Status of the LHCb experiment

CERN-RRB-2016-31

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1 Introduction

LHCb continued its succesful start to Run 2 by accumulating a total of 320 pb^{-1} in pp collisions at a global efficiency of around 90%. At the end of the year the experiment participated for the first time in heavy-ion data taking. Fixed target collisions were also collected using LHCb's unique SMOG gas-injection system. All sub-detectors were fully functional and acquired high-quality data. During the shutdown at the end of the year consolidation and maintenance work has been performed. Details are presented in Sect. 2.

During 2015 significant improvements to the running strategy were implemented. Most important of these was the move to a 'split HLT', where the second stage of the High Level Trigger is deferred and only run after a 'physics quality' alignment and calibration has been performed on the data. This approach allows for more discriminating selections to be applied, and ensures that the recorded data are more closely aligned with the requirements of the offline analysis. This revolutionary new scheme has been a great success, and has allowed the rapid release of first results from Run 2 data taking [1, 2]. Further refinements have been developed and will be deployed during 2016. The status of Run 2 operations is summarised in Sect. 3.

The LHCb collaboration has continued to release physics results of high scientific interest. A total of 305 papers have now been submitted to journals and several preliminary results have been shown at conferences. Recent highlights include a precise determination of the unitarity-triangle angle γ [3–6], new results on pentaquarks [7], and high sensitivity studies in the charm sector [8, 9]. Selected physics results are presented in Sect. 4.

Financial issues and collaborations matters are reviewed in Sects. 5 and 6, respectively.

Finally, significant efforts have been invested into preparations for the LHCb Upgrade, scheduled to be installed in Long Shutdown 2. This work is described in a separate document [10].

2 Detector sub-systems

After a successful completion of operation in the 2015 run, including the first ever LHCb participation in heavy-ion collisions at the end of the year, LHCb started the year-end technical stop (YETS) in December. All sub-detectors, except the VELO and RICH1, were opened for maintenance or repair work. Several consolidation activities were embarked upon and are now either finished or will finish very soon.

A temporary cooling system with maximal capacity of 400 kW was installed to allow maintenance of the general cooling towers. Furthermore, a back-up cooling system for the computing room is in preparation. The gas system for the Muon GEM detector was replaced by a closed loop system, thereby considerably reducing the amount of green-house gas released into the atmosphere. A non-negligible leak in the cooling system of the silicon tracker was localised and fixed.

The Maraton power supplies required a preventive maintenance intervention, which was successfully completed by the technical coordination team. The cooling connectors were replaced on 99 power supplies as indications of corrosion had been observed.

The new LHCb control room is being commissioned. In total, more than 150 work packages were processed and around 800 visitors were welcomed at Point 8 over the entire YETS.

All detectors are now closed, the beam pipe is back under vacuum and LHCb is ready for collisions.

2.1 Vertex Locator (VELO)

The VELO was operated successfully throughout 2015 with a trained team of experts and detector-specific monitoring in place. Special measures were introduced at the start of the PbPb collisions to follow closely the detectors response to this challenging new environment, but no problems were encountered.

The radiation damage to the VELO sensors is constantly monitored. Several methods are employed to this end, and there have been significant improvements in automating them. In particular, an analysis of all VELO sensor currents as a function of bias voltage (IV scan) is now performed after each fill. This had been put on hold early in 2015 due to safety concerns; it had to be made sure that the VELO high voltage (HV) is in a safe state for all changes in the LHC states – a technically complicated problem that is now solved in collaboration with the LHCb online operations team. These scans were reinstated late in the run and will be performed throughout 2016.

The VELO regularly requests special data-taking runs in parallel with the other LHCb silicon detectors to assess the charge collection efficiency (CCE) of the sensors. The latest results are illustrated in Fig. 1. The measurements are in good agreement with radiation-damage models and hence allow reliable predictions to be made. It is concluded that the most irradiated sensors will need to be biased with 450 V by the end of the LHC Run 2. As trips of the VELO HV system have

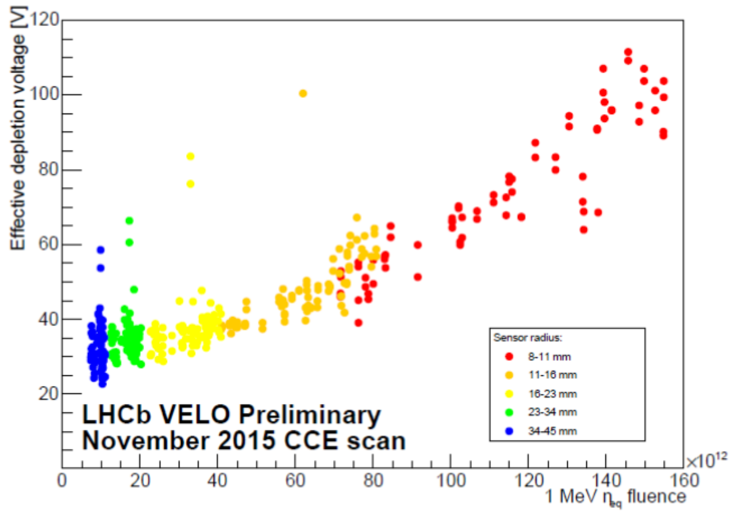

Figure 1: The effective depletion voltage for different radial regions of the VELO sensors versus fluence as determined from CEE scans.

previously been observed significantly below that setting, a thorough test of the HV system was performed in early 2016. The results show that the VELO can be operated safely and efficiently throughout 2016 and 2017, but more studies are required to understand the behaviour for the HV settings that will be required in 2018. Therefore the LHCb VELO group is considering the option to upgrade the VELO HV system.

