Status of the LHCb experiment

CERN-RRB-2014-091

15 October 2014

1 Introduction

Throughout 2014 the LHCb collaboration has continued to analyse at an undiminished rate the data collected in Run 1, and will soon have submitted 250 papers to journals. Important results have been obtained in the areas of suppressed B meson decays, CP-violation measurements and spectroscopy, as well as in non-flavour topics such as pPb collisions and electroweak boson production. Further important publications are anticipated before the resumption of data taking in 2015.

Intense shutdown activity has been ongoing on the experiment to prepare the sub-detectors and infrastructure for Run 2. We are confident that all interventions will be successfully completed on schedule, and that LHCb will be ready for first beams in the coming Spring. Significant improvements are foreseen to the running strategy. Most important of these is 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 will allow for more discriminant selections to be applied, and ensure that the recorded data are more closely aligned with that required for the offline analysis.

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 [1].

2 Detector sub-systems

The maintenance and consolidation work on all sub-systems and services is almost complete. On the detector side, the main ongoing activities are the installation of the beam pipe and the replacement and exchange of HPDs in the RICH. Once the beam pipe is installed, the detector will be closed and a survey of the sub-systems will be performed. Originally, it was foreseen to pump down the beam pipe after the detector's closure, but given that the LHC sector test has been moved to next year, the beam pipe will stay under neon until the end of November.

A magnetic field measurement campaign was launched during the month of August. Data were taken with both polarities and the positioning of the Hall probes were recorded during an extensive survey. The analysis of these data will continue and results are expected over the next three months.

Commissioning weeks are scheduled over the coming months, and data from an LHC injection test will be taken in November.

Water leaks in the power supplies of one of the LHC experiments triggered a closer look at the LHCb cooling circuit inside them. This issue will be followed up together with all other LHC experiments; there is a risk that all power supplies will have to be dismounted, opened and the cooling connectors replaced.

2.1 Beam pipe

The beam pipe re-installation started at the end of August. The first section UX85/1 was aligned and a new integrated support system was installed inside the magnet, which is made of two beryllium collars attached to carbon-fibre rods and cables. A continuous monitoring system of the tension of the cables/rods has been put in place, which consists of two radiation hard sensors and 16 regular sensors. The readout electronics is also installed and a first version of the readout in the PVSS control framework is operational. A more complete version will be deployed before the start of Run 2. The new beryllium UX85/3 section has just been installed. The two other sections, UX85/4 and UX85/2, stored in the LHCb cavern at Point 8 during LS1, will follow. Finally, new aluminum and stainless steel bellows will be put in place.

Bake-out of the re-installed sections is scheduled for the second half of October and connection to the remaining UX85/1 section will take place immediately after. The beam pipe is expected to be ready for operation in vacuum conditions around the end of November.

2.2 Vertex Locator (VELO)

The preventive maintenance and minor upgrades to the system scheduled for the long shutdown are almost finished. The preventive maintenance of the crates and power supplies is close to completion; all new bulk power supplies needed for the refurbishment of the LV system have been delivered. They will be integrated into the system at the end of November, when the VELO will be under vacuum again, as only under these conditions can the system be fully tested. The maintenance of the cooling, motion and vacuum system is nearly finished. The remaining maintenance tasks will be completed by November.

A few additional spare custom electronics boards have been prepared, qualified and are ready to use. The new control interface for the CAN bus has been commissioned.

The new SPECS control interface is expected in Autumn 2014 and will subsequently be integrated. Work on further improvements and streamlining of the

WinCC control software is still ongoing and will be finished in the next couple of months.

The software for monitoring the VELO data quality has been completely re-written and porting of the specific monitoring algorithms to the new framework is ongoing. The procedure for determining the configuration parameters of the TELL1 DAQ board has been further streamlined and will be fully commissioned by November. Work is ongoing to improve the monitoring of these parameters, expected to be completed within the same time scale.

