

Automated workflows for critical time-dependent calibrations at the CMS experiment

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Abstract. Fast and efficient methods for the calibration and the alignment of the detector are a key asset to exploit the physics potential of the Compact Muon Solenoid (CMS) detector and to ensure timely preparation of results for conferences and publications. To achieve this goal, the CMS experiment has set up a powerful framework. This includes automated workflows in the context of a prompt calibration concept, which allows for a quick turnaround of the calibration process following as fast as possible any change in running conditions. The presentation will review the design and operational experience of these workflows and the related monitoring system during the LHC Run I and focus on the development, deployment and commissioning in preparation of Run II.

1. Introduction

The Compact Muon Solenoid (CMS) is a multipurpose detector operated at the CERN Large Hadron Collider (LHC). The central feature the CMS apparatus is a superconducting solenoid of 6m internal diameter, providing a magnetic field of 3.8T. Within the superconducting 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. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [1].

The high level of complexity of the CMS experiment and its large number of detector channels reflect in an elaborated framework for the management and computation of the detector calibration and alignment.

Having the most accurate calibrations available with short turnaround is a key asset for several aspects of the detector operations. First, it allows for an efficient online event selection by the High Level Trigger (HLT) [2] while keeping the acquisition rate under control. Second, a quick turnaround for the calibration and alignment allows to deliver datasets ready for analysis within a few hours from their acquisition, profiting at best of the increased luminosity delivered by the LHC machine. Also, having refined calibrations in time for the first reconstruction of the physics objects limits the need for further processing of the data allowing the computing resources of the experiment to cope with a higher acquisition rate, thus broadening the physics reach of the experiment.



The present contribution reviews the workflows meant for the continuous monitoring and low-latency computation of calibration conditions which can change on short time scale and potentially affect the physics performance of the online and offline reconstruction algorithms.

2. Prompt calibration concept and data processing

The strategy for running low-latency calibration workflows is based on the delay between the reconstruction of a selection of the data feeding the calibration algorithms and the reconstruction of the bulk of the data for physics analysis.

This is implemented having dedicated data streams produced by the HLT and reconstructed with different latency on the Tier0 processing farm at CERN:

- **express processing:** reconstruction of a limited selection of data in order to give prompt feedback about the detector status and physics performance and to provide data for calibration workflows. The results of the express reconstruction for a given run are usually available one or two hours after collecting the raw data;
- **bulk processing:** reconstruction of the main data stream for physics analysis. This reconstruction step, also called *prompt reconstruction*, is delayed by 48 hours to allow for the computation of the fast-changing conditions. The output is divided in several Primary Datasets (PD) on the basis of the HLT paths used to select the events.

During normal operation of the CMS experiment in the LHC Run I about 300-400Hz of data were processed in the bulk processing. The average data-collection rate during a LHC fill is expected to be about 1kHz in Run II. Only a limited bandwidth, corresponding to about 30-40Hz, is allocated for the express processing in order to guarantee a fast reconstruction time.

The output of the express processing is further divided in smaller datasets dedicated to the calibration algorithms and optimized both in terms of event selection and event content. These are called *AlCaReco datasets* and they are used as input to the calibration workflows including those running unattended on the Tier0 computing farm. These workflows are executed for each run, producing sets of alignment and calibration conditions, together with plots monitoring the performance of the calibration algorithms, which are automatically uploaded to the Condition Database [3] and consumed, after a few hours, by the prompt reconstruction of the data belonging to the same run.

2.1. General design of the automated workflows running on the Tier0 computing farm

In the current implementation, already exercised during LHC Run I, the automated workflows are executed for each acquisition run, corresponding to a stable period of data-taking of the CMS experiment. Each of these runs can last between less than one and several hours depending on the length of the proton fill in the LHC and the detector status. Figure 1 illustrates in a schematic way the general mechanism utilized to compute the calibration conditions. Development is ongoing to be able, in the future, to compute calibrations collecting data across runs, however this is not covered in this document.

