

Status of the LHCb experiment

CERN-RRB-2014-031

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1 Introduction

In late 2013 and early 2014 the LHCb experiment has continued the analysis of data collected in Run 1, and the activities for the long shutdown LS1. A large effort has been devoted to the preparation of the Technical Design Reports (TDRs) for the upgrade. Moreover, the collaboration is preparing the necessary steps for the restart of the data taking in 2015, including an optimization of the HLT software running on the farm. The status of the upgrade is described in detail in a separate document [1]. Since the last RRB, several new results have been published and presented at the Spring conferences. Most of the analyses are now based on the full Run 1 statistics (3 fb^{-1}).

Among them, the most important have included the following: the observation of large local CP violation in $B \rightarrow 3$ hadrons, the first observation of photon polarization in $b \rightarrow s\gamma$ decays, the precise determination of b -hadron lifetimes, the isospin asymmetry in $B \rightarrow K^{(*)0}\mu\mu$ decays, the first determination of CKM angle γ via a single Cabibbo-suppressed D^0 decay in $B^+ \rightarrow D^0 h$, and the study of exotic charmonium-like spectroscopy.

Currently, LHCb has produced nearly 180 papers based on LHC collision data, out of which about 70 since the April RRB last year. Activities in LS1 are progressing well, with significant work on refurbishing the infrastructure, consolidating the magnet, and on the maintenance of detectors. Dry runs devoted to re-commissioning and testing the operation of the detector have been performed and will become more frequent after the Summer.

2 Detector sub-systems

Maintenance and consolidation work on all subsystems and services continued. Extensive interventions on the Calorimeter and RICH systems have started and are scheduled until the end of LS1. This required some modification of the access structures close to both detectors. Maintenance work on the infrastructure is

progressing well, with the full cooling power available by April 2014. The consolidation of the electrical network is completed and the risk of a longer stop of the experiment due to a failure of one of the experiment's transformers is reduced considerably. The major intervention on the magnet has been successfully concluded and a test remains to be performed once the cooling system is available again. A magnetic field measurement is scheduled for Summer 2014. Here, LHCb will take advantage of the absence of the beam pipe and its support structures inside the magnet. The preparation work has started already. Mixed water pollution resulted in serious problems with the cooling circuits for the electrical components. The water quality was analysed and as consequence the whole circuit was flushed with fresh water. In addition, a new chemical treatment was agreed on and a second analysis is scheduled for the end of LS1. All major interventions are on schedule and the installation of the beam pipe has moved by three months in agreement with the accelerator sector.

2.1 Beam pipe

Carbon fibre cables and rods for the new support structures for sections UX85/2 and UX85/3 have been delivered to CERN. All elements of the supports, including the beryllium collars, are ready for installation and stored by TE/VSC in their facilities. A continuous monitoring of the tension of the cables has been finalized. Three sensors qualified to work both in a high radiation environment and magnetic field have been purchased and delivered to CERN, and regular sensors for the remaining support cables have been ordered as well. A solution for the electronics and software for the readout of the tension cables has been chosen and the electronics has been purchased and delivered to CERN. Implementation of the monitoring in the PVSS control framework will be carried out in the coming months. New aluminum and stainless-steel bellows are ready for installation together with the new UX85/3 section of the beam pipe. Sections UX85/2 and UX85/4 removed last year are filled with nitrogen and stored in the LHCb cavern at Point 8, and are ready for re-installation. The re-installation of all beam pipe components and of the tension monitoring system is scheduled from August to November 2014.

2.2 Vertex Locator (VELO)

The preventive maintenance and minor upgrades to the system scheduled for the long shutdown is progressing well. The preventive maintenance of the crates and power supplies is almost complete. The LV system is being refurbished to address some reliability issues and the first of the new bulk power supplies has been delivered and successfully tested. The remaining supplies will be integrated in the pit in September 2014. The maintenance of the cooling, motion and vacuum system is ongoing and will be completed in Autumn 2014. A small number of additional spares of custom electronics boards are being prepared and qualified, this is an ongoing activity. The new control interface for the CAN bus has been delivered and is

in the process of being commissioned, the new SPECS control interface is expected in June 2014 and will subsequently be integrated. The VELO can only be fully powered when the beam volume is under vacuum, which will put some restrictions on the verification and commissioning activities over the next six months, in particular during the beam pipe replacement. The control software is fully migrated to WinCC and the work in this area continues with upgrades and improvements until Autumn 2014. The software for monitoring the VELO data quality has been completely re-written and the specific monitoring algorithms will now be ported to the new framework. The procedure for determining the configuration parameters of the TELL1 DAQ board has been streamlined and will be commissioned over the next few months. Work is ongoing to improve the monitoring of these parameters, expected to be completed in the next six months.

