research Center "Kurchatov Institute"; the Ministry of Education, Science and Technological Development of Serbia; the Secretaría de Estado de Investigación, Desarrollo e Innovación, Programa Consolider-Ingenio 2010, Plan Estatal de Investigación Científica y Técnica y de Innovación 2017–2020, research project IDI-2018-000174 del Principado de Asturias, and Fondo Europeo de Desarrollo Regional, Spain; the Ministry of Science, Technology and Research, Sri Lanka; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the Ministry of Science and Technology, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology of Thailand, Special Task Force for Activating Research and the National Science and Technology Development Agency of Thailand; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the National Academy of Sciences of Ukraine; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Scientific and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, project no. 02.a03.21.0005 (Russia); the

Tomsk Polytechnic University Competitiveness Enhancement Program; the Programa de Excelencia María de Maeztu, and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programmes cofinanced by EU-ESF, and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University, and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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