1 Introduction

No major interventions were required during the End of Year Technical Stop, and data taking operations restarted very smoothly. Modifications have been implemented in the operations strategy that have led to improvements in the data taking and processing for 2017, more information can be found in Secs. 2 and 3. LHCb has now recorded 1.1 fb$^{-1}$ of integrated luminosity in 2017 and has recently crossed the threshold of 6 fb$^{-1}$ of integrated luminosity over LHC run 1 and run 2, thus doubling the luminosity that was collected during run 1.

The year 2017 has, so far, been highly successful for the LHCb physics output, with 41 papers already submitted to journals. This total is in line with the number of publications by this time last year, and the total number of publications for the year is expected to be in line with last year taking into account the papers which are currently under review and will be submitted before the end of the year. In total 400 papers have now been published or submitted. Highlights since the last RRB include the observation of the doubly-charm baryon $\Xi_{cc}^{++}$ [1], the measurement of the ratio of branching fractions $R(D^*) = BR(B^0 \rightarrow D^{*-}\tau^+\nu_\tau)/BR(B^0 \rightarrow D^{*-}\mu^+\nu_\mu)$ using three-prong hadronic decays of the $\tau$ [2], and a new combination of measurements of the CKM angle $\gamma$ [3,4]. These and other results are discussed in Sect. 4.

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 [5].

2 Detector sub-systems

The LHCb experiment was well prepared for the restart of data taking after the Extended Year’s End Technical Stop (EYETS). Detectors, their services and the entire general infrastructure went through a thorough and successfully completed maintenance. Both cranes in the cavern were revamped and the passenger elevator
was replaced by one with higher occupancy and larger entrance. This work had been completed in time and the cranes and lift are in use now. Preparations for the next Years End Technical Stop (YETS) have already started.

2.1 Vertex Locator (VELO)

The VELO has continued to operate very efficiently with high quality data obtained throughout Run 2. Periodic CCE (charge collection efficiency) scans have been taken during favourable low intensity LHC conditions. These have been used to monitor closely the evolution of the radiation damage of the detector. The charge loss due to the so called double metal layer effect, which has been reported in previous meetings, has been stable since the start of Run II. There has also been an effect seen due to radiation damage on the innermost tips of the sensors, in particular around the interaction region. To counteract this the voltages have been raised to 300V throughout the detector, and a further CCE scan will be taken to ensure stable efficiency up to the end of 2017 and to prepare the 2018 running. The raising of the HV has implications for the operation, due to irregularities which have been observed in the operation of the HV supplies. An investigation was carried out after which it was decided to modify the firmware and the monitoring software in order to reduce the number of fake trips and ramp-downs experienced in the VELO. These modifications are under investigation and will be implemented during the YETS, in anticipation of further voltage increases during 2018. In addition the currents are monitored with regular IV (current vs voltage) scans and the dedicated VELO alert system provides an uninterrupted record of leakage currents during regular operation and reacts in case of unforeseen changes. The leakage current evolution continues to follow the predictions based on the detector operating temperature and delivered luminosity (see Fig.1 ), and the detector has now reached the original luminosity limit as defined in the VELO TDR and the performance will be followed very carefully. In connection with the raising of the HV the temperatures are being closely monitored. A campaign has been undertaken to re-optimise the Beetle front end chip settings and a selection has been found which delivers a slightly improved spillover performance and a simultaneous small power reduction, which will result in a 1-2 degree lowering of the silicon temperature. These settings will be implemented after the YETS.

During the running there were some sporadic issues which were promptly addressed. Two LV boards showed failures and were replaced, along with one TELL1 due to a credit card PC failure. Maintenance of a VELO cooling pump and pf the Freon chillers was performed. The VELO experienced various alarms due to a rise in temperature of the chilled water supply, which was solved together with the infrastructure team by guaranteeing a maximum temperature and a suitable adjustment of the alarms. One sensor showed a small efficiency loss due to pedestal fluctuations, which were traced to a fluctuating low voltage on a connector. This effect is now monitored and pedestal corrections have been applied.
Figure 1: Currents measured in the VELO for each sensor as a function of time (bottom). The luminosity delivered to LHCb and the average sensor temperature is shown over the same time scale (middle and top). Increases in the delivered luminosity are matched by increases in the sensor currents.

2.2 Silicon Tracker (ST)

The Tracker Turicensis (TT) and Inner Tracker (IT), which together form the Silicon Tracker (ST), operated successfully in the first half of 2017. Both sub-detectors are controlled and monitored by the central LHCb shift crew, with support from an on-call piquet and a small team of experts. The fraction of working channels is currently 99.27% and 98.96% in the TT and IT, respectively. The various ST hardware components in the LV, HV and readout chains performed reliably, with only one TT HV CAEN board replaced in June due to a single faulty channel.

At the end of August, electrical problems at the LHC triggered a fire alarm and a consequent power cut in the LHCb cavern. After this major incident, one sensor in a TT module close to the beam pipe has no power consumption, and thus sends no signal data. The origin of this problem is still under investigation, with only the corresponding HV CAEN board ruled out as a possible culprit at the time of writing this report. Additional checks on other elements (i.e. the sensor itself, or a connector in the patch panel) will be carried out as soon as is feasible.