Due to radiation damage in the innermost regions of the VELO sensors close to the interaction point, it is expected that the VELO can no longer be operated efficiently with uniform bias voltages across all sensors. The procedure to address this new node of operation will be defined and implemented over the next few months and will be fully tested and ready for the start of LHC Run 2.

2.3 Silicon Tracker (ST)

The Silicon Tracker was left in a safe state during LS1. The detector has been powered for short tests to check its status during the regular LHCb commissioning weeks. Several interventions have taken place to improve the ST operation and reliability for Run 2.

The cooling system was upgraded during LS1 to improve its reliability and remove the need for the daily interventions that were required during the last run (details are available in previous RRB reports). The system has been running without problems since it was installed in March. The old cooling plant is kept as a back-up system in case there are unforeseen problems during Run 2.

Minor maintenance work was performed on the HV and LV systems. In addition, many improvements were made to the control system code and the system was thoroughly tested.

A new system will be installed to monitor the movement of the IT stations. It is based on the Brandeis CCD Angle Monitor (BCAM) system developed for the ATLAS muon detectors. Two BCAMs will be installed per station with passive reflective targets on each half station. The system will be installed by the end of the year and will measure the relative movement of the stations with an accuracy of better than 1 mm.

Work is ongoing to improve positioning and alignment of the IT. The relative position of the two halves has been measured and small modifications were made to the stoppers that define the closed positions of the stations. The final adjustments can only be made after the installation of the beam-pipe.

A large number of channels were recovered in both detectors since the end of Run 1. This was achieved by replacing all broken VCSEL diodes in the TT and IT as well as by repairing two modules that could not be configured in the IT. As a result the number of working channels in TT and IT is 99.7% and 99.1%, respectively. The detectors are in good shape for the restart of data taking.

2.4 Outer Tracker (OT)

The Outer Tracker has had its LV power supplies successfully revisited after the discovery of the polluted water connectors in September 2013. The full readout chain was tested again in June and September 2014. All 432 front-end modules are still functioning properly.

Towards the start-up of the LHC Run 2, during the first half of 2015, the Outer Tracker group will consolidate the HV system (replacement of one HV power supply board), the gas monitoring system (replacement of the amplifier board that records monochromatic ^{55}Fe pulses in a dedicated setup), and will optimize the grounding of the readout electronics.

Furthermore, before LHC operation, a measurement of the response to ^{90}Sr sources of nine detector modules is foreseen, to provide a reference measurement to monitor possible gain deterioration during detector operation in Run 2.

2.5 RICH system

The preparation of the RICH detectors for Run 2 is progressing according to schedule. The biggest activity is the replacement of aging HPDs with new HPDs with very stable ion feedback. In the intervention carried out in September, all RICH1 HPDs that were expected to fail before 2018 were replaced or moved to positions with no impact on PID performance, while for RICH2 the HPD replacement will take place in November. In the same intervention the aerogel radiator was removed from RICH1, as extensive studies have shown that its presence brings negligible improvement to the performance. The space liberated by its removal will allow the gas radiator length to be increased, and therefore is expected to improve the π-K separation of the C_4F_{10} rings.

The initiative to increase the available output bandwidth to the HLT farm by 30% by equipping the RICH with new UKL1 boards is progressing well. The tests of the prototype board have shown no issues, and production is scheduled towards the end of the year. A new procedure to extract the correction parameters for the magnetic field distortions shows a potential improvement of 3-4% of the Cherenkov angle resolution for RICH1 and it is being verified with 2012 data.

Many other small activities are taking place in order to deliver in 2015 a more robust RICH system with improved performance.

2.6 Calorimeters (SPD, PS, ECAL and HCAL)

Maintenance activities are almost complete. The main activity was the fibre replacement of the ECAL monitoring system. The installation of the new 456 bundles on the ECAL detector was accomplished by the end of April, well within schedule. The commissioning of this new system went on in parallel. Very few problems were identified and most of those that did occur were not related to the fibres themselves, but to bad contacts at the PMTs or in the front-end electronics. These faults have been cured and a more general campaign for fixing the connectors on the front-end electronics will be pursued.