2.3 Silicon Tracker (ST)

The Silicon Tracker has been switched to a safe state during LS1. The detector is only fully powered for short tests to check the status after interventions on the detector hardware or during the regular LHCb commissioning weeks. Since October 2013, several interventions have taken place to improve the operation and reliability of the detector for LHC Run 2. A major upgrade of the cooling system was planned for LS1. This was needed as the current system is not reliable and interventions were required on a daily basis during the last run. The installation and commissioning of the new cooling system was finally completed in March 2014. The previous cooling plant has been serviced and will remain as a backup system. Filters were installed in the cooling circuits to remove the dirt responsible for the decrease in the flow of C_6F_{14} coolant. Faulty flow switches and flow meters have been replaced. The HV and LV power supplies were serviced at the manufacturers following their recommendations. Both systems were dismantled, serviced and reassembled successfully. This intervention was required to guarantee the operation of the power supplies until LS2. In addition, the turbines of the off-detector electronics racks have been serviced and the different DSS (Detector Safety System) thermo-switches will be serviced in Spring 2014. The planned rewrite of the control system code has finished: the code has been simplified and its maintainability improved. The time required to configure the front-end electronics has also been significantly reduced by more than 43%. The migration of the control system from PVSS 3.8 to WinCC 3.11 was made after the deployment of the new code. The control system is running stably and will be tested further during the coming months. The number of working channels is 99.52% and 98.52% in TT and IT respectively. Some of the residual inefficiency will be recovered before the end of LS1 by the replacement of broken VCSEL diodes in the TT, and the repair of two modules that are not configurable in the IT. Work has started to improve the alignment and positioning of the IT. The removal of the beam-pipe allows the stations to be fully closed and the relative positions of the two halves to be measured. Further work is required to move one station vertically with respect to the

beam pipe. Finally a survey of the stations will be made before the installation of the new beam pipe and the positions of the stations adjusted to their nominal positions to obtain a better alignment of the detector.

2.4 Outer Tracker (OT)

The Outer Tracker has been operated during Run 1 of the LHC in accordance with, or better than, specifications, despite the challenging run conditions at an average instantaneous luminosity of $4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ in 2012. The performance has been recently published [2]. Furthermore, studies are ongoing to prepare the simulation for the 25 ns running conditions in 2015. During LS1 the quality of the OT hardware has been consolidated. For example, the CERN gas group has consolidated the gas supply to the OT detector. However, in the commissioning week in September 2013, aimed at verifying the functionality of all LHCb subsystems, a problem with the water cooling of the low voltage power supplies was discovered. Due to polluted cooling water, the water connector were blocked, providing insufficient cooling to the power supplies. As a result, all six power supplies have been removed, and brought to the electronics department for thorough checks. Preliminary results show good performance. In addition to one existing spare power supply, a second spare power supply has been ordered.

2.5 RICH system

The consolidation activities for the RICH detectors are progressing well, without any delay. The main activities include the replacement of HPDs and detector maintenance, production of new UKL1 boards, investigation of the magnetic distortion corrections in RICH1 and upgrade all control software to the new online environment (WinCC 3.11). A new procedure for the production of refurbished HPDs has been defined using longer bake-out times and adding getter strips. HPDs produced with the new procedure have been under test for many months with very low and stable ion feedback, showing very good vacuum quality. It is expected that the new HPDs will last until the LHCb upgrade. More than 30 new HPDs have been produced and 23 were installed in RICH2 in March 2014. The replacement of HPDs for RICH1 will take place in September, and depending on the HPD availability a last intervention for RICH2 is scheduled in Autumn 2014. The available bandwidth between the UKL1 boards and the HLT farm in 2012 was close to the limit, with very little margin. As the conditions with higher LHC energy are not known very well the available bandwidth will be increased by the production of new UKL1 boards and installation of new links. The new UKL1 boards will be installed according to demand with an increase in the bandwidth of up to 30% removing all bottlenecks in the RICH system. A prototype board is being produced and will be tested during April. Production of new boards is expected in Summer 2014. The Cherenkov angle resolution of the RICH detectors has been very good, reaching Monte-Carlo predictions in RICH2 after careful alignment and