The express data belonging to the same run are processed by parallel jobs using the CMSSW reconstruction package [4] on the Tier0 computing farm. These jobs perform both the reconstruction of the physics objects for analysis purposes and the selection of events for the alignment and calibration algorithms storing them in the AlCaReco datasets. The next step in the processing uses these AlCaReco datasets as input and executes the calibration algorithms in parallel on a limited set of events of the run. This step is usually the most CPU intensive of the whole workflow and produces as output intermediate calibration products specific to the given quantity that needs to be calibrated: these products can be histograms or calibration constants computed by the single job. The job splitting is optimized to provide each application with

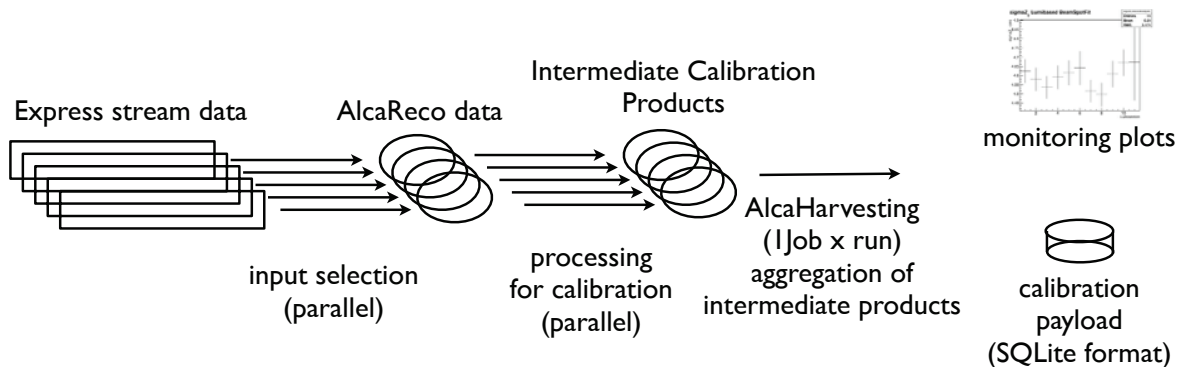


Figure 1. Schematic view of the automated workflows for the computation of alignment and calibration constants for one run on the Tier0 computing farm.

chunks of contiguous events keeping as atomic quantum of the processing a so called *luminosity-section* corresponding to about 23s of data-taking. This logic is functional to the calibration of quantities which might vary within the run allowing for their computation on time intervals as small as one *luminosity-section*.

The last step consists in the aggregation of all the intermediate products for a given run into a set of conditions for future consumption by the reconstruction jobs. This step, called *AlCa Harvesting*, is actually performed by a single job per run and produces as output one or more database payloads (depending on the time granularity of the quantity being computed) stored in a SQLite file. Monitoring histograms in ROOT [5] format are also produced utilizing the powerful Data Quality Monitoring (DQM) [6] framework. These histograms are uploaded to the web-based Graphical User Interface for inspection of the performance of the calibration algorithms by the detector experts.

2.2. Condition database and tools for automatic handling of the calibration constants

The non-event data resulting from calibration and alignment algorithms, usually referred as *conditions*, are stored in the CMS *Condition Database* [3] for consumption by the online HLT selection and offline reconstruction of the physics objects. This database relies on the Oracle technology for the persistency of the data and their retrieval according to their validity in time and their aggregation in consistent sets. These sets describe the conditions for a particular configuration of the detector, a given LHC running conditions and the particular scope of the application that will consume them. Each set of data for a given calibration condition is referred to as *payload* and is described in the CMSSW applications by a user defined C++ class (*payload type*). The condition framework maps the instances of the payload types to the data stored in the underlying database.