The LED control voltages and the timing of their control boards have been tuned. The PIN diodes, which are used to monitor the stability of the LED light, were calibrated so that the signal amplitudes fit the ADC range (500, 3500) and the timing of their readout board was adjusted.

A total of 186 PMTs were exchanged in the HCAL; of these 109 were replaced by new tubes, while the remainder were swapped with good PMTs from the peripheral regions, where a degraded performance can be tolerated. The replaced PMTs need to be calibrated with a ^{136}Cs source, which will be re-installed in the HCAL at the end of October after the beam pipe installation.

Four TELL1 modules (two for the PS/SPD and two for the HCAL) were added to increase the security margin for throttling when running at high luminosity.

The refurbishment of the flexible pipes and water connectors of the cooling system of the Wiener Maraton power supplies is on-going.

Finally, an automated detector calibration is being prepared, which will allow us to follow detector ageing fill by fill.

2.7 Muon system

Most of the maintenance work on the muon chambers is now complete and the muon group is currently proceeding with the final tests and re-commissioning.

The work on the PNPI MWPC HV system hardware upgrade is now finished and the deployment of the improved control software is progressing, which will allow a seamless integration of the new hardware in the current experiment control system (ECS). The ECS software has been upgraded from PVSS 3.8 to WinCC-OA 3.11 and the final testing phase has started. During the coming months the muon system will be closed after which the space alignment of the half-stations will be performed.

The emphasis will then move to the general commissioning of the whole Muon system, performing front-end board threshold scans with chambers in operating conditions and various other types of technical runs (e.g. noise scans, pulsing runs).

2.8 Online system

The replacement of the CAN interfaces is finished and many control PCs have been moved to virtual machines. The SPECS interfaces will follow in the coming months, when the new hardware is available.

A significant effort is being directed into the controls system to support the split High Level Trigger, described in Sect. 3, and the automatic alignment and calibration procedures that are necessary in this scheme.

The disks for upgrading the farm PCs have arrived and will be installed in the near future. We shall also replace the oldest CPUs of the farm. Here we have decided to take advantage of the tender procedure IT Department has performed for the CERN computing centre. This has the benefit of increasing the total size of the order and may result in a more favourable price.

3 Operations

Operational activities are currently focused on preparing the 'split HLT'. In this new approach the data passing HLT1, the first stage of the software trigger, will be temporarily saved to disc. The alignment and calibration of these data will be assessed, and if necessary new constants determined. Then HLT2, the second stage of the software trigger, will be deployed. Having access to 'physics quality' alignment and calibration performance in the online will allow more discriminant selections to be performed, for example making use of RICH information, and thereby permit larger signal samples to be selected at a given output rate. Furthermore the offline processed data are guaranteed to be suitable for final analysis, with no need to wait for a final end-of-year reprocessing.

3.1 Trigger

A baseline HLT reconstruction sequence is under development, taking advantage of the factor of two increase in the Event Filter Farm (EFF) CPU power, and improvements in the reconstruction algorithms. Inspired by studies towards the LHCb upgrade, VELO tracks can now be confirmed by the TT station before running the forward tracking algorithm. In HLT1, we can also now reconstruct all tracks down to a p_T threshold of 500 MeV without any impact parameter requirements. This opens up the possibility for key exclusive selections already in HLT1 to complement the inclusive single track line, for example lifetime unbiased two body B and D selections, and lines for modes with soft muons like $K^0_S \to \mu^+\mu^-$ and $\tau \to \mu\mu\mu$. The 2-body inclusive B line can also be moved to HLT1. The proposed HLT1 output rate is 150kHz, given the available disk space on the EFF. This value allows for a possible increase in event size due to the persistence of HLT1 tracks for re-use in HLT2.

A preliminary set of L0 trigger thresholds has been evaluated based on our existing bandwidth division algorithm. These will evolve in the coming months through iteration between the Trigger project and Physics Working Groups, in order to ensure optimal performance for both leptonic and hadronic final states. We plan to rerun this bandwidth division as soon as 13 TeV data are available, and work is ongoing to parallelise the bandwidth division algorithm for running on the HLT farm itself, so that the turnaround can be as fast as possible.