calibration. However, the resolution in RICH1 has always been a little worse than expected. It is believed that this is due to the bigger influence of the magnetic field in the HPDs of RICH1, so studies have been launched to find the systematic accuracy of the correction procedure and whether it can be improved. Finally, all the control software has been moved to the new online environment without any issues. New hardware for the ELMB and SPECS interface is expected later in the year and the preparation of the software is progressing well.

2.6 Calorimeters (SPD, PS, ECAL and HCAL)

Maintenance activities during the long shutdown period are progressing well. The main activity was related to the replacement of fibres for the ECAL monitoring system. 456 bundles of fibres have been produced between October 2013 and January 2014 and tested in a workshop at CERN before the installation on ECAL A-side started end of January. For this intervention a design of new extensions for the RICH2 tower was required to allow access to the detector. With the use of these platforms the work on the ECAL system over the entire width was possible. The fibre installation on the A-side was completed and tested in March. The intervention on C-side has started end of March and will be completed in May. We experienced some problems during the displacement of the detectors on their rails. A coupling piece broke on the SPD system and was replaced. For this reason, the whole calorimeter moving system is under review. After the maintenance of the SPD electronics, inspection of the PS electronics followed and only one VFE board had to be exchanged. The refurbishment of Wiener power suppliers and air cooling units is completed. The demineralized water filters have been cleaned. Some unstable PMTs have been exchanged on the HCAL C-side. Criteria for the replacement were defined depending on the PMT dark current or rate effect according to their location. 49 dismantled PMTs were re-used for replacement at the periphery and 60 PMTs were replaced by new ones. The same operation has been scheduled for the A-side starting in April. One additional TELL1 crate has to be installed to host additional TELL1 for the PS/SPD and HCAL detectors allowing data taking at higher luminosity.

2.7 Muon system

The Muon system is undergoing extensive maintenance, consolidation and preparation work for Run 2 during LS1. An extra shielding, consisting of 30 tons of iron (2100 blocks), was added behind the last muon station (M5) to reduce particle back-scattering on the upper part of the station. The PNPI MWPC HV system hardware was upgraded successfully by doubling the channel number to improve the system redundancy, and its software upgrade is currently ongoing. The maintenance work on the detector is in progress: all issues on stations M2-M5 A-side were fixed and all chambers were re-commissioned. The maintenance work has now switched to the C-side and will take about two months to be completed, followed

by the maintenance work on station M1. All work on the detector will be finished before the beam pipe re-installation foreseen to start in August 2014. The commissioning of the entire Muon system is scheduled after the beam pipe installation. The ECS software was migrated from PVSS 3.8 to WinCC-OA 3.11 and no major problems were discovered. At the same time most of the control PCs were moved from Windows to Linux systems running on virtual machines. Only PCs running OPC servers were kept under the Windows operating system, but they will soon be replaced with a new credit-card PC (CCPC) based infrastructure. Preliminary test performed on the C-side were successful and have shown an improvement in performance.

2.8 Online system

In the reference period the various operating system and control system upgrades were finished. 95% of the control systems were upgraded to the new version of WinCC-OA, and only isolated systems still remain to be done. Also the upgrade of the HLT farm to SLC 6 proceeded well and only a few subfarms are missing. Progress was significantly hampered by the lack of cooling for the last seven months. Main activities are concentrating on the control of the “split HLT” and the operational procedures concerning the calibration and alignment constants needed for the new HLT2. Other activities involve the replacement of the hardware interfaces for CAN and SPECS, because the old servers are being phased out. Preparations are being started in conjunction with the acquisition of disks and replacement of the very old servers in the HLT farm. For the LHCb upgrade major R&D progress was achieved in view of the Trigger and Online TDR in June.

