# Status of LHCb Upgrade I and future prospects

CERN-RRB-2024-040

LHCb collaboration

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# 1 Introduction

The LHCb experiment will have three major phases of detector technology. The original detector completed data-taking at the end of LHC Run 2 in 2018. Physics results arising from the analysis of data collected in this phase are described in this document. The LHCb Upgrade I was primarily installed during LHC Long-shutdown 2 (LS2) in 2018-2022. The final subsystem, the Upstream Tracker (UT), was put in place during YETS 2022/23, successfully completing the installation. The LHCb Upgrade II is planned to be primarily installed in LS4, with some smaller modifications foreseen in LS3. Progress on the R&D for this detector is also described in this document.

A total of $10\,\text{fb}^{-1}$ were delivered to LHCb in Run 1 and Run 2 data taking periods, with $9\,\text{fb}^{-1}$ recorded. The LHCb Run 1 and Run 2 dataset comprises $pp$, $p$Pb, and PbPb at various centre-of-mass energies, as well as $p$A (A = He, Ne, Ar) collisions in fixed target mode, using the experiment's unique gas injection system. Exploitation of Run 1 and Run 2 data is still progressing.

The LHCb Upgrade I is arguably the largest CERN particle-physics detector project to begin operation since the completion of the LHC. It has been completed on-budget. All subsystems have been operated during 2023 and their commissioning has successfully proven their functionality. An incident occurred in the LHC vacuum system of the VELO detector during YETS 2022/23 which has damaged the aluminium foil that separates the secondary and primary vacuum volumes. This has prevented the closure of the VELO to its minimum aperture in the 2023 run and the foil has been replaced in the YETS 2023/24.

The Upgrade I detector is based on a novel trigger system able to read out all sub-detectors at 40 MHz and to select physics events of interest by means of a pure software trigger at the bunch crossing rate of the LHC. The software trigger allows the experiment to collect data with high efficiency at a luminosity of up to $2 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$. Flavour-physics measurements are going to be performed with higher precision than was possible with the previous detector and across a wider range of observables. The flexibility inherent in the new trigger scheme will also allow the experiment to further diversify its physics programme into important areas beyond flavour.

The Upgrade I detector was proposed in the Letter of Intent [1] in 2011, and its main components and cost-envelope were defined in the Framework TDR [2] one year later. Technical Design Reports (TDRs) were written for all systems [3–11] and approved by the Research Board. Addenda to the Memorandum of Understanding (MoU) were presented to the RRB in April and October 2014, covering the division of resources and responsibilities for Common Project items [12] and sub-system items [13], respectively. Enhancements to the ECAL and RICH systems are proposed for LS3 and have been approved in December 2023. A draft TDR for additional enhancements to the Online system has been submitted to the LHCC in February 2024 and it is now under review.

The LHCb Upgrade II detector was proposed in the Expression of Interest [14] in 2017 and the Physics Case described in [15]. Its main components, cost-envelope and descopes are defined in the Framework TDR [16] that was approved in 2022. A Scoping Document, describing various scoping scenarios in terms of cost and physics performances, is now under development. The document will be submitted to the LHCC in September 2024, and preliminary results will be shown at this RRB meeting.

# 2 Collaboration matters

The collaboration is constantly growing. It has now reached a total number of about 1700 members, including 1120 authors.

Since the October 2023 RRB, two new institutions have joined LHCb as associate members:

- Ohio State University, funded by DOE and associated through Los Alamos National Laboratory;
- Ruhr-Universität Bochum, associated through the Technische Universität Dortmund.

The Ruhr-Universität Bochum became the 100$^{\text{th}}$ institute to join the LHCb collaboration.

# 3 Project organisation

Up to this February 2024, the management of the experiment was composed of the Spokesperson and two deputies, the Technical Coordinator and the Resource Coordinator. Commencing March, a new member has been added: the Software and Computing Coordinator (SCC). The SCC chairs a newly established body, the Software and Computing Board (SCB). The SCB includes the project leaders of the software and computing projects, and the software coordinators of the various subdetectors. The SCB supersedes the Upgrade Software Planning Group (USPG), which has now been disbanded.

The Upgrade I detector is overseen by the LHCb Technical Board. The Technical Board is chaired by the Technical Coordinator and is comprised of all detector project leaders. Day-by-day detector work is overseen by the technical coordination team. The commissioning and operations of the Upgrade I detector are overseen by the Run coordinator and discussed at Run meetings, with representation from all projects. Physics aspects are overseen by the Physics Coordinator and discussed at the Physics Planning Group, whereas Operational ones are overseen by the Operations Coordinator and discussed at the Operations Planning Group.