2.2 Silicon Tracker (ST)

The Silicon Tracker, consisting of the Tracker Turicensis (TT) and the Inner Tracker (IT), operated successfully throughout 2015. The operation of both detectors was under the control of the central LHCb shift crew with support from the on-call ST piquet. The fraction of working channels is currently 99.59% and 99.30% in TT and IT, respectively. The performance of the detector has been studied using the data collected in 2015. Measurements of the hit efficiency and resolution were made, and the effects of spill-over clusters on the track-reconstruction performance were evaluated. Preliminary results show that the hit efficiency and resolution are within expectations, while spill-over clusters do not degrade the track reconstruction performance significantly.

Changes in the depletion voltage of the sensors are monitored using dedicated CCE scans. Data are collected with different voltage and timing settings, and the depletion voltage is extracted from the distribution of the collected charge as a function of the applied voltage. The depletion voltage measured in the TT is shown in Fig. 2 as a function of the 1 MeV equivalent fluence, and the measurements agree well with the predictions. The CCE scan will be repeated at the start and end of 2016 to monitor the effects of radiation damage. The sensor leakage currents are also monitored continuously and increase in line with expectations.

A BCAM (Brandeis CCD Angle Monitor) system was installed during LS1 to monitor the movement of the IT detector boxes. The system is used to correlate movements with changes in, for example, the magnet polarity or temperature. Initial studies show movements of $\sim$ (0.3, 0.2, 10) mm in (x, y, z) for the station closest to the magnet when the magnet polarity changes. Smaller movements, $\sim 30\,\mu$m, are observed when powering the detector electronics. Further work is required to understand these results and to correlate the measurements with the alignment obtained using reconstructed particle trajectories.

A few tasks were scheduled for the YETS. One control board was exchanged in TT as the part of its SPECS mezzanine responsible for environmental monitoring was broken. The IT stations were opened, together with those of the Outer Tracker, and three broken VCSEL diodes were replaced. All Maraton low-voltage power supplies (5 for IT and 4 for TT) were removed for scheduled preventive maintenance. Several leaks were found in the C_6F_{14} cooling circuit of the IT during 2015. Repairs were made to the cooling plant during all technical stops but the largest leak was thought to be located in the transfer line between the cooling plant and the detector boxes. The detector was warmed up during the YETS so that this leak could be repaired. After this intervention, another leak developed on a connector near one of the IT detector boxes, and this connector was replaced. The leak search was narrowed down to a single connector in one station and this connector was replaced.

Finally, a problem developed recently with one HV channel in the TT. The channel, which supplies the power to three read-out sectors, tripped when powered for the first time during the YETS. The TT detector box was opened to try to identify where the problem is located but no visual indication of a short circuit was observed. The channel recovered after temporarily disconnecting the cables. A spare module will be prepared for installation during the extended YETS in 2016/7. The single read-out sector that causes the trip has been identified and can be disabled if the problem occurs again.

2.3 Outer Tracker (OT)

The Outer Tracker experienced a successful data-taking period during the start-up of the LHC in summer 2015, and during the intensity ramp-up in the months that followed. No hardware interventions were necessary during the technical stops of the accelerator.

During LS1 a considerable effort had been invested into preparing the real-time calibration of the time constants. The procedure has been shown to perform as expected, keeping the drift-time measurement accurate within ± 0.1ns (a factor of five improvement on the Run 1 performance) during the entire 2015 data-taking period, as shown in Fig. 3.

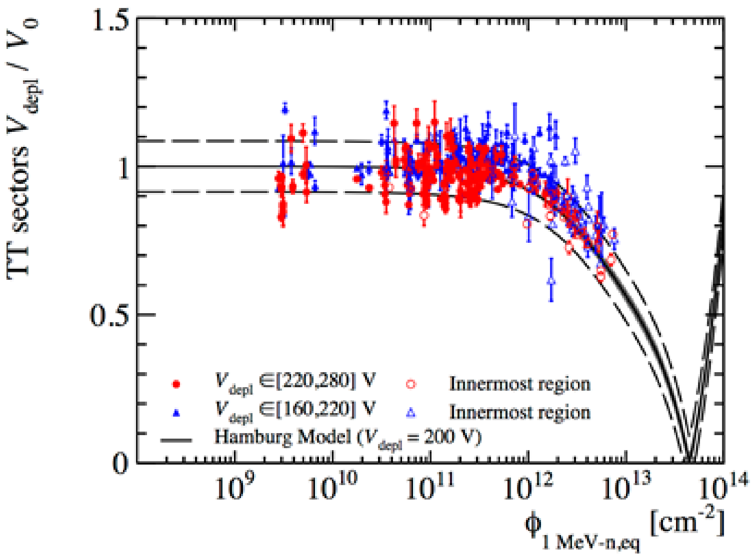

Figure 2: Depletion voltage measured in the TT as a function of the 1 MeV equivalent fluence. The hollow points show the depletion voltage measured in the read-out sectors closest to the beam-pipe. The predicted depletion voltage is shown as a solid black line and the dashed lines indicate the average systematic uncertainty on the measured depletion voltages. The depletion voltage is normalised to the initial value, and there is good agreement between the measurements and predictions.

LHCb participated in the PbPb data-taking period at the end of 2015, which meant particularly high per-event hit occupancies of up to 100% for the Outer Tracker. Although the integrated delivered dose during the PbPb run was negligible, the different operational conditions justified special care regarding radiation damage. Two special runs were taken, in November and December 2015, where the amplifier threshold was varied to measure the absolute gain at each position in the Outer Tracker. No irradiation damage was observed.

During the YETS a minor detector maintenance was carried out. One front-end module was replaced to recover a faulty TDC chip affecting 32 straws (corresponding to 6×10^{-4} of all channels). In addition the grounding was improved for a dozen front-end modules. In total, the OT now contains as few as 70 straws with a noise level higher than 1%, and less than 10 unresponsive straws.