For security and reliability reasons, calibration data can be written in the condition database only from within the technical network of the experiment which is protected by a firewall separating it from the general purpose CERN network. This design does not allow for direct export to the Oracle database of the payloads computed on the Tier0 farm. The *Offline Drop-Box service* [7] is a web application which is used for the automatic upload of calibration payloads to the condition database. This service hides the complexity of the low level database operations and of the network configuration allowing for insertion of new calibration payloads by authenticated users or applications operating in the general purpose network. SQLite files are used as portable interchange format of the calibration data and can be pushed to the

Drop-Box service together with a metadata file, in JSON format, specifying the details of the export operation such as target dataset and target interval of time-validity of the payload. The automated workflows running on the Tier0 computing farm use the Offline Drop-Box service for the upload of the newly created conditions: a dedicated daemon sends the SQLite files created by the AlCa Harvesting step to the web application together with metadata files created on the fly on the basis of a configuration stored in the Condition Database itself.

The Offline Drop-Box also guarantees the reproducibility of the results of the online HLT and of the prompt reconstruction avoiding accidental overwriting of condition payloads already consumed by these applications. This is enforced for each new upload checking the time validity specified in the metadata against a dedicated APIs exposing the last run processed by the HLT farm and by the prompt reconstruction of the bulk of the data running on the Tier0 farm.

3. Performance and Operational Experience

The automated calibration system has already been successfully utilized during the data taking in the LHC Run I. In preparation to the Run II, a general consolidation effort was put in place and new calibration algorithms have been integrated. Currently, the following workflows are operated in this framework:

- fit of the luminous region: track beam-spot 3D position and size as a function of time, delivering up to one set of measurements every 23s;
- identification of transient problematic channels in the SiStrip tracker for event-by-event optimization of the pattern recognition reconstructing the trajectories of charged particles;
- determination of charge gains of the SiStrip tracker sensors to correct for radiation induced effects;
- track-based alignment of the large structures in the silicon pixel detector.

In addition, applications monitoring the radiation damage of the ECAL crystals run on dedicated resources within the online computing cluster, delivering one measurement for all the 76000 PbWO₄ scintillating crystals about every 30 minutes. This workflow uses the same mechanism described for the Tier0 ones but it is performed online due to the dependency on custom hardware for the monitoring of the laser pulses used to measure the crystal transparency.

A comprehensive description of these calibration algorithms is beyond the scope of this document. In the following we report on the operational experience and performance for a few of them.

3.1. Fit of the luminous region

The measurement of the three-dimensional profile of the luminous region where the LHC beams collide in the CMS detector [8] is an important component of the event reconstruction being used as an estimate of the primary interaction point prior to the reconstruction of the primary vertex. The position of the center of the luminous region and its width are determined using two independent methods with different systematic uncertainties. The first uses the distribution of the reconstructed primary vertices over several events to map the shape of the beam line; the mean three-dimensional position is determined with a 3D likelihood fit. The second method exploits the correlation between the transverse impact parameter and the azimuthal angle ($d_0 - \phi$) of tracks when the beam line is displaced from the expected position. With a sample of 1000 tracks, the position can be determined with a statistical precision of about $5\mu\text{m}$. The fit is performed once per luminosity-section using tracks selected in the express stream. In the AlCa Harvesting step, ranges with stable parameters are "collapsed", increasing the statistical precision and reducing the database storage size. This allows for the best possible knowledge of the position of the luminous region within a few hours of data being collected, with a time granularity fine enough to track possible movements during the fill, as shown in Figure 2.