Coordination between the software projects is managed by the Upgrade Software Planning Group (USPG). The USPG membership consists of the USPG chair, representatives of the Computing, Online, Real-Time Analysis, Data Processing and Analysis projects and of the Simulation project, the Physics Coordinator, the Operation Coordinator, as well as the management. The development of the Upgrade II detector design is overseen by the Upgrade II Planning Group.

Because the Run 3 LHCb detector is fully read out into a software trigger, the first level of this trigger (HLT1) plays a critical role in monitoring the datataking performance and selecting events based on technical triggers which are then used for specific subdetector monitoring tasks. Additionally much of the online and offline monitoring and data quality, as well as subdetector-specific monitoring, now relies on specific configurations of the second-level software trigger (HLT2). This has led to a greater degree of interdependence between the systems than had been the case in the previous LHCb experiment. Consequently, a subcommittee of the technical board (TBSC) was formed in January 2024 to strengthen communication between the Real Time Analysis project, Online, and the LHCb subdetectors around software tools and components of common interest. An additional deputy Technical Coordinator was appointed for a period of one year with a mandate to chair this subcommittee.

The subcommittee has met on a weekly basis since being formed. Following an initial proposal from operations and run coordination, the subcommittee agreed on a list of technical components required for the 2024 restart and a timeline for their delivery, which is tracked in the subcommittee meetings. The subcommittee also agreed to improve documentation for certain items of common interest, in the first instance by adding documentation of subdetector data encoding and decoding algorithms to the existing EDMS documentation on subdetector firmware. The subcommittee has also held topical discussions on the readiness of detector alignment, reconstruction robustness against detector effects, how best to provide data for subdetector time alignment, the measurement of subdetector hit efficiencies in data, as well as the trigger-unbiased measurement of higher-level performance metrics in data.

# 4 Financial matters

According to the financial plan for the M&O Cat. A levels, which was finalised, submitted and approved by the Scrutiny Group and by the RRB in 2017 and 2018, the proposed and subsequently approved budget for M&O Cat. A is 3,070 kCHF for the year 2024. The book closing on the 2023 M&O Cat. A shows sustained activities and a slightly under-spent budget. As expected, no cash flow issues were present, as most members have contributed to the budget (multi-annual). Some stress is again visible for the various Service Level Agreements.

We continue to study all options to face the effects of the war of the Russian Federation against Ukraine on our experiment and its resources. The proposed resource sharing for 2024 includes contributions from Russian funding agencies and institutes. However, following the resolution of June 2022, in 2024 CERN Council intends to terminate the International Collaboration Agreement with Russia at its expiration date (November 2024). As at this moment Russian funding agencies should stop contributing, we plan to share the shortfall proportionally to the number of PhD-equivalent among the remaining funding agencies (see also CERN-RRB-2024-045).

The funding requirements for the LHCb Upgrade construction have been defined in detail in Addendum No. 1 to the Memorandum of Understanding (MoU) for Common Projects [12] and in the Addendum No. 2 to the MoU for the Upgrade of the Sub-Detector Systems [13], which refer to the LHCb Upgrade Framework Technical Design Report [2] and the Technical Design Reports [3–8] for all Upgrade subdetectors. At present, the LHCb Upgrade project continues to progress well. All of the sub-detectors have been installed and are in their operational phases. Spending of core funds is essentially over. The final Common Project funds have been spent in 2020-2024 and are now also finished. In order to ensure the optimal value-for-money and performance for the experiment, we have now acquired a new slice of the computing farm.

The Upgrade I construction project is thus ended and has been achieved within the agreed cost envelope. No request for further funds has been put forward and the RRB has agreed to close the books in the last meeting held in October 2023.

# 5 Operations

Since the end of data taking last year, operations have been focused on: completing the data processing activities, related to both Run 2 data and Run 3 data; providing the simulations needed for performance and analysis studies; refining data processing operations in preparation for the 2024 data taking.

In 2023 the collaboration decided to perform an incremental re-Stripping campaign of the datasets collected in 2016, 2017 and 2018 to enhance the physics reach of Run 2 data. The Stripping is the process of offline selection and streaming used for Run 1 and 2 data. The implementation of new selections and the validation of the physics outcome had already been completed by October. The actual processing, instead, started in November, to avoid any conflict with 2023 data taking regarding the usage of computing resources. It was successfully completed by the end of January, as originally planned.