2.4 RICH system

The RICH detectors performed very well throughout 2015. An issue with the firmware of the UKL1 boards causing incomplete events appeared after the online farm was moved to SLC6; this problem was rapidly solved without affecting the data taking. Two power supply channels for the 80 V silicon bias voltage failed during operation and a second spare board was bought for extra security. The

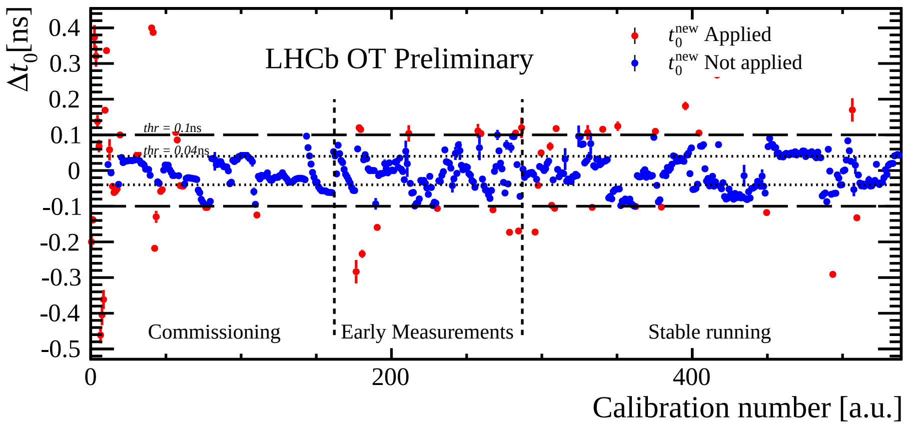

Figure 3: Real-time t_0 calibration keeps the OT drift-time measurement within ± 0.1ns.

liquefying procedure of the C_4F_{10} gas during normal circulation was tested successfully, and removed all the air contamination. The procedure is expected to be deployed once or twice a year to keep the air contamination below 2%. The gas refractive index is calibrated run-by-run to take the change in radiator purity into account, as shown in Fig. 4. During the YETS only minimal maintenance of the detectors was required. RICH1 was not touched since the HPDs showed no significant ion feedback, as expected. Only a few HPDs (9) were replaced in RICH 2. New UKL1 boards are being installed and will be tested in March. The new boards are expected to be included in the DAQ chain in April and May, increasing the available data bandwidth.

On the software front a new particle hypothesis was added to the RICH reconstruction to search for deuterons. As the deuteron is a heavy particle, this hypothesis is below the Cherenkov threshold for most tracks, and so this change to the algorithm adds only 2% to the time of the RICH reconstruction. The mirror alignment, the Cherenkov angle resolution and the PID performance are being studied extensively to test stability and in order to identify areas for improvement. More scans of the magnetic distortions will be taken at the start of operation to test if the calibration can be improved. Comparisons of the photon yield between 2012 and 2015 data show improvements in the number of signal photons for RICH1 and improved PID performance, as expected, due to the increase in radiator length resulting from the removal of the aerogel.

2.5 Calorimeters (SPD, PS, ECAL and HCAL)

Following the successful 2015 data taking with the calorimeter system, all detectors were opened during the YETS for maintenance and consolidation work. A considerable number of tasks have been brought to completion over the last two

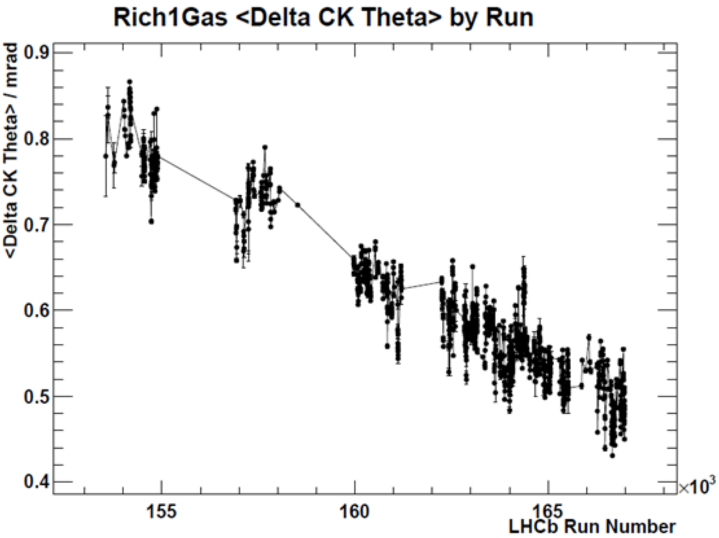

Figure 4: Deviation of the measured RICH Cherenkov angle from expectation. The visible evolution is driven by an increase in air contamination in the RICH1 radiator, which will be more strictly regulated during 2016.

months.

One malfunctioning VFE board was replaced in the PS. All the 456 LEDs of the ECAL monitoring system were replaced with LEDs of a different model. This replacement was necessary as the LEDs used in the 2015 run (MULTICOMP OVL-5523, installed in 2013-2014) were very unstable and sometimes broke. It turned out that they had an insufficient reverse breakdown voltage, which made them incompatible with the existing LED electronics and drivers. The new LEDs (CREE LC503) have similar parameters, but higher breakdown voltage. After this replacement it will be possible to operate the automatic following of the PMT gains, without the need for validation by a system expert. All the necessary adjustments after the ECAL LED replacement were performed, which comprises LED flash duration, magnitude and timing. The ECAL LED system is equipped with PIN photodiodes to monitor the LED flash magnitude (Fig. 5 left).

A degradation of the HCAL PMTs has been observed since 2011. This manifested itself as a gradual increase of the PMT dark current affecting the L0 trigger-rate stability within a fill. Such a degradation was not observed in the ECAL PMTs or in those replacement HCAL PMTs that have been installed after construction. Studies performed by the PMT manufacturers in 2014 showed that the reason for such a degradation is a migration of alkalis from the PMT photocathode inside the PMT bulb. During the YETS the 104 most degraded PMTs in HCAL were replaced with new ones.

Several unstable and malfunctioning ECAL and HCAL components (LED drivers, PMT Cockcroft-Walton HV sources, *etc.*) were fixed. They were identified by means of the ECAL and HCAL LED monitoring systems, which were running most of the time during the whole YETS period. An extended HCAL calibration with the ^{137}Cs source was required after the replacement of a significant number of PMTs (Fig. 5 right).