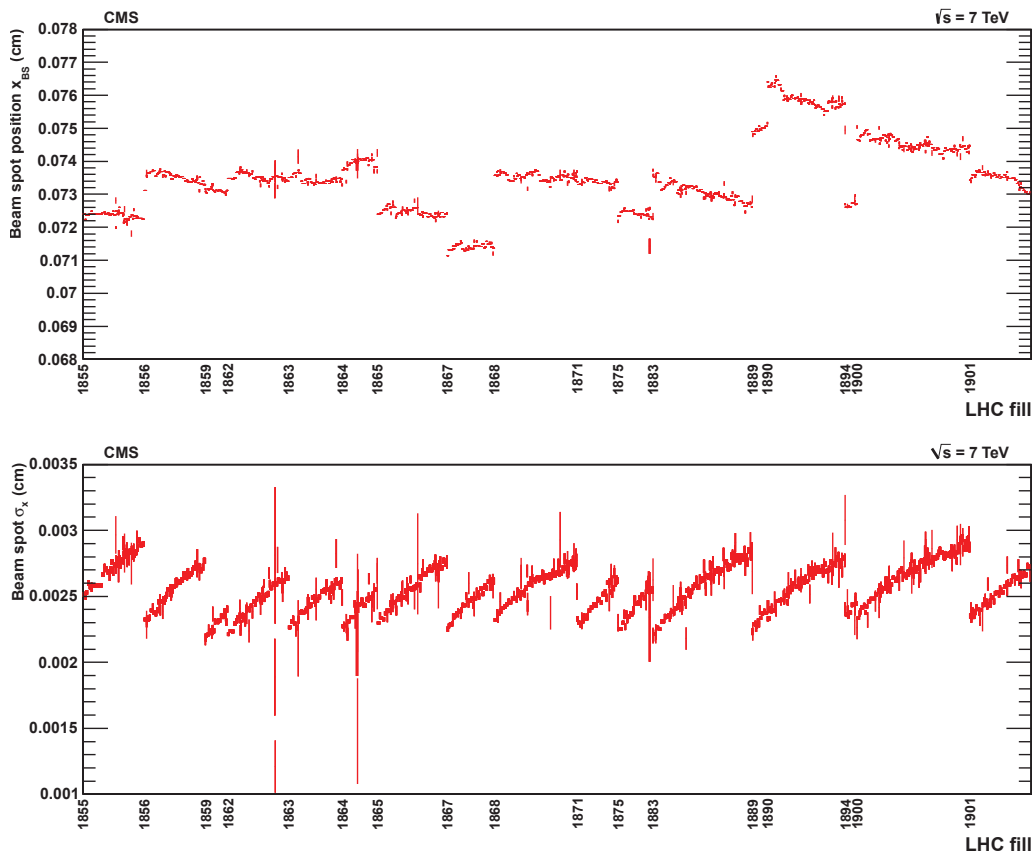


Figure 2. Fitted positions of the centre x_{BS} (top) and width σ_x (bottom) of the luminous region in the transverse plane as a function of time during early 2011 running. The position is extracted from the fit to the $d_0 - \phi$ distribution while the width is measured from the fit to the distribution of reconstructed primary vertices. Each point represents one luminosity section of 23 seconds. The error bars reflect the statistical uncertainty from the fit [8].

3.2. Alignment of the large structures of the pixel barrel detector

The barrel of the silicon pixel detector is composed of two half-shells positioned around the beam-pipe. It has been observed that the two structures move with respect to each other in time, with the biggest excursions along the longitudinal coordinate z . These movements are correlated with power and thermal cycles of the detector component and, as a consequence, need to be monitored and corrected for during the operation of the CMS detector. Specifically, the position of the large structures in the pixel detector is relevant for the performance of b-tagging algorithms which are affected by misalignment at the level of a few tens of microns.

The half-shell separation along z is monitored using unbiased vertex-track residuals. Day-by-day values of the relative longitudinal shift are shown in Figure 3 for a period during the LHC Run I in which an exceptionally large movement has been spotted in connection with a cooling accident. The prompt calibration of this quantity has been activated soon after this episode correcting completely the mis-alignment observed in the previous data. The alignment algorithm is based on global minimization of track-to-hit residuals using the MillepedeII program [9]. The input dataset is a selection of high quality tracks reconstructed during the express processing. Given the need to determine only 6 parameters considering the large structures as rigid bodies, a