In case the problem is in the sensor inside the module, the repair will only be possible during YETS 2017, resulting in the loss of 512 readout channels (0.36% of the total detector readout) for the rest of 2017 data-taking. The impact on track reconstruction is expected to be close to negligible given that the problem is restricted to a single sensor with small area in one TT layer. This is confirmed by the
negligible change in the number of long-reconstructed tracks seen in prompt data quality monitoring. Additional studies are being performed in order to evaluate any potential impact on downstream tracks.

Radiation damage of the silicon sensors is monitored using measurements of the depletion voltage obtained from periodic Charge Collection Efficiency (CCE) scans, and leakage current measurements taken continuously throughout the year. Data analysed from the most recent CCE scans, performed on June 5 and July 12 this year, are consistent with predictions from simulation, and show an aging of the detector at the level expected. The performance of the ST detectors is periodically monitored with a dedicated software package. Previously, the performance was evaluated using all hits, with a correction factor included to minimize the bias introduced by the hit in the analysed sensor. Improvements to the software now enable an estimation of the detector performance without using hits from the sensor under study. This is done by first masking the relevant layer, running the pattern recognition and track fit, and finally reusing the removed cluster to calculate the performance in that sector. Occupancy, residual distribution, efficiency, noise and cluster properties were studied for 2015-2017, and show that the detector is performing as expected in Run 2.

2.3 Outer Tracker (OT)

The Outer Tracker (OT) has operated successfully in 2017. The sub-systems (LV, HV, RASNIK, gas monitoring and DAQ system) functioned reliably during the whole summer, with little to no problems.

Prior to the start of data-taking in June, a set of commissioning activities took place: upgrading of the readout system of the RASNIK system, testing of spare boards of the HV system, adjusting amplifier threshold values, and testing new firmware to prepare for higher data-taking rates. The commissioning was concluded with running all OT sub-systems to take cosmic data as the final test of the full Outer Tracker readout chain.

With the advent of the larger number of colliding bunches at LHCb, the natural current limit was reached for the central modules causing the HV system to trip. A modification of the current limit for all modules was carried out in order to avoid future problems.

During the data-taking, a few minor issues occurred as described below.

- A short-circuit caused a trip in the HV system. This required an intervention on the HV patch panel to disconnect a single HV board on the detector. As a consequence 32 straws are switched off (out of 53760).

- A limited number of Front-End boards exhibited a noisy behaviour compatible with grounding problem. This issue was addressed, during the Technical Stop in July, by improving the grounding of the affected boards.
• Desynchronisation of individual “control boxes” reported in the last report (CERN-PRB-2017-034-01) are occurring less frequently now, and do not affect the data-quality. In addition, occasionally, single events are observed with a wrong event ID. This problem appears to affect the whole LHCb detector. This does not affect the data-quality, but the error monitoring of the OT needs to be improved.

• The Outer Tracker was the first detector that could not sustain the highest data rates, beyond 1 MHz after L0 (CERN-PRB-2017-034-01). The small increase of the amplifier threshold in a noisy front-end, in combination with an extra veto on events with busy preceding events, reduced the bottleneck, allowing the LHCb experiment to surpass the 1 MHz readout rate.

• One amplifier board of the gas monitoring system of the OT malfunctioned, leading to wrong absolute values of ingoing gas gain, displayed by the monitoring system. However, the relative variations are still monitored, in addition to proper monitoring of the outgoing gas. A replacement is ordered.

Finally, a document summarising the Outer Tracker performance using Run2 data has been submitted for publication.

2.4 RICH system

The RICH detectors were ready for data acquisition at the start of the 2017 LHC run. Improvements in the automatic software calibration, mainly in the alignment, were made for 2017 operations. The hardware maintenance during the EYETS went according to plans with the usual number of HPDs exchanged and some minor issues in the RICH1 electronics solved.

In LS2 all HPDs in the RICH system will be replaced with MaPMTs for the LHCb upgrade. This means that the 2017 HPD repair campaign is the last time HPDs will be refurbished. The ion feedback performance of all HPDs has been looked at in detail to estimate the number of HPDs that will require replacement at the end of 2017 for the 2018 run. The numbers have been calculated and the last few HPDs will be delivered by the manufacturer in autumn 2017. This will bring to an end the HPD repair campaign that lasted almost a decade. Despite the lifetime issues, the HPDs have been very succesful giving single photon detection and providing excellent performance for the LHCb hadron particle identification.

The performance of the UKL1 boards has been monitored closely, and there is a lot of spare bandwidth. Most links operate at around 0.6–0.7 Gb/s (1 Gb/s available) and so far the boards have been extremely reliable. The programme for producing new boards has been suspended, although new boards could be introduced with a delay of a few weeks if needed.

The alignment of the RICH mirrors has been fully automated and is running at every LHC fill. This has allowed the RICH group to follow the evolution of the mirror movements. The mirrors have been shown to be very stable, with small
Figure 2: Rotation around the local Y axis of support for the RICH1 spherical mirrors. A mirror alignment is performed in each LHC fill, and it is clear from the observed variations that the mirror positions were very stable for the 3 months of the summer 2017. The observed variations have negligible impact on the Cherenkov angle resolution.

movements occurring when the polarity of the LHCb magnet is changed. Figure 2 shows the measured rotations around one of the two local axes of support for the RICH1 spherical mirrors during the summer of 2017 (typically one alignment for every LHC fill). The mirrors show a very good stability in time. Any variation below 0.05 mrad has no impact on the Cherenkov angle resolution.