3.2 Detector calibration

The increased selectivity of HLT1 has an impact on the planned automatic alignment and calibration strategy.

The RICH refractive index and HPD image calibration parameters will be computed for each run separately, while all other alignment and calibrations constants will be calculated each fill. At the start of each fill, HLT1 will use the alignment from the previous fill. A small amount of data, collected over 5-10 minutes, is sufficient to re-align the tracker. Only if the new alignment is outside some predefined tolerance, will the new alignment be applied, for use in HLT1 and all subsequent processing. Any change of tracking alignment will be flagged for special attention in the offline data quality procedure. HLT2 will process each run with the same alignment as used in HLT1. A monitoring procedure for the HLT2 output (which is not necessarily run ordered) has also been developed.

3.3 Computing

The computing usage in 2013 [2] and the resources estimates for 2015 and beyond [3] are discussed in separate documents.

4 Physics results

Between April 2014 and October 2014 LHCb increased its output rate of physics papers compared to the previous six-month period, in spite of the absence of new data. At the time of writing LHCb has submitted 238 papers of which 193 are published.

The most recent highlight is the combined re-analysis of the $B \to \mu^+\mu^-$ data of the LHCb and CMS experiments. This is the first time a combined fit to the data of two LHC experiments has been performed.

The rare decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are very suppressed in the Standard Model with precisely predicted branching fractions of $(3.65\pm0.23)\times10^{-9}$ and $(1.06 \pm 0.09) \times 10^{-9}$, respectively [4].

The 2011 and 2012 data samples, corresponding to 3 fb^{-1} (LHCb) and 20 fb^{-1} (CMS) have been re-analysed, retaining the selections of the original publications [5] but aligning the fit models where appropriate. A mass projection for the combined analysis is shown in Fig. 1 (left).

The measured combined branching fractions are

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.8\,^{+\,0.7}_{-\,0.6} \times 10^{-9} \quad (6.2\sigma)$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9\,^{+\,1.6}_{-\,1.4} \times 10^{-10} \quad (3.0\sigma).$$

The latter is compatible with the Standard Model expectation at the 2.2σ level. The confidence level contours is shown in Fig. 1 (right). These results are about to be submitted to Nature [6].

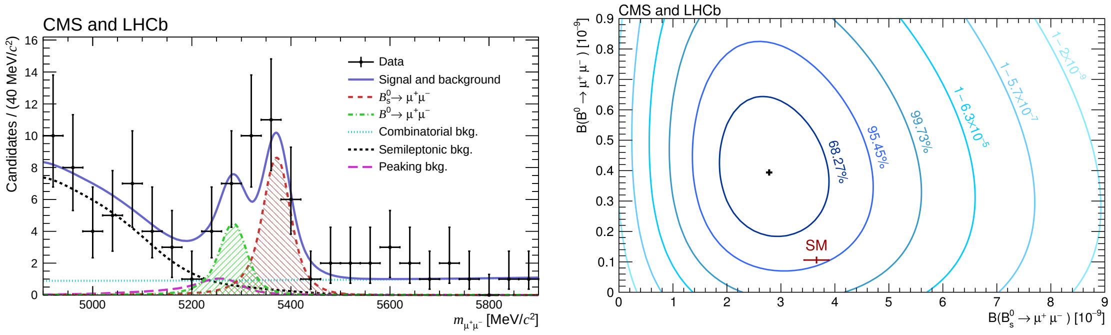

Figure 1: (left) Dimuon mass distribution for the six more significant BDT bins. (right) Likelihood contours for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ branching fractions. Figures from Ref. [6].