A special processing activity concerned the re-reconstruction of 2022 data. Exceptionally for this dataset, taken in the early commissioning phase of the LHCb upgrade, the raw detector information had been saved to allow a new reconstruction with improved alignment, calibration and understanding of the detectors. The re-reconstruction is now complete and available for additional physics and performance studies.

Concerning data collected in 2023, they were processed following the computing model foreseen for the LHCb Upgrade [17]. As reminded in Fig. 1, after data are collected and processed by the first stage of trigger based on GPUs (HLT1), they are stored in a buffer, waiting for an update of the alignment and calibration constants. As this happen, in real time, they are processed by the second stage of trigger based on CPUs (HLT2). The data are then sent offline and undergo the concurrent Sprucing process, i.e. the centralised skimming, trimming and streaming of the data, before being made available to the analysts (see Fig. 2). In particular, the data in the Turbo and TurCal streams undergo a pass-through processing, while the data in the FULL stream undergo exclusive physics selections. Since these selections might be improved during the data taking, an end-of-year re-Sprucing is foreseen for the FULL and TurCal streams.

In 2023, the HLT2 processing of the proton-proton dataset had been partially delayed after the interruption of the LHC colliding operations in mid-July, in order to include developments and improvements in the alignment and calibration of the detectors. The HLT2 processing was finally completed during the YETS and the data went also through the concurrent Sprucing. Similarly, data collected during heavy-ions collisions in October successfully went through HLT2 processing and concurrent sprucing. A couple of months later, the end-of-year re-sprucing of the proton-proton FULL stream took place, in order to profit of the latest improvements in selections and to ensure that all steps of the processing chain were successfully tested.

The quality of the data collected in 2023 has been routinely assessed offline by data quality shifters. About 96% of the data collected after the end of the commissioning period, both for proton-proton and heavy-ions collisions, were evaluated as good for physics, although with the performance limitations due to the incident occurred to the VELO.

Analysts have been increasingly using the new centralised analysis production scheme on spruced data for producing ntuples and performing performance and physics studies. The 2023 data have been used, for example, to evaluate preliminary track reconstruction efficiencies using muons and electrons. Work is ongoing to compare data with simulation, and all the machinery is in place and ready to be used for the 2024 data taking. Hadron identification efficiencies have also been evaluated, both with 2022 and 2023 data, showing that the two RICH sub-

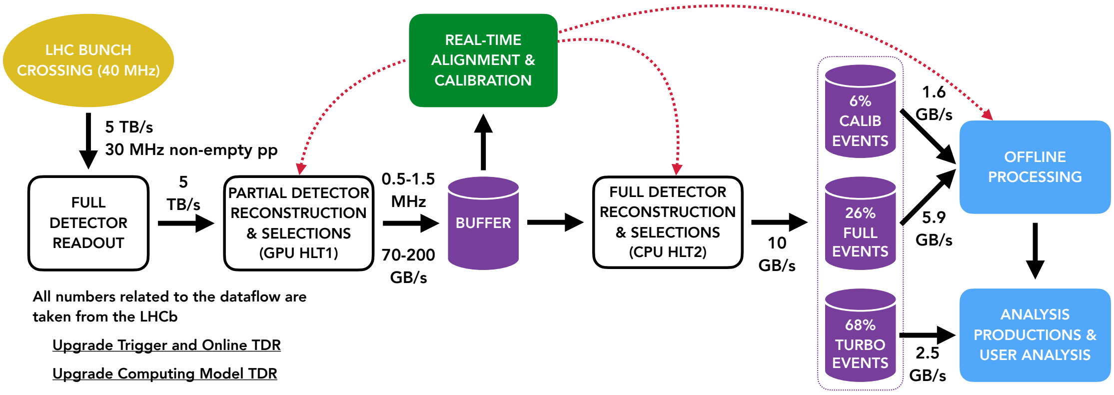


Figure 1: Schematic view of the online processing for the LHC upgrade.