Work is ongoing to improve the ECAL π^0-based online calibration. In 2015, a lack of statistics limited the precision of the calibration for the central ECAL cells; because of high occupancy in the centre, isolation criteria rejected most of the photon clusters. In 2016, a preselection of events will be used to enrich the calibration sample with π^0's in this region. The selection algorithm is under development.

In summary, all calorimeter maintenance and consolidation activities were successfully completed during the YETS and the sub-detectors are ready for data taking in 2016.

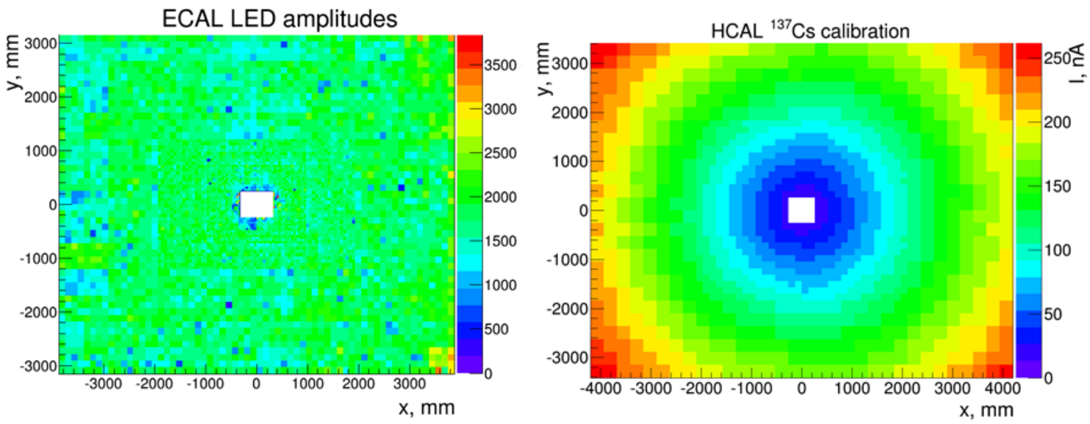

Figure 5: Left: LED signal amplitude in ECAL PMTs (ADC counts). Right: DC current in the HCAL cells using a ^{137}Cs source.

2.6 Muon system

During the YETS the muon detectors were opened for maintenance, allowing access to the M2-M5 C-side and M1 A- and C-side detectors. Some interventions on various MWPCs were required to fix unresponsive or noisy front-end boards. Two M1 GEM detectors were repaired because of HV-related problems, which did not allow these detectors to operate properly in the second half of 2015.

In addition to the interventions on the detectors some other maintenance work took place in January and February. 33 MWPCs were trained with negative polarity to cure Malter-induced extra-currents and a few HV power supplies and electronics modules were replaced. Before closing the muon system extensive tests were performed to check the proper operation of all the muon chambers.

During this technical stop the GEM open-loop gas system was replaced with a closed-loop gas recirculation system, which will allow a significant reduction in CF_4

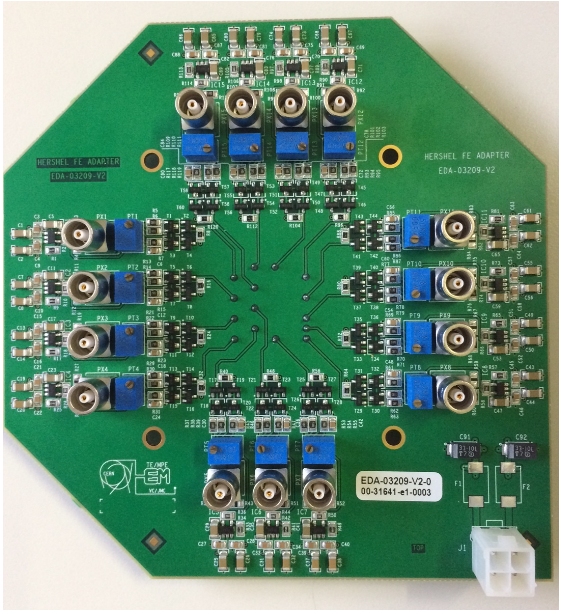

Figure 6: New analogue board used to adapt the PMT signal to the input specification of the PreShower front-end board used in the HeRSCheL readout, EDMS EDA-03209-V2-0.

usage during LHCb operations. Its commissioning was completed by mid-March.

The frequent crashes of OPC-servers for the Service Board (SB) on M2-M5 C-Side were carefully investigated during the YETS. To improve the system robustness the number of PCs controlling the M2-M5 SBs was increased from two to six, and some debugging is still ongoing to improve further the chamber control system reliability.

Some general threshold scans will be performed in the near future to optimise the working point of the chambers and system noise. Special data taking will be performed with the first *pp* collisions to check the system timing and allow an improvement of the system efficiency. Some special runs featuring a lower HV on the MWPCs, together with data taking at high instantaneous luminosity conditions (up to 10^{33} cm^{-2}s^{-1}), will take place during 2016 to understand better the performance of the muon system after the LS2 upgrade.

The muon system was finally closed at the beginning of March and a survey was performed to check the absolute positions of the stations. The muon system is now ready for collisions and it is currently included in a global cosmic data taking.

2.7 Forward shower counters (HeRSCheL)

After the initial commissioning phase, the HeRSCheL detector took data in 2015 with the rest of LHCb. HeRSCheL was included in the LHCb DAQ for about 90% of the 320 pb^{1} recorded *pp* data as well as for the full PbPb run and the various

SMOG runs.

A full calibration of the 2015 data has recently been performed and preliminary studies show a factor two to five in reduction of the inelastic background in non-resonant di-muon central exclusive production. The first physics analysis using HeRSCheL information is on-going.

A new analogue board for the adaptation of the signal from the PMTs to the readout electronics was designed, as shown in Fig. 6. It features a gain in signal of a factor three compared to the prototype board, a reduced noise and increased stability, which will ease 2016 operation.