Following the surprising evidence for a deviation from the Standard Model prediction in the angular distributions of the decay $B^0 \to K^*\mu^+\mu^-$ [7], we continue to investigate similar $b \to s\ell\ell$ transitions. The CP asymmetry in $B^0 \to K^*\mu^+\mu^-$ and $B^\pm \to K^\pm\mu^+\mu^-$ turns out to be compatible with zero as expected [8], while the lepton universality ratio $R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$ is measured to be $0.745\,^{+\,0.090}_{-\,0.074} \pm 0.036$ [9] in the $1 < q^2 < 6$ GeV/c^2 range, which indicates a 2.7σ tension with unity. Although not yet significant, this result has attracted considerable attention in the theory community, where models involving a heavy Z' boson have been invoked to explain both the above-mentioned deviations.

This analysis shows the capability of the LHCb experiment to do physics with electrons, in spite of the large loss of mass resolution due to bremsstrahlung. Fig. 2 shows the $B^+ \to K^+e^+e^-$ mass distributions for events selected by an electron in the L0 hardware trigger.

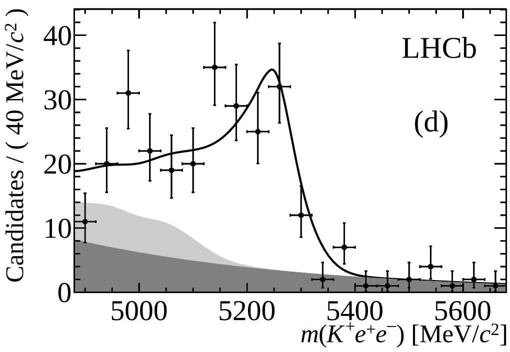

Figure 2: Mass distribution of $K^+e^+e^-$ candiadtes with $1 < m^2_{e^+e^-} < 6$ GeV/c^2, for events triggered by an electron. Figure from Ref. [9].

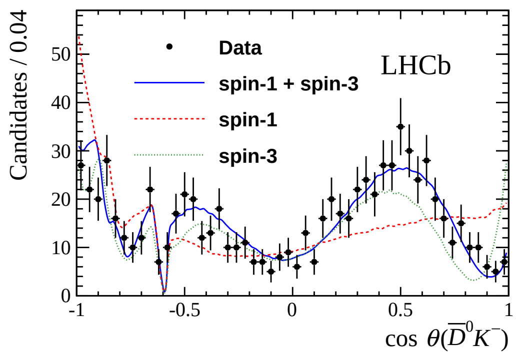

Figure 3: Fit of the $\overline{D}^0 K^+$ angular distribution in $B_s^0 \to \overline{D}^0 K^+\pi^-$ decays. Three spin hypotheses are superimposed. Figure from Ref. [10].

LHCb has shown on many occasions that the clean environment of b-hadron decays provides an ideal laboratory for spectroscopy studies with a well defined initial state. Recently this has been used in the decay $B_s^0 \to \overline{D}^0 K^- \pi^+$ to study resonances decaying to $\overline{D}^0 K^-$ [10, 11].

For the first time, the spin of the $D_{s2}^*(2573)^-$ meson is determined to be 2, as expected, and its mass and decay width are measured with unprecedented precision. We also determine that the $D_{sJ}^*(2860)^-$ state is actually a superposition of a spin-1 and a spin-3 meson, as shown in Fig. 3. We report the mass and the width for both states, now to be called $D_{s1}^*(2860)^-$ and $D_{s3}^*(2860)^-$. This is the first observation of a heavy-flavoured spin-3 particle, as well as of a spin-3 particle produced in b-hadron decays.

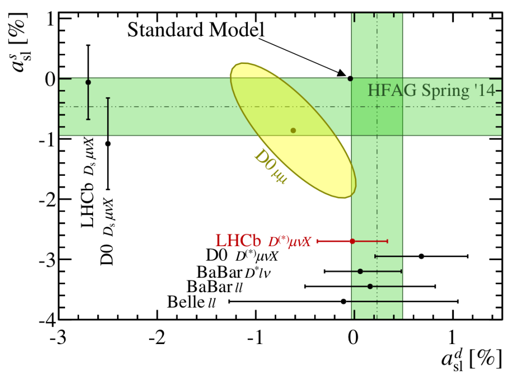

Figure 4: Overview of all measurements of the semileptonic asymmetries $a_{\rm sl}^d$ and $a_{\rm sl}^s$