3 Operations

The operational activities are currently focused on designing and implementing the automatic online calibration and alignment procedures, that will allow LHCb during Run 2 to automatically calibrate the data in real time, at the pit. This will allow the later stage of the software trigger (HLT2) and the full offline reconstruction, to be processed with the same, optimal calibrations as the data is taken. This is in contrast to the procedures employed in Run 1, where the calibrations were produced offline, and as such only available for the final end-of-year data reprocessing.

3.1 Detector calibration

Work is progressing on implementing the changes to the online database, that are required to accommodate the automatic calibration procedures, and on how this database will be populated by the sub-detector calibration tasks, and accessed by the HLT, in a fully automatic and fail-safe manner.

3.2 Trigger

The split between HLT1 and HLT2 mentioned in the previous RRB report [3] has been accomplished as concerns the software itself. We are now in the process of tuning the HLT reconstruction and selections for the anticipated 2015 conditions. This includes a factor of two increase in the expected farm processing power as well as the expected change to 25 ns running and the increase in beam energy to 6.5 TeV. We are pursuing both simulation and data-driven studies in order to determine how the trigger algorithms' performance scales with energy, as well as to define a set of baseline hardware trigger thresholds which will be able to reduce the 30 MHz input rate to 1 MHz for readout. We have defined the data samples required for the real-time detector calibration which will occur between HLT1 and HLT2, and are now concentrating on the mechanism by which these calibration parameters will be passed to HLT2. We are also making progress on updating the HLT monitoring code to cope with the new split HLT. A particular difficulty is that the events coming out of HLT2 are not necessarily run-ordered (since HLT2 begins processing a run when that run's calibration parameters become available), and the monitoring has been rewritten to take this properly into account. Finally we are working in parallel on the trigger upgrade TDR, which will be delivered in late Spring.

3.3 Computing

The computing usage in 2013 [4] and the resources estimates for 2015 and beyond [5] are discussed in separate documents. Only a few pertinent points are mentioned here.

Following the successful reprocessing of the 2011 and 2012 datasets (Reco14), we now believe it is unlikely that a further "final" reprocessing will be needed. Thus the computing model now considers Reco14 to be the legacy dataset of LHC Run 1.

The output of the LHCb stripping can either be in DST or microDST (mDST) format, the latter being an order of magnitude more compact, since it does not contain information on the full event, only the selected candidate decays of interest. Analysts have proved reluctant to move to this format, as there are concerns it might not contain information they later discover they require. Therefore, to encourage the migration to this format, a new MDST.DST format is being commissioned that will allow production to rapidly regenerate any mDST sample, without requiring the full stripping to be run.

The LHCb trigger rate for LHC Run 2 is expected to increase to 12.5 kHz and to remain roughly constant throughout the run. Of the 12.5 kHz, 2.5 kHz will be analysed directly in the HLT farm and will not be reconstructed offline (TURBO stream). The remaining 10 kHz will be split between a FULL stream for prompt physics analysis, and a PARKED stream to be reconstructed and analysed later, once resources allow (e.g. during LS2).

The main computing model change for Run 2 concerns the processing model for the FULL stream, to adapt to the prompt calibration and alignment procedures that are under development. In order to allow time to validate any unexpected changes, we plan to buffer the RAW data of the FULL stream for up to two weeks, after which the reconstruction will be run. In this model, this reconstruction pass will be the only reconstruction taking place during Run 2; any reprocessing will be postponed until after the run, during LS2.

4 Physics results

Between October 2013 and April 2014 LHCb has kept its steady output rate of physics papers, in spite of the absence of new data. At the time of writing LHCb had submitted 178 papers of which 163 are published.

One of the highlights of this year's winter conferences was the observation of photon polarization in $B^+ \rightarrow K\pi\pi\gamma$ decays [6]. This decay belongs to the family of neutral flavour changing current decays $b \rightarrow s\gamma$. This transition is a standard candle as its decay rate sets very strong constraints on all extensions of the Standard Model (SM). While the measured decay rate is consistent with the SM prediction, the other prediction has never been tested significantly: the photon should have a left-handed polarization.