2.5 Calorimeters (SPD, PS, ECAL and HCAL)

The calorimeters have been running smoothly since the beginning of the 2017 LHC run. At present, there are a few dead and noisy cells in the Calorimetry detectors which can be seen from Fig. 3; two dead channels in ECAL and one in HCAL. They will be repaired during the 2017/2018 YETS, once the Calorimeter detector can be opened. The initial calibration of the Calorimetry detectors was obtained prior to the start and at the start of the 2017 data taking; similar to the 2016 data taking procedure. An HCAL calibration run with the $^{137}$Cs source was performed immediately before the LHC start-up and new HV settings for the
HCAL PMTs were obtained from the calibration data. Furthermore, the time alignment constants of all the Calorimetry detectors were updated using the data from the first collisions in May. In addition, for the ECAL calibration the period of the LHC intensity ramp in May was used to collect a large sample of $\pi^0 \rightarrow \gamma \gamma$. The new HV settings for the ECAL PMTs were obtained from these data and were applied in early June.

The automatic procedure for the ECAL and HCAL HV correction based on the LED monitoring system is running (since 2015). This system efficiently stabilises the PMT gain by adjusting their HV settings after each fill. During the data taking, the ECAL $\pi^0$ calibration is performed every 1-2 month, and an update of the HV for each ECAL cell is produced. It is worth mentioning that during the EYETS the ECAL calibration procedure using photons from the $\pi^0 \rightarrow \gamma \gamma$ decay was optimised. In particular, the time taken by the procedure was reduced by a factor of five; the stability of the procedure was also significantly improved. For the HCAL, the $^{137}$Cs calibration runs are performed during each technical stop.
2.6 Muon system

The maintenance work performed during the winter shutdown ensured a smooth and efficient operation of the muon system during the first half of the 2017 data taking. Most of the FEE channels are working efficiently, with only one quarter of a chamber in M1 missing, over a total of 1380 chambers in the whole system. As a result, all stations M1 to M5 have an average efficiency for muon detection exceeding 99%.

At the beginning of the run, the detector space and time alignment were verified with the first collision data, and corrected where needed. After this procedure, all muon stations are aligned within 1 mm of the position assumed by the level 0 muon trigger projectivity. In addition, as in the past years, the stability of the time response has been measured to be much better than 1 ns on average (Fig. 4), with only 0.2% of the channels requiring a correction of more than 4 ns.

![Figure 4: Average muon track hit times for each region of the M1-M5 stations, for 2017 and 2016 reference data.](image)

During the first part of the run, which included the LHC luminosity ramp, we had on average two HV trips per week in the MWPCs. The gaps affected, a total of 26 so far, are being trained with the beam at nominal HV. This is the standard procedure which allows to recover the gaps in the presence of Malter current and other deposits on the cathode planes, while keeping the chamber efficient during data taking. In this respect, we have implemented this year a fully automated software procedure for the HV training, integrated in the detector ECS. This program allows to configure in detail the parameters to be used for each gap under training, and to monitor its behaviour with time.

In parallel to that, we are preparing the interventions to be made during the next winter shutdown, and in particular the replacement of a few chambers. For this reason, the entire stock of spare chambers, including the ones recently produced at INFN-Frascati and arrived at CERN, are being retrained under HV and prepared for the cosmic-ray test in the experimental area at building 169 at CERN.

2.7 Forward shower counters, Herschel

The new HERSCheL detector, after replacement of all the scintillating plastic and the light-guides, was successfully recommissioned with beam early in 2017
during the LHC luminosity-ramp period. Data collection then continued, with the HERSCHEL detector included for the vast majority of 2017 data-taking. The degradation of the light yield from the scintillators has been monitored daily with the aim of achieving more frequent updates to the applied high-voltage to compensate for this. With the increased frequency of HV changes comes a need for careful monitoring of the detector’s time-alignment, and effort has been invested to automate the daily monitoring of the alignment. It is desirable that a higher level study of the data should happen faster to understand the impact on the offline analysis. An effort is ongoing to encourage analysts to start to integrate the new data into ongoing analyses as soon as possible, in order to have additional feedback on the data quality.

Work has continued towards an integration of the HERSCHEL detector response with the LHCb “L0” hardware trigger. All preparations are complete on the software side: code to emulate the HERSCHEL trigger bit production has been released and modifications have been made to the central L0 decision unit (L0DU) software to accept those decisions. Preliminary thresholds have been determined, using data taken during 2015 and 2016 as a guide. On the hardware side the work is nearly complete: the firmware handling the creation of the HERSCHEL trigger bits (‘counter over/under threshold’) has been finalised and installed on the two boards in the LHCb cavern (one for each arm of the HERSCHEL detector), and the alignment of the decisions arriving at the L0DU is underway. It is hoped that operation within the L0 trigger will be successfully achieved for a substantial portion of the remaining 2017 data-taking period.

2.8 Online system

Upgrades of the online machines were performed from the Linux operating system SLC6 to CentOS7. Following this we observed a series of problems that affect the operational stability of the system. The problems are exclusively due to bugs in the Linux kernel. The symptoms mainly affect the NFS sub-system, these include hanging while accessing directories and the dropping of NFS mount points in the middle of operations.