Scintillator ageing was studied and a procedure to compensate it by increasing the PMT HV has been developed to stabilise the performance during the 2016 data taking. A new firmware was developed for the trigger FPGA on the PS front-end board, which is used for the HeRSCheL readout. The new functionalities, which are still under test, will provide HeRSCheL input to the L0 trigger.

2.8 Online system

The YETS was used for several improvements. To enhance the bandwidth from the farm to the storage, each of the 62 High LevelTrigger (HLT) farm racks now has, in principle, one Gb/s link to the storage system. The aggregated bandwidth to the storage is still, however, limited by the link bandwidth to the surface of 20 Gb/s. Nonetheless this value matches quite well with the bandwidth to the disks.

Another major intervention was the abandoning the mirror set of the data disks on the farm nodes. This will double the available buffer space for the output of the HLT1 accepted events by a factor two, which is expected to improve the trigger efficiency for certain channels by upto 15%. The expected risk of data loss in disk failure without the mirroring is estimated to be less than 1 per mille.

To improve the performance of the file writing, a simplification in the storage system was performed by removing one layer of interfacing to the disk storage. Each node receiving data from a set of sub-farms now writes its own files belonging to the desired data streams. This increases the maximum possible event rate between the HLT farm and the storage by approximately a factor of three.

To maximise the HLT farm usage, a dynamic creation/deletion mechanism for copies of HLT processes (HLT1 or HLT2) was implemented. This prevents the necessity to stop completely and restart the entire HLT system when the LHC mode changes *e.g.* from physics to re-filling. These transitions will be handled automatically by the LHCb ECS system.

All these improvements are expected to increase the overall performance of the system and thus help in coping with the limited resources available for operating the HLT during 2016 data taking.

3 Operations

The period between October 2015 and March 2016 was characterised by three main activities: the end of the *pp* data taking, lead-lead and lead-argon (fixed target with the SMOG system) data taking, and, during the YETS, preparation for the 2016 restart.

In 2015 LHCb collected a total integrated luminosity of 320 pb^{-1}, with a global efficiency of around 90%. For the first time, LHCb recorded lead-lead collisions (the experiment had already taken part in the proton-Lead run in 2013). The integrated luminosity of the lead-lead data is between 5 and 10 $\mu\mathrm{b}^{-1}$; the precise number will be obtained once the analysis of the van der Meer scan performed during the PbPb run will be completed.

In fifteen fills the SMOG system was used to inject Argon gas into the VELO detector region, to act as a fixed target for the lead beam; in this configuration the experiment took simultaneously PbAr and PbPb data. The data collected were temporarily 'parked' offline, without running any reconstruction. Preliminary studies have established that selecting events with less than 20k VELO clusters and using the same primary vertex reconstruction as in *pp* collisions allow these data to successfully reconstructed. The time needed to process an event is on average 1.5 s, while the event size is twice the typical one of *pp* collisions. The cut on the number of VELO clusters allows for the study of the centrality region between 100% (ultra-peripheral collisions) and 50%, and hence to investigate the unexpected J/ψ production excess observed by ALICE in ultra-peripheral collisions. The LHCb capability to separate prompt and delayed production for hidden and open charm is crucial in this rapidity region and these centralities. In addition, the possibility to reconstruct D-mesons down to zero p_{T} in the forward region is unique to LHCb. Preliminary results from the PbPb and PbAr runs are expected to be presented at the summer conferences. The analysis of the 2015 PbPb data will also provide vital input in the preparation for the next LHC PbPb run in 2018.

3.1 Preparation for the 2016 data taking

During the YETS several activities were carried out to guarantee an efficient restart in April 2016. The studies performed to improve the reconstruction performance are presented in Sect. 3.1.1. Particular attention was paid to reducing further the CPU-time needed for track reconstruction and to study performance improvements that can be achieved by including calorimeter reconstruction in the online sequence. These improvements were included in the HLT optimisation studies, as discussed in Sect. 3.1.2, and allow for the expansion of the Turbo-stream concept, as explained in Sect. 3.1.3.

Detector real-time alignment and calibration were already successfully commissioned during the 2015 data taking. Studies performed during the YETS were focused on the optimisation of the thresholds used to update the constants, and on the validation of the stability of the methods. Results are presented in Sect. 3.1.4. The status of the data-quality monitoring is reviewed in Sect. 3.1.5.

3.1.1 Reconstruction

In 2015 the same tracking reconstruction was run online and offline; only the calorimeter reconstruction was different in the two environments. It has now been decided to upgrade the HLT calorimeter reconstruction to the same version that is run offline, at the acceptable cost of adding 4% extra time to the HLT processing. This modification now ensures a completely identical online and offline reconstruction, which brings simplicity, homogeneity, and other benefits to the physics analysis.

Various refinements to the code resulted in a few percent gain in the time needed to run the reconstruction sequence. Moreover work is ongoing to introduce multivariate analysis methods, with the aim of improving the track reconstruction efficiency and reducing the ghost rates, while decreasing the time required to run the algorithms.

3.1.2 Trigger

During the YETS, the track reconstruction and Kalman-filter fitting algorithms were optimised leading to an increase by several percent of the HLT speed. The muon reconstruction was also optimised and made faster, which allowed reconstructing softer muons in HLT1; this provides up to a factor of two increase in the selection efficiency for rare muonic kaon decays.

In 2015, the HLT2 reconstruction was almost exactly the same as the offline reconstruction, except for a difference in electron and photon identification. Thanks to the increased disk-buffer space resulting from the removal of the mirroring, as described in Sect. 2.8, and the code optimisation, it is now possible to accommodate an additional 4% in CPU time for the full ECAL reconstruction, and around 1% extra for deuteron identification. The maximum HLT2 throughput was measured to be around 60 kHz when out of fill. Assuming conservatively that HLT2 can only be run out of fill, and that the full farm is required for HLT1 during fill, it is estimated that HLT1 can operate at an output rate of 150 kHz. The evolution of the farm disk usage in 2016 is studied with a toy model, including the fill/interfill structure from 2012 operation, and the present plan of technical stops from the LHC schedule (Fig. 7). The risk of overfilling the buffer is estimated to be at the percent level, based on the current performance parameters and an HLT1 output rate of 150 kHz.