We use four-body decays of a B meson, where three charged particles are emitted along with the photon. The angular distributions in this three-body system allow to determine the polarization of the recoiling photon — or more precisely, allow to determine that this polarization is non-zero. In the published paper, the so-called Up-Down asymmetry is built in for four regions of invariant mass (Fig. 1)

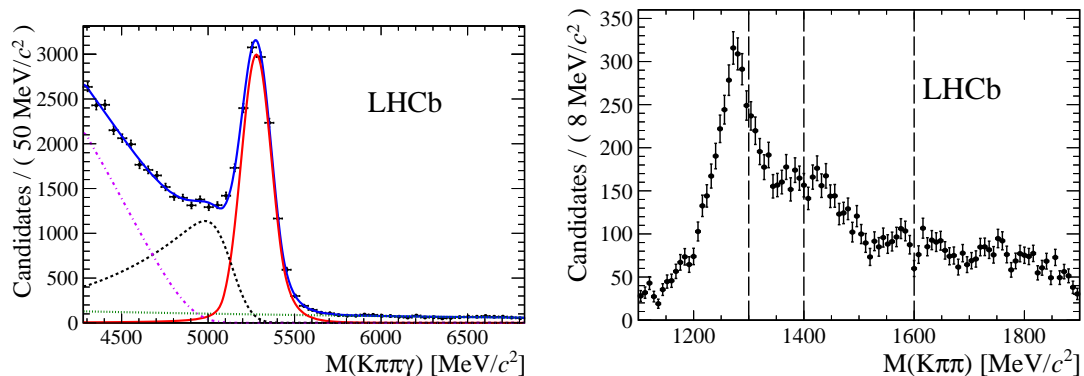


Figure 1: Photon polarization analysis in $B^+ \rightarrow K\pi\pi\gamma$ decays. Left: $K\pi\pi\gamma$ mass fit. Right: background subtracted $K\pi\pi$ mass distribution [6].

of the three-particle system and a total 5.2σ observation of non-zero asymmetry is measured. This is a first step to measuring the actual value of the polarization. The drawback of this approach is that each strange resonance contributes differ-

ently and thus one needs to resolve them in order to turn the observation into numbers.

The other major news was the update of our isospin analysis in $B \rightarrow K\mu^+\mu^-$ [7]. In the analysis using 1 fb^{-1} we measured a 4σ evidence for isospin asymmetry between $B^0 \rightarrow K_s^0\mu^-\mu^+$ and $B^+ \rightarrow K^+\mu^+\mu^-$. In the eagerly awaited 3 fb^{-1} update this asymmetry is more compatible with zero, at the 1.5σ level, where the change is mostly due to the addition of more data. We now assume isospin invariance in $B \rightarrow J/\psi K$ and measure $B \rightarrow K\mu^+\mu^-$ with respect to this. Interestingly the differential branching fractions versus the dimuon mass squared are below the SM expectation for both modes, but not to a significant extent (Fig. 2).

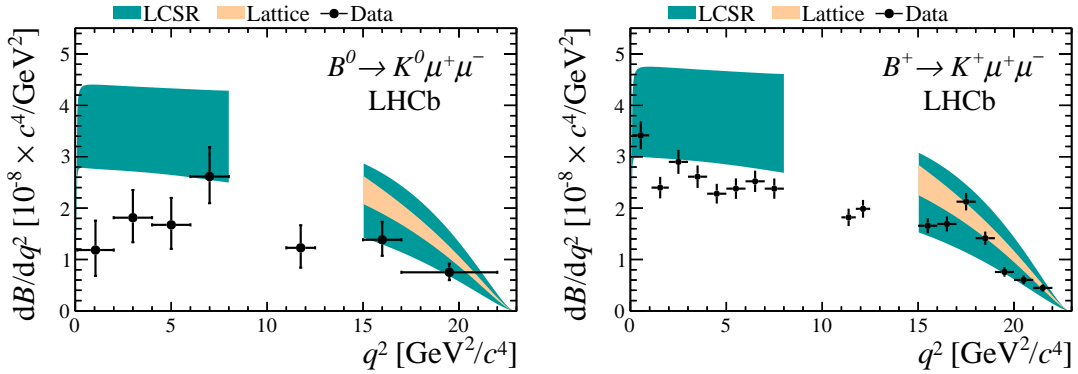


Figure 2: Differential branching fractions of $B^0 \rightarrow K^0\mu^-\mu^+$ (left) and $B^+ \rightarrow K^+\mu^-\mu^+$ (right) versus the dimuon mass squared [7].