As NFS is one of the backbones of our system these problems hit us very hard. We mitigate the issues by using more recent kernel versions which address the bugs. In some occasions this is not possible, as third-party drivers do not support these. In this case bug-fixes from newer kernel versions were back-ported to the supported kernel.

One problem still persists in that virtual machines (of the control system) occasionally run out of memory and get completely stuck. A power-cycle is needed to recover but during the interruption no operations, e.g. ramping voltages, are not possible. This problem is still not understood and no fix is available yet.

Besides these issues the online system runs very well and the efficiency losses are only in the order of 1%. The online alignment procedures for the various sub-systems work very well.
3 Operations

In the period between April and October 2017, LHCb collected a total integrated luminosity of about 1.1 fb$^{-1}$, with a global efficiency above 90%. Since the first day of data taking in run 1, LHCb collected more than 6 pb$^{-1}$. Figure 5 summarises the delivered and recorded luminosity and the LHCb data taking efficiency.

The first week of data taking was used for the commissioning of the detector. The detector was fully calibrated and aligned already at the beginning of June.

The SMOG system was used to inject gas into the VELO detector region, to act as a fixed target for the proton beam. In this configuration, the experiment took a small sample ($\sim 0.15$ nb$^{-1}$) of proton-He data and about 1 nb$^{-1}$ of proton-Ne collisions profiting of the few colliding bunches in LHCb during the van der Meer scan for the other LHC experiments. During the ramp period of the LHC, a few dedicated $\sim 30$ minute runs were taken to study the vacuum conditions as a function of the LHC beam intensity when running in the fixet target configuration.

3.1 Trigger

The online-farm disk buffers, with a capacity of about 10 PB, are used to store the output data of the first stage of the software trigger (HLT1). This allows the real-time alignment and calibration to be performed and to defer the second stage of the software trigger (HLT2). This has the double advantage of providing

![Figure 5: Delivered and recorded integrated luminosity for the first period of 2017 proton-proton run (left) and for the full LHC data taking period (right).](image)
Figure 6: Evolution of the farm disk usage in 2017 (black line) and projection to the end of the year for several toy models based on the assumption of a flat LHC availability for each 2-week period, uniformly distributed between 15% and 85% (red lines).

Fully calibrated and aligned data to the HLT2 trigger selections and of optimising the usage of the online-farm resources. The disk buffer occupancy is monitored and filling projections are provided. To avoid the risk to overfill the disk buffer, two sets of HLT1 thresholds were prepared: a tighter one with an output rate of 80 kHz and a looser one with an output rate of 105 kHz. A toy model was used to evaluate the disk occupancy for the entire year, by assuming a flat LHC availability for each 2-week period, uniformly distributed between 15% and 85%. The looser selection has been used since the beginning of the data taking and the projections were updated every two weeks. Due to the reduced efficiency of the LHC, the loose selection could be maintained throughout the run as the projections showed no risk of filling the buffer. Figure 6 shows the latest projection, evaluated in the middle of September.

For 2017 data taking, the hardware trigger (L0) thresholds of all physics channels were optimised by the same tool used last year. A compromise between stability (minimum number of threshold sets) and maximisation of the trigger rate was made to adapt to the variation of the number of colliding bunches in LHCb. Most of the data were collected with 4 different thresholds sets.

3.2 Turbo and Calibration streams

The Turbo stream provides a framework in which physics analysis can be performed directly on the trigger-reconstructed candidates. This stream requires a much smaller event size than in the standard data. In 2016, the possibility to save the entire trigger-reconstructed event was also added. This led to an increase of the Turbo output bandwidth by more than a factor of three and to a significant increase of the Turbo dataset size. In addition to an optimisation of the selection
Figure 7: Left: kaon identification efficiency and pion misidentification rate as a function of track momentum as measured using 2017 data. Right: muon identification efficiency and pion misidentification rate as a function of track momentum as measured using 2017 data.

of all the lines, an effort was made to reduce the resources required for this stream, without limiting the physics analyses using it. Two new concepts were introduced: each physics analysis in the Turbo stream can be configured to 1) selectively store raw banks and 2) selectively store physics objects in addition to those related to the selected decay tree. This was implemented for the 2017 data taking and used for charm spectroscopy where the event size is now reduced by a factor of two without affecting the physics performance.

The calibration stream is used to measure efficiencies and other performance metrics directly from the data. Events in the calibration stream contain the persisted trigger candidates in addition to the raw sub-detector data. This stream is used for the evaluation of the tracking efficiency and for the charged particle identification calibration. This sample also allows the evaluation of the particle identification efficiency, as shown in Figure 7.

3.3 Real-time alignment and calibration

The real-time alignment and calibration was implemented at the beginning of Run 2 and improved in the following years. The real-time procedure allows to profit from the fully aligned and calibrated detector already in the software trigger. The alignment is evaluated on a fill-by-fill basis and is updated when a significant variation is observed. This includes the alignment of the vertex detector, the tracker system, the muon chambers and the RICH mirrors. The calibration is evaluated and updated on a run-by-run basis for the RICH detector and for the global time calibration of the OT, and on a monthly basis for the electromagnetic calorimeter.

In 2016, the RICH mirror alignment was automatically evaluated for each fill but no update was applied, although a clear dependency of the mirror position on the magnet polarity was observed. During the EYETS further tuning of the
fitting procedure has been worked out and the full automatisation of the RICH mirror alignment was implemented. In the first commissioning period the stability of the procedure was studied and the criteria to apply automatic updates were determined. In this period, the alignment was updated after an expert’s check at each magnet polarity switch. Since October, the updates are automatically applied.