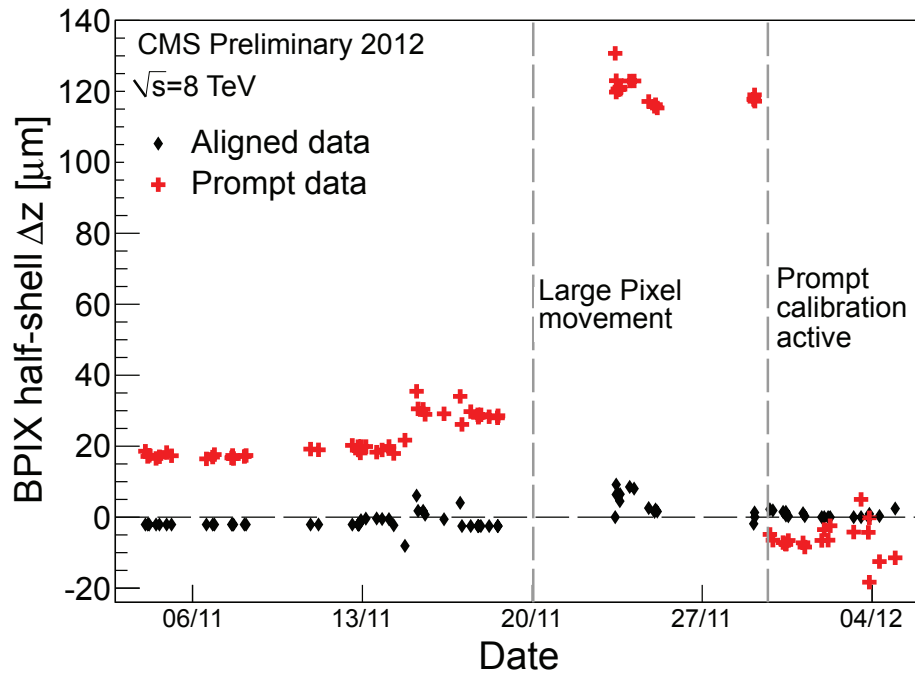


Figure 3. Day-by-day value of the relative longitudinal shift between the two half-shells of the barrel pixel as measured with the primary vertex residuals, for the last month of pp data taking in 2012. Red crosses show the shift observed using the data coming from the prompt reconstruction. The same events, re-reconstructed after the 2012 alignment campaign, which accounts for the major changes in the positions of the half-shells, are represented by black lozenges. A major displacement of the half-shells $O(100\mu\text{m})$, occurred during the technical stop in the week of 20th of November, is recovered by the prompt alignment of the pixel large structures that became active on the 30th November.

few thousands of events are sufficient to reach the desired accuracy. Module by module alignment requires higher statistics of tracks and is performed only offline.

4. Monitoring of the automatic workflows and of the physics performance of the calibrations

As for any unattended workflow, a continuous monitoring, both on the infrastructure side and on the physics performance of the algorithm, is crucial. Three layers of systematic checks are implemented in the automated system for prompt calibration.

The first level of scrutiny monitors the functionality of all the components involved in the workflows. It is performed by a dedicated web service, called *pclMon* aggregating information from various sources with the goal of promptly identifying possible hiccups which might delay or impede the computation or deployment of updated calibration sets. The service issues automatic alarms exploiting the delay between the express and bulk processing for possible corrective interventions. An expert on-call shifter, acting as *offline run manager*, is responsible for the operation of this infrastructure.

The second layer of monitoring concerns the physics performance of the calibration algorithms. It is implemented using the DQM framework running during the actual computation of the calibration and alignment constants. Monitoring plots are produced during the AICa Harvesting and the previous steps, their statistics is merged for all the jobs belonging to the