This is intriguing as it could be due a modified C_9 Wilson coefficient, which could also be causing the P'_5 anomaly in $B^0 \rightarrow K^*\mu^-\mu^+$ [8]. We also updated our angular analysis of the $B \rightarrow K\mu^+\mu^-$ decays but see no signs of deviation from the SM expectation [9]. The update of the $B^0 \rightarrow K^*\mu^-\mu^+$ to 3 fb^{-1} is still work in progress.

Similar decays but with two muons of the same charge allow a search to be made for Majorana neutrinos [10]. Using the $B^+ \rightarrow \pi^-\mu^+\mu^+$ decay we have improved the limits on the couplings to such neutrinos in the mass range $250\text{--}5000 \text{ MeV}/c^2$ and lifetimes from zero to 1000 ps .

We continue to investigate the nature of exotic charmonium-like states. The neutral $X(3872)$ was studied in the decays $B^+ \rightarrow X(3872)K^+$ [11]. The ratio of the branching fractions of $X(3872)$ to $\psi(2S)\gamma$ and $J/\psi\gamma$ was measured to be $2.46 \pm 0.64 \pm 0.29$, corresponding to a 4.4σ evidence for the $X(3872) \rightarrow \psi(2S)\gamma$ decay. This value is inconsistent with the interpretation of the $X(3872)$ as a $D\bar{D}^*$ molecule.

LHCb studied the resonant character of the charmonium-like charged $Z(4430)^+$ state [12] first reported by Belle. The minimum quark content of such a state is $c\bar{c}u\bar{d}$, which makes it unambiguous evidence for mesons beyond the $q\bar{q}$ model. Both model independent and dependent searches have been pursued using $B^0 \rightarrow \psi(2S)K^+\pi^-$ decays. In the former, it is tested whether the data can be described

only in terms of strange resonances. This approach was previously pursued by BaBar [13] who did not find evidence for the need of a resonance decaying to $\psi(2S)\pi^-$. With our data the need for an additional resonance is clearly established (Fig. 3, left).

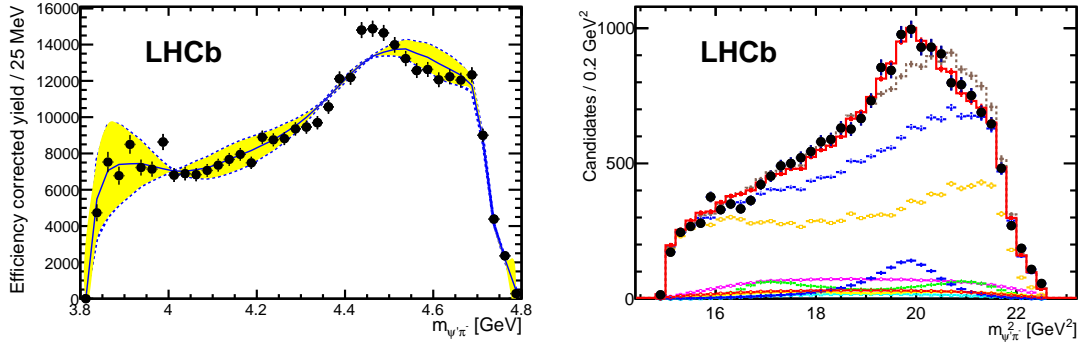


Figure 3: Model-independent (left) and dependent (right) fits of the $\psi(2S)\pi^-$ mass distribution in $B^0 \rightarrow \psi(2S)K^+\pi^-$ decays. The yellow band (left) shows the statistical uncertainty on the fit. In the right plot the red solid (brown dashed) histogram shows the fit with (without) the $Z(4430)^+$ included. The other histograms show various sub-components [12].