Since 2017, the electromagnetic calorimeter is calibrated on a fill-by-fill basis by an automatic LED system that allows to evaluate the HV settings needed to compensate the aging of the detector. The absolute calibration of the detector is based on a $\pi^0$ sample studied cell by cell and run by run on a monthly basis. The full automatisation procedure was implemented during the EYETS and is running smoothly since the beginning of 2017 data taking. Figure 8 shows the trend of $\pi^0$ mass peak over the time, showing a good stability thanks to the frequent LED calibration and the adjustment due to the global calibration.

All the other tasks of the real-time alignment and calibration are also running smoothly in 2017. The VELO alignment was updated on average every three fills and the tracker alignment was mainly updated only after each magnet polarity change. Figure 9 shows the relative variation of some of the VELO and IT alignment constants with respect to the previous alignment update.

### 3.4 Computing

The computing usage for 2016 [6], the re-assessed estimates for 2018, incorporating the increased LHC efficiency, and a preview of requests for 2019 [7,8], are discussed in detail in separate documents.
Figure 9: Variation of the VELO (top) and of the IT boxes (bottom) alignment constants for the first part of the 2017 data taking. The dashed lines indicate the minimum variation at which an alignment difference is considered significant. Each point shows the variation of the alignment parameter with respect to the constants used. The full markers indicate when an alignment update was needed.

4 Physics results

Since the last RRB in April 2017, the LHCb collaboration submitted 30 new publications, for a total of 400 papers at the time of writing. Ten further publications are being processed by the LHCb Editorial Board and are close to submission. In the following, some selected results in the sectors of heavy flavour spectroscopy and production, gauge boson production and decay, CP violation, lepton-flavour universality tests and searches for new physics with rare decays are highlighted.

4.1 Heavy flavour spectroscopy

During the summer, the observation of a highly significant structure in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the $\Lambda_c^+$ baryon is reconstructed in the decay mode $pK^-\pi^+$, has been published [1]. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon $\Xi^{++}_{cc}$. From an unbinned extended maximum likelihood fit to the invariant mass distribution, the $\Xi^{++}_{cc}$ mass is determined to be $3621.40 \pm 0.72$ (stat) $\pm 0.27$ (syst) $\pm 0.14$ (\Lambda_{c}^{+}) MeV/c^2, where the last uncertainty is due to the limited knowledge of the $\Lambda_c^+$ mass (see Fig. 10). The state is observed in a sample of $pp$ collision data collected at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 1.7 fb$^{-1}$, and confirmed in an additional sample of data collected at 8 TeV. The mass of the observed $\Xi^{++}_{cc}$ state is greater than that of the $\Xi^{++}_{cc}$ peak reported by the SELEX collaboration by $103 \pm 2$ MeV/c$^2$. This difference would imply an isospin splitting vastly larger than that seen in any other baryon system and is inconsistent with the expected size of a few MeV/c$^2$. Consequently, while the state is consistent with most theoretical expectations for the $\Xi^{++}_{cc}$, it is inconsistent with being an isospin partner to the $\Xi^{+}_{cc}$ state reported previously by the SELEX collaboration.

Another very relevant result in the sector of heavy flavour spectroscopy is the first observation of the the decays $\chi_{c1} \to J/\psi \mu^{+}\mu^{-}$ and $\chi_{c2} \to J/\psi \mu^{+}\mu^{-}$ [9].
The mass of the \( \chi_{c1} \) meson together with the mass and natural width of the \( \chi_{c2} \) are measured with high precision for the first time at a collider. The results for the mass measurements are \( m(\chi_{c1}) = 3510.71 \pm 0.04 \pm 0.09 \) MeV, \( m(\chi_{c2}) = 3556.10 \pm 0.06 \pm 0.11 \) MeV, \( m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07 \pm 0.03 \) MeV, where the first uncertainties are statistical and the second systematic. The measurements are in good agreement with and have comparable precision to the best previous ones, made using antiproton annihilations on a fixed target by the E760 and E835 experiments at Fermilab. The result for the \( \chi_{c2} \) natural width is \( \Gamma(\chi_{c2}) = 2.10 \pm 0.20 \text{ (stat)} \pm 0.02 \text{ (syst)} \) MeV. These observations open up a new avenue for hadron spectroscopy at the LHC. Importantly, it will be possible to extend measurements down to very low \( p_T(\chi_{c1,2}) \) probing further QCD predictions. In addition, measurements of the transition form factors will provide inputs on the interaction between charmonium states and the electromagnetic field. With larger data samples, studies of the Dalitz decays of other heavy-flavour states will become possible. For example, measurement of the transition form factor of the \( X(3872) \) via its Dalitz decay may help elucidate the nature of this enigmatic state. The invariant mass distribution along with the result of the best fit to the data are reported in Fig. 11.