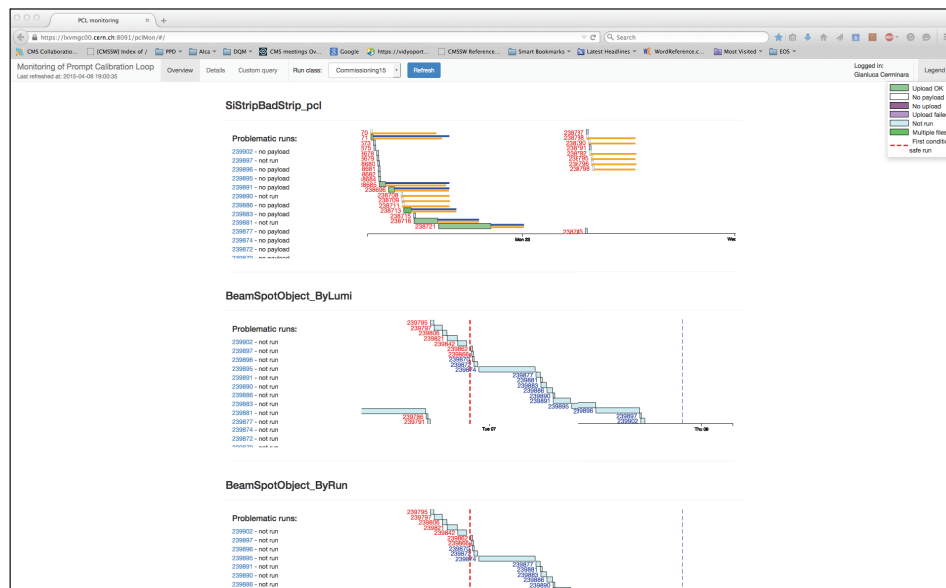


Figure 4. Screenshot of the pclMon web interface displaying the status of the various workflows for cosmics runs acquired during the recommissioning phase in preparation to the LHC Run II.

same run and they are displayed on a GUI for regular scrutiny by the experts of the given workflow.

Finally, the same DQM infrastructure is used during the reconstruction of the bulk of the data with dedicated applications monitoring the reconstructed quantities most sensitive to the updated calibrations. Potential issues spotted at this level by the detector experts can be addressed only applying re-computed calibrations in further reconstruction passes. The corresponding data can be temporarily flagged as not suitable for analysis. By design these cases are limited to rare incidents with the automated calibration machinery not spotted by the other two validation steps.

4.1. pclMon: an application for the monitoring of unattended automatic calibration workflows

The pclMon web-based application is meant for continuous monitoring of all the steps of the automated workflows running on the Tier0 computing farm. Its backend, implemented using the CherryPy python framework and SQL technology for the caching and storage of the data, fetches information from various other services aggregating and elaborating it for all the runs. For each of the calibration workflows listed in Section 3 the following information is displayed:

- start and end time of the run to be calibrated;
- status of the Tier0 processing and in particular of the AlCa Harvesting step;
- delay between the end of the run and the completion of the AlCa Harvesting step;
- display runs for which the minimal requirements in terms of statistics are not met;
- status and delay of the upload of the SQLite files containing the calibration conditions to the Offline Drop-Box;
- status of the payload in the target calibration set in the Condition Database;
- status of the advancement of the bulk processing for prompt reconstruction on the Tier0 computing farm.

Whenever one of the above quantities displays a problem which might impact the availability of the updated calibration conditions in time for the prompt processing of the bulk of the data an

alarm is issued both via e-mail and on the on the javascript based front-end. The web interface allows the offline run manager shifter to visualize a time ordered information on the status of all the processed runs as shown in Figure 4. The application also allows for error acknowledgment to facilitate the communication between the Tier0 operators, the offline run manager and the detector experts in case of issues identified by the application.

5. Conclusions

The optimal alignment and calibration of each detector component is a key requirement in order to achieve the full resolution and physics performance of the CMS detector. For this purpose, the collaboration set up a powerful framework that has demonstrated the required robustness and flexibility since the beginning of the LHC operation, delivering accurate calibrations with a fast turnaround and thus minimizing the need for offline reprocessing of the data.

In view of the second LHC run, new workflows have been integrated in this framework and the setup for running them and monitoring their performance underwent a general consolidation effort.

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