We then build a model including a $Z(4430)^+$ state (Fig. 3, right) and obtain an overwhelming significance in excess of 13σ . The quantum numbers determined to be $J^P = 1^+$, ruling out other possible assignments by more than 9σ . This confirms the Belle observation for this state [14] and evidence for its J^P assignment.

We are starting to exploit the very large Λ_b^0 cross-section in our acceptance [15] to study decays of beauty baryons. Several new decay modes have been observed both in $b \rightarrow c$ [16, 17] and charmless transitions [18]. These decays offer new potential for searches of new physics in rare decays and CP violation.

We also reported improved measurements of lifetimes for B^0 , B_s^0 and Λ_b^0 decays [19, 20]. In particular the measured ratio of the Λ_b^0 and B^0 lifetimes is now $0.974 \pm 0.006 \pm 0.004$, which is consistent with theoretical expectations. This closes a long standing discrepancy between the measured Λ_b^0 and B^0 lifetimes which could not be understood using heavy quark expansion.

Using 2 fb^{-1} 2012 data also reported the most precise measurement of the B_c^+ lifetime [21] using semileptonic $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$ decays. The lifetime and $J/\psi \mu^+$ mass distributions are shown in Fig. 4. The measured lifetime is $509 \pm 8 \pm 12 \text{ fs}$ which has an uncertainty half of the present world average. This measurement is systematically limited by the knowledge of the the signal and background models.

A major milestone in our quest for a precision measurement of the CP -violating phase in B_s^0 -mixing was the measurement of the resonant structure and CP components of $B_s^0 \rightarrow J/\psi \pi^- \pi^+$ [22, 23]. An amplitude analysis in the $J/\psi \pi^- \pi^+$ mass and angular distributions shows that the final state is entirely CP -odd. The CP -even fraction is less than 2.3% at 95% confidence level. This will allow this decay to be

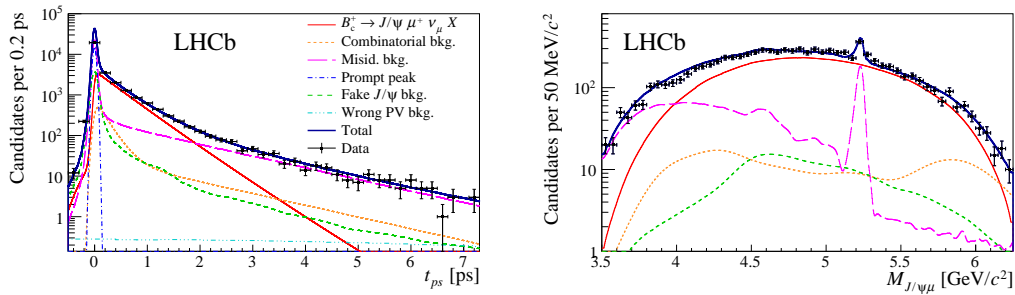


Figure 4: Simultaneous fits to the decay time (left) and mass (right) of $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$ decays and backgrounds. The mass distribution is shown for candidates with a decay time larger than 150 fs [21].