4.2 Heavy flavour productions in \( p\text{Pb} \) collisions

The LHCb collaboration published the first LHC paper on results obtained using the latest \( p\text{Pb} \) data at a centre-of-mass energy per nucleon of 8.16 TeV [10]. The differential production cross-sections of prompt \( J/\psi \) and \( J/\psi \)-from-\( b \)-hadrons in \( p\text{Pb} \) and \( \text{Pb}p \) collisions are measured in the range \( 0 < p_T < 14 \text{ GeV}/c \). The nuclear
Figure 7.2: Mass distribution for $J/\psi \mu^+ \mu^-$ candidates after the tight selection. The total fit PDF is shown in orange, the $\chi^c_1$ and $\chi^c_2$ signals are shown by the red solid lines and the combinatorial background in blue. The double Gaussian resolution model is used. The residual and pull distributions are shown in Fig. 7.3.

is evaluated to be $47 \pm 7$ keV/$c^2$ and $29 \pm 10$ keV/$c^2$ for the $\chi^c_1$ and $\chi^c_2$ respectively. The 195 central values of the mass measurements are corrected accordingly and the uncertainty...

modification factors are similar to the findings at a collision energy per nucleon of 5 TeV, but with increased precision thanks to 10 and 40 times larger data sets in pPb and PbPb collisions, respectively. A suppression of prompt $J/\psi$ production compared to $pp$ collisions of up to 50\% (25\%) in pPb (PbPb) at the lowest transverse momentum is observed. In both configurations, the nuclear modification factor approaches unity asymptotically at the highest $p_T$. Theoretical calculations for the nuclear modification factor based on collinear factorisation with different nuclear parton distribution functions, coherent energy loss as well as the colour glass condensate model can account for the majority of the observed dependences. In addition, for the first time, beauty-hadron production is measured precisely down to $p_T = 0$ at the LHC in pPb and PbPb collisions. In pPb, a weak suppression at the lowest transverse momenta is observed, whereas in PbPb no significant deviation from unity in the nuclear modification factor is found. This weak modification of beauty production in proton-ion collisions is an important ingredient for the investigation of the modifications of beauty production in heavy-ion collisions. Although these measurements have improved precision, it is not possible to single out the main nuclear modification mechanism between different phenomenological approaches for charmonium production in proton-lead collisions at the TeV scale. This measurement of $J/\psi$ production is the first step towards measurements of other charmonium states as well as complementary observables like Drell-Yan production, to improve the understanding of quantum chromodynamics at low $x$ and in dense nuclear environments.
4.3 Gauge boson production and decay

The decay $Z^0 \rightarrow b \bar{b}$ is reconstructed in $pp$ collision data, corresponding to $2 \text{ fb}^{-1}$ of integrated luminosity, collected by the LHCb experiment at a centre-of-mass energy of 8 TeV [11]. The $Z^0 \rightarrow b \bar{b}$ branching fraction is measured for candidates in the fiducial region defined by two $b$-quark jets with pseudorapidities in the range $2.2 < \eta < 4.2$, with transverse momenta $p_T > 20$ GeV and dijet invariant mass in the range $45 < m_{jj} < 165$ GeV. From a signal yield of $5462 \pm 763$ $Z^0 \rightarrow b \bar{b}$ decays, a production cross-section times branching fraction of $332 \pm 46 \pm 59$ pb is obtained, where the first uncertainty is statistical and the second systematic. The expected cross-section in the fiducial region of the experimental measurement is $\sigma(pp \rightarrow Z^0)B(Z^0 \rightarrow b \bar{b}) = 272^{+9}_{-12} \pm 5$ pb, where the first uncertainty is related to the missing higher-order corrections and to the value of the strong coupling constant, and the second uncertainty is related to the PDFs. The prediction and the measurement are compatible within one standard deviation. The additional data being collected by LHCb will allow a more stringent comparison with the theoretical prediction in the future. Moreover, the systematic uncertainty on the heavy-flavour tagging efficiency will be reduced by collecting more data.

4.4 CP violation

The decays of $B^0_s$ and $\bar{B}^0_s$ mesons into the $J/\psi K^+ K^-$ final state are studied in the $K^+ K^-$ mass region above the $\phi(1020)$ meson in order to determine the resonant substructure and measure the CP-violating phase, $\phi_s$, the decay width, $\Gamma_s$, and the width difference between light and heavy mass eigenstates, $\Delta \Gamma_s$ [12]. A decay-time dependent amplitude analysis is employed. The data sample corresponds to an integrated luminosity of $3 \text{ fb}^{-1}$ produced in 7 and 8 TeV $pp$ collisions at the LHC. The measurement determines $\phi_s = 119 \pm 107 \pm 34$ mrad. A combination with previous LHCb measurements using similar decays into the $J/\psi \pi^+ \pi^-$ and $J/\psi \phi(1020)$ final states gives $\phi_s = 1 \pm 37$ mrad, consistent with the Standard Model prediction. The efforts of the collaboration are now focusing on performing new measurements of $\phi_s$ using the Run-2 data sample.