A new tool was developed to perform the L0 bandwidth division in a few hours on a single machine. Threshold sets were optimised for several of the planned filling schemes during the machine ramp.

The HLT2 output bandwidth is currently under review by the physics working groups, under the supervision of the HLT group and physics management. The

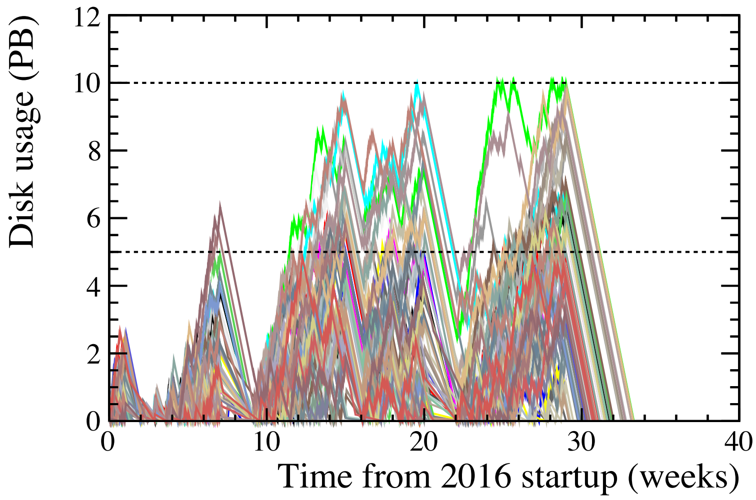

Figure 7: Evolution of the farm disk usage in 2016 for 50 toy models based on the latest machine schedule and a 2012-like filling pattern.

core inclusive beauty physics lines are already tuned at around 30% of the total bandwidth, in the interest of providing a uniform dataset. All other lines, most of which are for specific analyses, will be reviewed several times per year throughout Run 2.

3.1.3 Turbo stream

The Turbo stream provides a framework in which physics analysis can be performed using directly the trigger-reconstructed candidates, which requires a much smaller event size. This allows the output rate to be increased, thus boosting all physics channels that are limited by trigger output-rate constraints, such as charm, and facilitates fast analysis turnaround. The development of the Turbo stream called for having the same reconstruction offline and online, and storing information with sufficient flexibility to fit the needs of a broad range of physics analyses. It is important to note that Run 2 represents a unique test bench to validate concepts such as the full-software trigger that will be needed in the LHCb upgrade.

3.1.4 Calibration and alignment

All calibration and alignment tasks for Run-2 operation were successfully commissioned in 2015. Algorithms that need to update the constants frequently, such as the VELO alignment, were already fully automated before the end of data taking. The π^0 calibration code was improved, resulting in a 30% reduction of the computing time. The RICH mirror-alignment stability was studied to investigate whether the magnet polarity had any effect on the physics performance, in order to assess whether it is necessary to have a separate alignment for each polarity. It was

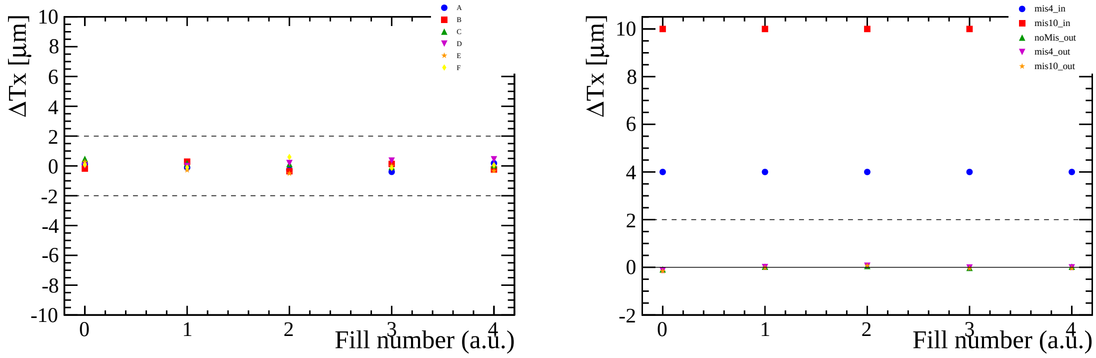

Figure 8: Left: variation of the x-translation of two VELO halves when different data sets, in the same fill, are used for the alignment (six separate subsamples are considered for each fill). Right: variation of the x-translation of the two VELO halves when different starting misalignments are used. The points at around ΔT_x are the input misalignments, those closely clustered around $\Delta T_x = 0$ are the results after the alignment procedure.

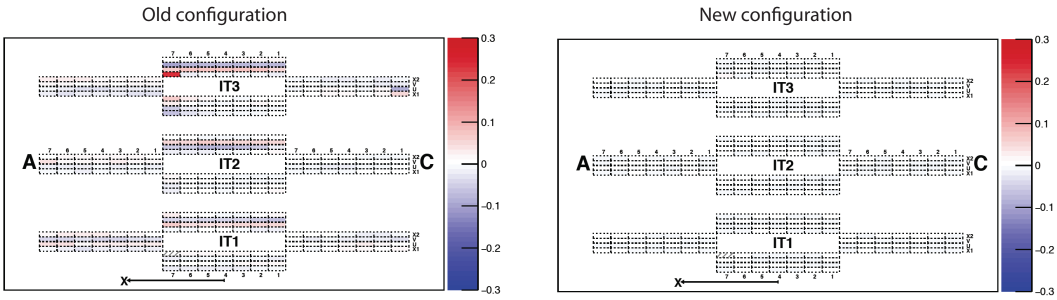

Figure 9: IT residuals (mm) computed between the old and the new procedure. The new procedure is based on an alignment at the module level. The biases present with the old procedure (left plot) are no longer present after introduction of the new degrees of freedom (right plot).

concluded that one set of alignment constants is sufficient for the full data-taking period.