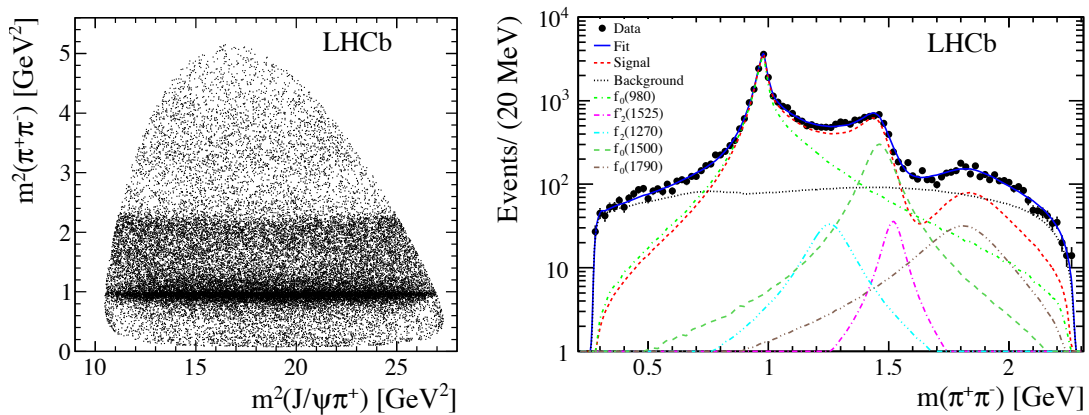


Figure 5: Dalitz plane of the $B_s^0 \rightarrow J/\psi \pi^- \pi^+$ decay (left) and projection of the data and amplitude fit on the $\pi^- \pi^+$ mass [22].

used to measure the B_s^0 -mixing phase ϕ_s without the need for an angular analysis or a restriction to a given mass range. Previously only the $B_s^0 \rightarrow J/\psi f_0(980)$ decay had been used [24]. Updated measurements of ϕ_s using this and the $B_s^0 \rightarrow J/\psi KK$ decays are also being worked on.

We measured track multiplicities in pp collisions at $\sqrt{s} = 7$ TeV [25]. The agreement with recent event generators is not perfect (Fig. 6) but much improved compared to generators that did not use LHC data in their tuning. This is important input for future Monte-Carlo tuning.

The collaboration is also working on improving the analysis tools. This has led for instance to the first paper using jets [26] with many more to come.

5 Financial issues

The status of the accounts is healthy and there is no cash flow problem foreseen. For the 2013 M&O Cat.A budget the expenditures have generally respected our

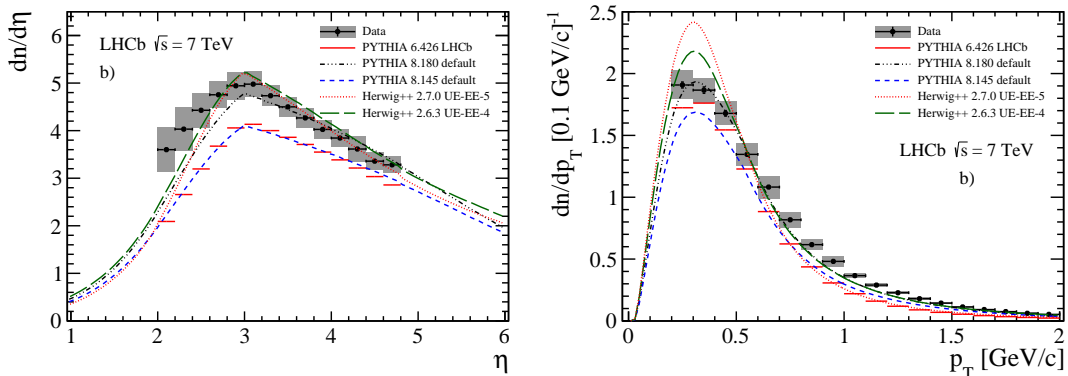


Figure 6: Comparison of measured charge multiplicities versus η and p_T and various predictions from modern generators [25].

forecast. Due to the long shutdown in 2013–14 and the planned important interventions on subdetectors and on general safety and infrastructure, LHCb has overspent the M&O Cat.A budget in 2013. However, taking in account the Cat.A funds buffered in the previous years, as often anticipated, we are confident to be able to satisfy all requirements with a constant budget.

6 Collaboration matters

At the LHCb Collaboration Board meeting of December 2013, a new group has been accepted as full member and one more as associate.

The Aachen RWTH group led by Prof. S. Schael has a strong expertise in the area of tracking with fibres and has expressed intention to take part to the construction of the Scintillating Fibre detector for the upgrade. The Aachen group has been accepted as full member. The Wuhan CCNU group led by Prof. Y. Xie, with interest in the area of CP violation in B hadronic decays, has been accepted as member associated to Tsinghua. After these new entries, the LHCb Collaboration is currently composed of 66 institutes from 17 countries, including 7 associates.

In the December meeting, the Collaboration Board has unanimously nominated G. Wilkinson (Oxford) as the new Spokesperson. His mandate will start July 1st, 2014.

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