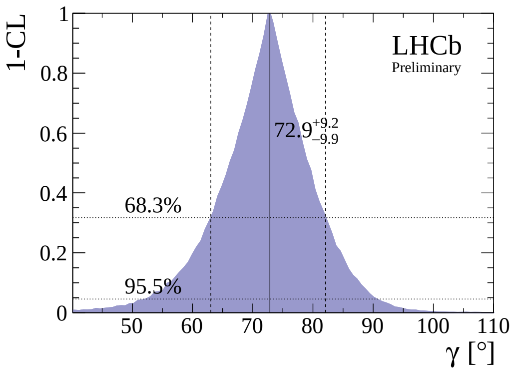

Figure 5: Confidence level of the LHCb γ combination from $B \to DK$ decays. Figure from Ref. [12].

Following the D0 evidence for a deviation from the Standard Model in the semileptonic asymmetries in B_s^0 ($A_{\rm sl}^s$) and B^0 decays ($A_{\rm sl}^d$), we performed a new measurement of the latter with the full Run 1 dataset [13]. The result $A_{\rm sl}^d = (-0.02 \pm 0.19 \pm 0.30)\%$ is compatible with the Standard Model, but also with the D0 measurement, as can be seen in Fig. 4. The analogous measurement with B_s^0 mesons, $A_{\rm sl}^s$, is being worked on. A by-product of this analysis is the measurement of the B^0-meson production asymmetry at the LHC. The measured value of $(-0.5 \pm 0.2)\%$ is slightly negative as expected.

Many new measurements of the CKM angle γ have been published for the summer conferences. Notable examples include a time-dependent tagged analysis of the decay $B_s^0 \to D_s^\mp K^\pm$ [14], and time-integrated analyses of the decays $B^0 \to D^0 K^*$ [15], and $B^+ \to D^0 K^+$ with $D^0 \to K_{\rm S}^0 \pi^+ \pi^-$. For the latter, the knowledge of the strong phase along the Dalitz plane of the D^0 decay is needed, which can be obtained from a BaBar model, as in Ref. [16] or CLEO-c data, as in Ref. [17]. These and previous results are averaged in a new LHCb γ combination shown at the CKM workshop in Vienna [12]. For the first time the LHCb average of $(72.9\,^{+\,9.2}_{-\,9.2})^\circ$ using only $B \to DK$ modes is more precise than that arising from the combined data set of both B factory experiments. The confidence level distribution is shown in Fig. 5.

Similarly, we provided measurements of the phase of B_s^0 mixing using the decay $B_s^0 \to J/\psi\pi^+\pi^-$ [18] and $B_s^0 \to D_s^+ D_s^-$ [19]. Both results are consistent with zero and with the Standard Model expectation. The pure penguin counterpart of this measurement using the decay $B_s^0 \to \phi\phi$ has also been updated to 3 fb^{-1} [20]. The latter mode achieves a tagging power ϵD^2 in excess of 5% thanks to recent new developments, notably in the same-side kaon tagging.

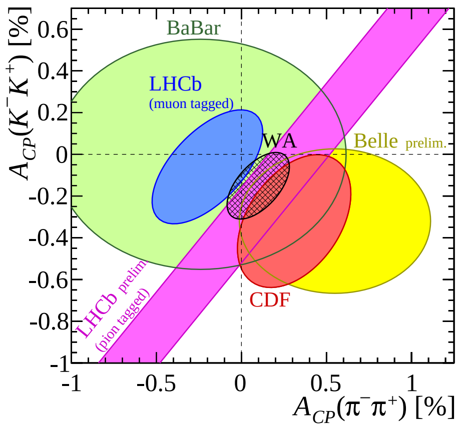

Figure 6: Measurements of $A_{CP}(D^0 \to hh)$ with the latest LHCb result [21] shown in blue.