Detailed studies of the VELO-alignment stability were performed on the 2015 data, as illustrated in Fig.8, which allowed optimising the minimum constant variations that trigger the need for a new alignment.

For the IT/OT alignment, different configurations of the elements to be aligned were tested. It was found that an alignment at the module level for the IT, and half-module for the central modules of the OT significantly improves the alignment precision (Fig. 9).

3.1.5 Data-quality monitoring

In 2016 data-quality (DQ) monitoring will be based on an entirely new system. It will consist of two steps: (i) real-time monitoring performed by the data manager at the pit to guarantee that no major failures are affecting data taking, (ii) DQ-checking and flagging of the data after HLT2 to be used for physics analyses. In Run 1 this second step was performed after offline processing of the data, introducing a delay of order of days. In Run 2 a so-called "prompt DQ" is designed to flag the data only a few minutes after HLT2. Only in case of very short runs, or of poorly understood behaviour, will the full offline-DQ be run. While the DQ system was commissioned last year by a few experts, this year regular DQ shifts are being organised. A detailed review of the histograms used for the prompt-DQ was also completed during the YETS.

3.2 Offline processing

The computing usage in 2015 [11] and the resource estimates for 2016 and beyond [12] are discussed in detail in separate documents.

4 Physics results

Since the last RRB in October 2015, LHCb submitted 18 new publications, for a total of 305 papers at the time of writing. Eleven further publications, whose principal results have been unveiled at the winter conferences, are close to submission.

In the sector of CKM metrology, there have been two notable achievements, namely an improvement in the precision of the γ angle of the unitarity triangle (UT) and the world's best measurement of the B^0 oscillation frequency, which is related to the length of one UT side. The improvements on γ are driven by new results in various decay modes, including the measurement of *CP* observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with two- and four-body D meson decays [3], and the analysis of $B^0 \to DK^{*0}$ decays, with $D^0 \to K^0_S\pi^+\pi^-$ [4, 5]. Figure 10 shows the invariant mass distributions for $B^- \to [\pi^- K^+]_D K^-$ and $B^+ \to [\pi^+ K^-]_D K^+$ decays, where the effect of *CP* violation is clearly visible. An update on the combination of the many $B \to DK$ decay modes used to constrain γ at LHCb was also made [6]. The result is $\gamma = (70.9\,^{+7.1}_{-8.5})^\circ$. This is by far the most precise single-experiment measurement of the CKM angle γ to date.

The oscillation frequency Δm_d of B^0 mesons has been precisely measured using semileptonic decays with a D^- or D^{*-} meson in the final state [13]. The combination of the two decay modes gives $\Delta m_d = (505.0 \pm 2.1\ (\text{stat.}) \pm 1.0\ (\text{syst.}))\ \text{ns}^{-1}$. This is the most precise single measurement of this parameter, with a smaller uncertainty than the current world average.

In the sector of spectroscopy, considerable effort has been devoted to strengthening the observation of the first pentaquark states, which was performed by LHCb in 2015 using a model-dependent amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays [14].

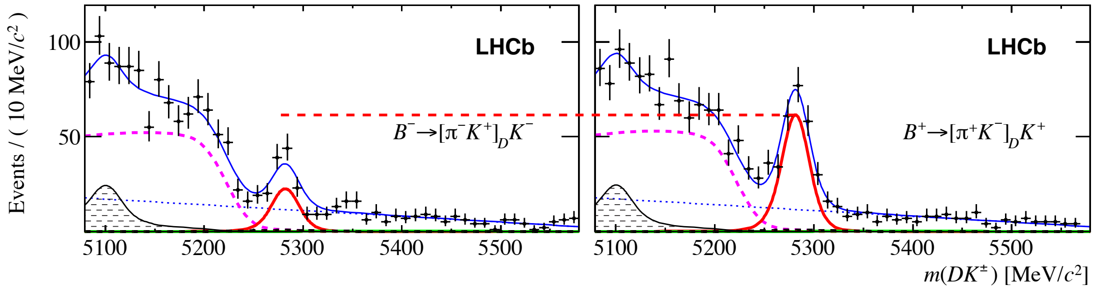

Figure 10: Invariant mass distributions for $B^- \to [\pi^- K^+]_D K^-$ and $B^+ \to [\pi^+ K^-]_D K^+$ decays. The difference in the heights of the two mass peaks, highlighted by the horizontal dashed line, is due to CP violation. Figure from Ref. [3].

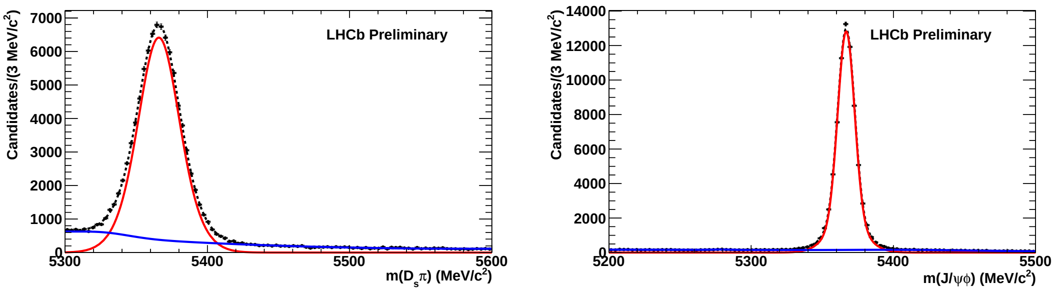

Figure 11: Selected candidates for (left) $B_s^0 \to D_s^- \pi^+$ and (right) $B_s^0 \to J/\psi\, \phi$ decays. Results of the fits are superimposed with the total fit result shown as a dashed black line, and signal and background components as red and blue solid lines. Figure from Ref. [15].