Another notable result in the sector of time-dependent CP violation is the measurement of $B^0 \rightarrow J/\psi K^0_S$ and and $B^0 \rightarrow \psi(2S) K^0_S$, where the $J/\psi$ is reconstructed from two electrons and the $\psi(2S)$ from two muons [13]. The analysis uses a sample of $pp$ collision data recorded with the LHCb experiment at centre-of-mass energies of 7 and 8 TeV, corresponding to an integrated luminosity of $3 \text{ fb}^{-1}$. The CP-violation observables are measured to be $C(B^0 \rightarrow J/\psi K^0_S) = 0.12 \pm 0.07 \pm 0.02$, $S(B^0 \rightarrow J/\psi K^0_S) = 0.83 \pm 0.08 \pm 0.01$, $C(B^0 \rightarrow \psi(2S) K^0_S) = -0.05 \pm 0.10 \pm 0.01$, $S(B^0 \rightarrow \psi(2S) K^0_S) = 0.84 \pm 0.10 \pm 0.01$, where $C$ describes CP violation in the direct decay and $S$ describes CP violation in the interference between the amplitudes for the direct decay and for the decay after $B^0 - \bar{B}^0$ oscillation. The first uncertainties are statistical and the second systematic. The two sets of results are compatible with the previous LHCb measurement using $B^0 \rightarrow J/\psi K^0_S$ decays, where the $J/\psi$
meson was reconstructed from two muons. The averages of all three sets of LHCb results are $C(B^0 \to [cc]K_S^0) = -0.017 \pm 0.029$, $S(B^0 \to [cc]K_S^0) = 0.760 \pm 0.034$, under the assumption that higher-order contributions to the decay amplitudes are negligible. The uncertainties include statistical and systematic contributions.

Finally, it is worth emphasising the first results with Run-2 data on $CP$ violation in the sector of the $\gamma$ angle of the unitarity triangle. Measurements of $CP$ observables in $B^\pm \to D^{(*)}K^\pm$ and $B^\pm \to D^{(*)}\pi^\pm$ decays have been published [3], where $D^{(*)}$ indicates a neutral $D$ or $D^*$ meson that is an admixture of $D^{(*)0}$ and $D^{(*)+}$ states. Decays of the $D^*$ meson to the $D\pi^0$ and $D\gamma$ final states are partially reconstructed without inclusion of the neutral pion or photon, resulting in distinctive shapes in the $B$ candidate invariant mass distribution. Decays of the $D$ meson are fully reconstructed in the $K^{\pm}\pi^{\mp}$, $K^+K^-$ and $\pi^+\pi^-$ final states. The analysis uses a sample of charged $B$ mesons produced in $pp$ collisions collected by the LHCb experiment, corresponding to an integrated luminosity of 2.0, 1.0 and 2.0 fb$^{-1}$ taken at centre-of-mass energies of 7, 8 and 13 TeV, respectively. The study of $B^\pm \to D^*K^\pm$ and $B^\pm \to D^*\pi^\pm$ decays using a partial reconstruction method is the first of its kind, while the measurement of $B^\pm \to DK^{\pm}$ and $B^\pm \to D\pi^{\pm}$ decays is an update of previous LHCb measurements. The $B^\pm \to DK^{\pm}$ results are the most precise to date. As an example, Fig. 12 shows the invariant mass distributions of selected $B^\pm \to [K^+K^-]Dh^{\pm}$ candidates. A related measurement is that of $CP$ observables in $B^\pm \to DK^{*\pm}$ decays [14], where $D$ denotes a superposition of $D^0$ and $\bar{D}^0$ meson states. Decays of the $D$ meson to $K^-\pi^+$, $K^-K^+$, $\pi^-\pi^+$, $K^-\pi^-\pi^-$ and $\pi^-\pi^+\pi^-$ are used and the $K^{*\pm}$ meson is reconstructed in the $K_S^0\pi^{\pm}$ final state. This analysis uses a data sample of $pp$ collisions collected with the LHCb experiment, corresponding to integrated luminosities of 1 fb$^{-1}$, 2 fb$^{-1}$ and 1.8 fb$^{-1}$ at centre-of-mass energies of 7, 8 and 13 TeV, respectively. A new combination of tree-level measurements of the angle $\gamma$ from $B \to DK$ decays at LHCb has been made for the Summer conferences [4]. This combination uses both new and updated results compared to an earlier LHCb combination, and gives $\gamma = (76.8^{+5.1}_{-5.7})^\circ$ modulo 180$^\circ$, where the uncertainty includes statistical and sys-
Figure 13: 1−CL curve for the LHCb γ combination, with the central value (solid vertical line) and 1σ uncertainties (dashed vertical line) labelled. The 1σ and 2σ levels are indicated by the horizontal dotted lines.

4.5 Lepton-flavour universality tests

A test of lepton universality has been performed by measuring the ratio of the branching fractions of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ and $B^0 \rightarrow K^{*0} e^+ e^-$ decays, $R_{K^{*0}}$ [15]. The $K^{*0}$ meson is reconstructed in the final state $K^+ \pi^-$, which is required to have an invariant mass within 100 MeV/c² of the known $K^{*0}(892)$ mass. The analysis is performed using $pp$ collision data, corresponding to an integrated luminosity of about 3 fb⁻¹, collected by the LHCb experiment at centre-of-mass energies of 7 and 8 TeV. The ratio is measured in two regions of the dilepton invariant mass squared, $q^2$, to be $0.66^{+0.11}_{-0.07}$(stat) ± 0.03(syst) for $0.045 < q^2 < 1.1$ GeV²/c⁴, and $0.69^{+0.11}_{-0.07}$(stat) ± 0.05(syst) for $1.1 < q^2 < 6.0$ GeV²/c⁴. The results, which represent the most precise measurements of $R_{K^{*0}}$ to date, are compatible with the Standard Model expectations at the level of 2.1–2.3 and 2.4–2.5 standard deviations in the two $q^2$ regions, respectively. Figure 14 shows a comparison of the LHCb measurements with the Standard Model theoretical predictions.