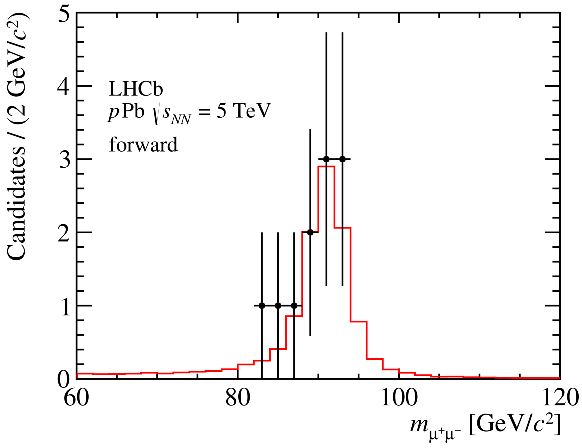

Figure 7: $Z \to \mu^+\mu^-$ mass distribution in pPb data (black points) compared to simulation (red histogram). Figure from Ref. [22].

In a recent Run 1 update of the CP asymmetries in two-body D^0 decays, we published separate CP asymmetries for $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ for the first time. This was achieved using semileptonic B decays, using the charge of the muon to tag the flavour of the D^0. We measure $A_{CP}(K^+K^-) = (-0.06 \pm 0.15 \pm 0.10)\%$ and $\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$, from which we infer $A_{CP}(\pi^+\pi^-) = (-0.20 \pm 0.19 \pm 0.10)\%$, all compatible with CP symmetry [21]. The likelihood contour of this measurement is compared with previous publications in Fig. 6.

A recent re-analysis of the luminosity calibrations allowed us to perform the best luminosity determination at a hadron collider. It is based on van der Meer scans and beam imaging using neon gas injected into the beam pipe. The complementarity of the two methods allows us to achieve a reduction of the uncertainty from 3.5% to 1.1% for 2012 data [23]. The first measurement to benefit from this improved precision was a determination of the W cross-section at 7 TeV [24]

The same methods have also been used during the pPb run in 2013. We continue to analyse this unique data set and recently published the Υ cross-section [25] and, for the first time in pPb collisions, the observation of Z bosons [22], as shown in Fig. 7.

There has been significant progress in the jet reconstruction algorithms and the number of analyses using them is increasing rapidly. Following the hints of unexpected asymmetries in t-quark production at the Tevatron, we recently published the first measurement of the charge asymmetry in b-jet pairs [26]. Here we search for asymmetries in the angular distributions of b-jets and find no deviation from the Standard Model expectation. The jet flavour is identified by the corrected mass of the leading particles in the jet, an algorithm initially developed for and heavily using in the HLT [27].

As the new 13 TeV data are near, we are preparing for a series of cross-section measurements at this unprecedented energy. Of particular interest will be the $b\bar{b}$, $c\bar{c}$, charmonium, Υ, Z and W cross-sections, as well as the b-hadronisation fractions.

5 Financial issues

The status of the accounts is healthy and there are no cash flow problems foreseen. The expenditures on the 2013 M&O cat. A budget have followed our forecast. Due to the long shutdown in 2013-14 and the planned significant interventions on the sub-detectors, together with the work required for general safety and infrastructure, LHCb overspent the M&O cat. A budget in 2013 and most likely will also overspend in the year 2014. However, taking into account the cat. A funds buffered from previous years, accumulated with these expenditures in mind, we are confident to be able to satisfy all our requirements within a constant budget.

6 Collaboration matters

On July 1st 2014 Guy Wilkinson (Oxford) began his term as Spokesperson with Monica Pepe-Altarelli (CERN) as his Deputy. They and the collaboration warmly thank the outgoing Spokesperson, Pierluigi Campana, and his deputies, Roger Forty and Burkhard Schmidt, for their tireless efforts over the preceding three years.

At the LHCb Collaboration Board meeting of June 2014 the Universidad Nacional de Colombia, Bogota, was accepted as an associate member of the collaboration.

In the LHCb Collaboration Board meeting of September 2014, Bernhard Spaan (Dortmund) and Patrick Koppenburg (NIKHEF) were re-elected as Collaboration Board chair and Physics Coordinator, respectively.

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