As a follow up to that analysis, a model-independent study using the same Λ_b^0 decay mode has been made [7]. On the basis of a minimal set of assumptions, it is demonstrated at more than nine standard deviations that $\Lambda_b^0 \to J/\psi\, pK^-$ decays cannot be described with $K^- p$ contributions alone, and that exotic $J/\psi\, p$ contributions (*i.e.* pentaquarks) play a dominant role in this incompatibility.

Another important spectroscopy result is the outcome of the search for the presence of structures in the $B_s^0\pi^\pm$ invariant mass spectrum [15]. In this analysis, the recent claim by the D0 collaboration of a tetraquark state, dubbed the $X(5568)$ [16], in the $B_s^0\pi^\pm$ invariant mass distribution is investigated using Run-1 data. Invariant mass spectra for $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to J/\psi\, \phi$ candidates are shown in Fig. 11, whereas the Q-value distributions studied to search for $B_s^0\pi^\pm$ resonances are shown in Fig. 12. Despite the much cleaner and larger sample of B_s^0 mesons at LHCb, about a factor 20 more abundant than that used by D0, no signal was found, and stringent upper limits were placed on the production rate of such a state.

Two important results were obtained in charm physics. A new measurement of the difference of time-integrated CP asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^-\pi^+$

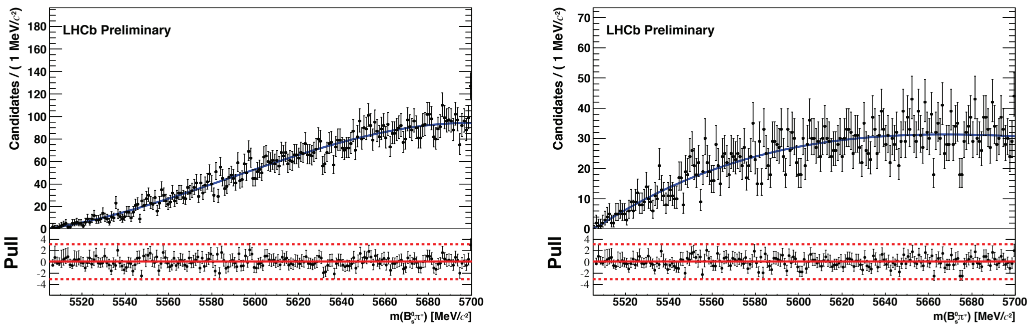

Figure 12: Fits to the Q-value distributions, shifted to display the $B_s^0\pi^+$ invariant mass, for $B_s^0\pi$ candidates with minimum B_s^0 p_{T} of (left) $5\,\mathrm{GeV}/c$ and (right) $10\,\mathrm{GeV}/c$. The signal claimed by D0 is clearly absent from both the spectra. Figure from Ref. [15].

decays, $\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$, was performed using the full Run-1 dataset [8]. The flavour of the charm meson is inferred from the charge of the pion in $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$ decays. The value of ΔA_{CP} is measured to be $(-0.10 \pm 0.08\ (\text{stat.}) \pm 0.03\ (\text{syst.}))\,\%$. This is the most precise measurement of a time-integrated CP asymmetry in the charm sector from a single experiment. In time-dependent studies an observation of D^0–$\overline{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$ decays was performed, together with a measurement the associated coherence parameters. This was achieved by means of a time-dependent analysis of the ratio of $D^0 \to K^+\pi^-\pi^+\pi^-$ to $D^0 \to K^-\pi^+\pi^-\pi^+$ decay rates, using the full Run-1 data set [9]. The analysis gives the most precise measurement of the $D^0 \to K^+\pi^-\pi^+\pi^-$ branching fraction, and the first observation of D^0–$\overline{D}^0$ oscillations in this decay mode, with a significance of 8.2 standard deviations.

LHCb is also becoming a major player in the sector of heavy ion physics. Studies of cold nuclear matter effects with prompt D^0 production [17] and $\psi(2S)$ production [18] in pPb collisions were performed, determining forward-backward production ratios and the nuclear modification factors. Furthermore, the $b\bar{b}$ cross-section in pPb collisions at the nucleon-nucleon centre-of-mass energy of 5 TeV has been measured [18].

LHCb has made a major contribution to the field of gauge boson production by performing a measurement of forward W and Z production in pp collisions at $\sqrt{s} = 8$ TeV [19]. The bosons are identified in the $W \to \mu\nu$ and $Z \to \mu^+\mu^-$ decay channels. Results are in good agreement with theoretical predictions at next-to-next-to-leading order in perturbative QCD. Furthermore, a preliminary measurement of the production cross-section for Z bosons in pp collisions at $\sqrt{s} =$ 13 TeV was also performed [20], considering Run-2 events in which the Z boson decays to two muons. Differential cross-sections were measured as functions of the Z boson rapidity, transverse momentum and ϕ^*_η, where the ϕ^*_η variable is precisely determined exclusively from the measured lepton directions. The Z-boson rapidity distribution is compared to theoretical predictions at next-to-next-to-leading order in perturbative QCD. The predictions vary with the choice of parton distribution functions used, but the data are not yet precise enough to favour a specific selection. Future LHCb measurements at $\sqrt{s} = 13\,\text{TeV}$ with more data will strongly constrain the PDFs.

5 Financial issues

The status of the accounts is healthy and no cash-flow problems are foreseen. The expenditure on the 2015 M&O Cat. A budget has followed forecasts. Due to a delayed acquisition of online components, the impact of the variation of the Euro/CHF exchange rate and a machine restart with less beam time than foreseen, the underspending was 15% of the overall M&O Cat. A budget. This surplus will be used partly to finance the consolidation of the farm and storage foreseen for the beginning of year 2017, and also to provide a buffer in view of the proposed 2% decrease of the M&O Cat. A budget in the coming years.

6 Collaboration matters

At the LHCb Collaboration Board meeting of December 2015 the Yandex School of Data Analysis, Russia, was accepted as a full member of the collaboration.

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