Another relevant measurement to test lepton-flavour universality has also been published. The ratio of branching fractions $R(D^{*-}) = B(B^0 \rightarrow D^{*-} \tau^+ \nu_{\tau})/B(B^0 \rightarrow D^{*-} \mu^+ \nu_{\mu})$ is measured using a data sample of $pp$ collisions collected with the LHCb detector at centre-of-mass energies of 7 and 8 TeV, corresponding to an integrated luminosity of 3 fb⁻¹ [2]. For the first time $R(D^{*-})$ is determined using the τ lepton decays with three charged pions in the final state. The $B^0 \rightarrow D^{*-} \tau^+ \nu_{\tau}$
yield is normalized to that of the $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ mode, providing a measurement of $\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+) = 1.93 \pm 0.13 \pm 0.17$, where the first uncertainty is statistical and the second systematic. The value of $\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (1.39 \pm 0.09 \pm 0.12 \pm 0.06)\%$ is obtained, where the third uncertainty is due to the limited knowledge of the branching fraction of the normalization mode. Using the well-measured branching fraction of the $B^0 \to D^{*-}\mu^+\nu_\mu$ decay, a value of $R(D^{*-}) = 0.285 \pm 0.019 \pm 0.025 \pm 0.013$ is established, where the third uncertainty is due to the limited knowledge of the branching fractions of the normalization and $B^0 \to D^{*-}\mu^+\nu_\mu$ modes. This measurement is in agreement with the Standard Model prediction and with previous results.

4.6 Searches

A search for the decay $K^0_S \to \mu^+\mu^-$ has been performed, based on a data sample of $pp$ collisions corresponding to an integrated luminosity of $3 \text{ fb}^{-1}$, collected at centre-of-mass energies of 7 and 8 TeV [16]. The observed yield is consistent with the background-only hypothesis, yielding a limit on the branching fraction of $\mathcal{B}(K^0_S \to \mu^+\mu^-) < 0.8(1.0) \times 10^{-9}$ at 90\% (95\%) confidence level. This result improves the previous upper limit on the branching fraction by an order of magnitude.

On the subject of lepton-flavour violating decays, a search for $B^0_s \to e^+\mu^+$ and $B^0 \to e^+\mu^+$ decays has been performed, again based on a sample of $pp$ collision data corresponding to an integrated luminosity of $3 \text{ fb}^{-1}$, collected at centre-of-mass energies of 7 and 8 TeV [17]. The observed yields are consistent with the background-only hypothesis. Upper limits on the branching fractions are deter-
Figure 15: Regions of the \([m(A'), \varepsilon^2]\) parameter space excluded at 90% CL by the prompt-like \(A'\) search compared to the best existing limits.

 mined to be \(\mathcal{B}(B_s^0 \to e^+\mu^-) < 5.4(6.3) \times 10^{-9}\) and \(\mathcal{B}(B^0 \to e^\mp \mu^\mp) < 1.0(1.3) \times 10^{-9}\) at 90% (95%) confidence level, which are the strongest limits on these decays to date.

Finally, it is worth emphasising a search for both prompt-like and long-lived dark photons, \(A'\), produced in pp collisions at a centre-of-mass energy of 13 TeV, using \(A' \to \mu^+\mu^-\) decays and a data sample corresponding to an integrated luminosity of 1.6 fb\(^{-1}\) [18]. The prompt-like \(A'\) search covers the mass range from near the dimuon threshold up to 70 GeV, while the long-lived \(A'\) search is restricted to the low-mass region \(214 < m(A') < 350\) MeV. No evidence for a signal is found, and 90% confidence level exclusion limits are placed on the \(\gamma-A'\) kinetic-mixing strength. The constraints placed on prompt-like dark photons are the most stringent to date for the mass range \(10.6 < m(A') < 70\) GeV, and are comparable to the best existing limits for \(m(A') < 0.5\) GeV. The search for long-lived dark photons is the first to achieve sensitivity using a displaced-vertex signature. Figure 15 reports a comparison of the result for the prompt-like search to existing constraints from previous experiments.

5 Financial issues

The status of the accounts is healthy and no cash flow problems are foreseen. The expenditure on the 2016 M&O Cat. A budget followed well our forecasts. As expected, a small overspending is registered, due to late bills from 2015, and due to the anticipated acquisition of a new farm slice (CERN-RRB-2016-113_rev). As proposed in CERN-2016-RRB-114_rev and accepted by the RRB, the surplus from 2015 has been used to offset the overspending from this year. Year 2017 is following expectation and expenditures are in line with a well balanced budget. A financial plan for the M&O cat.A levels for the forthcoming LS2 and the following upgrade detector operational phase has been finalised and submitted to the Scrutiny Group and RRB.
6 Collaboration matters

In July 2017 the new Spokesperson, Giovanni Passaleva (INFN Firenze, Italy) and his Deputy, Chris Parkes (University of Manchester, UK), started their three year mandate. Marie-Helene Schune (LAL, Orsay, France) has been elected as the next Physics Coordinator and will start her mandate in January 2018. Silvia Borghi (University of Manchester, UK) has been appointed as Operation Coordinator for two years from March 2017.

Two new groups joined LHCb in the last six months. MISiS University (Moscow, Russia) and the University of Michigan (Ann Arbor, USA) were elected as associated members of the collaboration in June and September respectively.
References


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