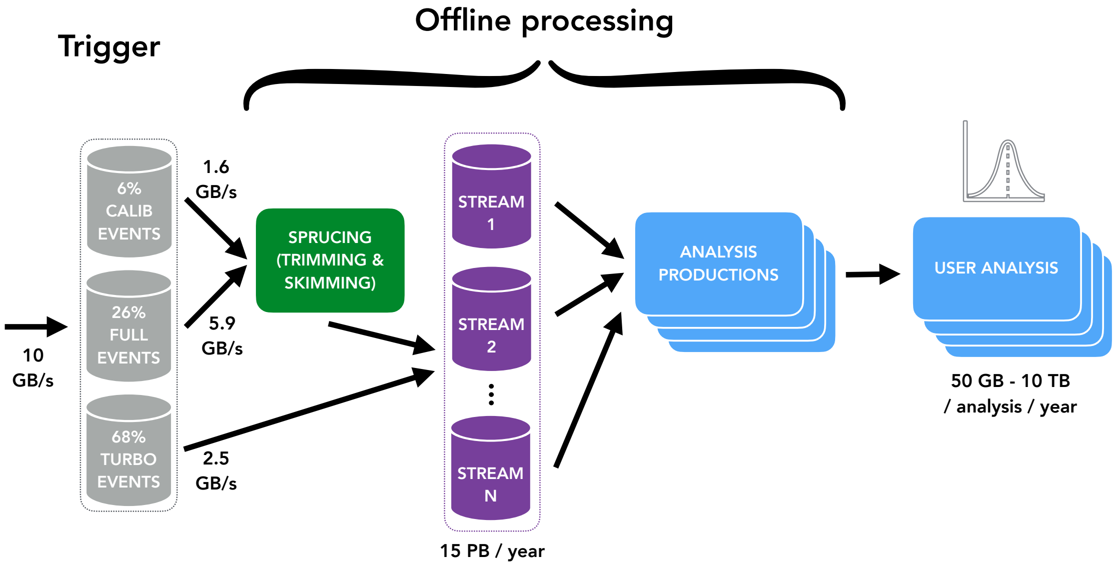


Figure 2: Schematic view of the offline processing for the LHC upgrade.

detectors have already reached the expected performances. Early studies on the heavy-ion datasets [18], instead, confirm the potential of the upgraded LHCb to reach centrality regions lower than in the past (see Fig. 3).

The dataset was also used to provide the ghost charge fraction measurement for the ATLAS and CMS van-der-Meer calibration fills of June 2023 [19]. As requested by the two collaborations, the measurement was available by the end of January. Like the previous one of 2022, it is in agreement with the the LHC's Beam Synchrotron Radiation Telescope bunched measurement, as shown in Fig. 4.

In preparation of 2024 activities, the Operations Planning Group has established a detailed plan for the main operational activities in 2024, incorporating the input from the TBSC. It includes milestones and timelines for all activities relevant for data taking, simulation and data processing, which are further described in the dedicated sections of this document. The plan is weekly tracked for ensuring prompt reactions to issues. Among the numerous developments, it is worth mentioning: the technical trigger selections for rapid detector commissioning and qualification of the detector performance (as for example, selections for sub-detectors time alignment and for the VELO tomography); an additional automatised online component for the monitoring of high-level physics quantities; the optimisation of the HLT1, HLT2 and Spurcing bandwidth division to cope with computing resource constraints; further data compression; the implementation of metadata for storing additional quality information per sub-detector; a tool to access the luminosity from a web-based database.

Simulations for the 2022 and 2023 data taking conditions were produced. These allowed numerous studies to be performed, like optimising the High Level Trigger bandwidth balancing physics and computing requirements, tuning the reconstruc-

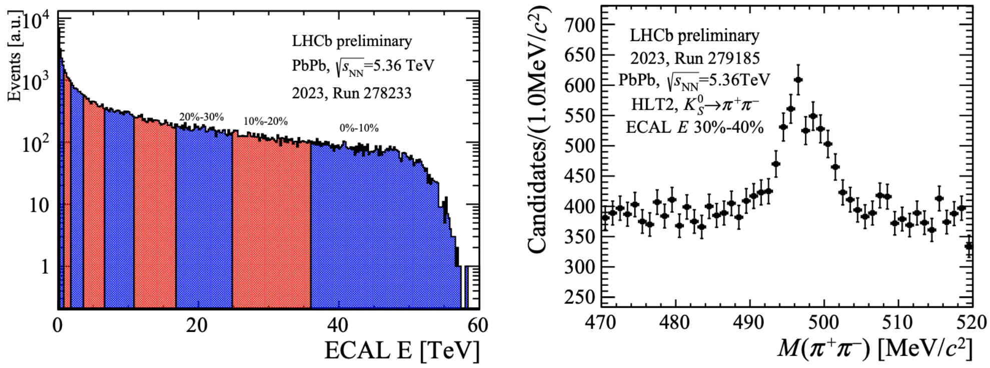


Figure 3: Left: Distribution of the total energy collected in the ECAL for PbPb collision events divided in event activity classes. Right: Invariant mass spectrum of $K^0_s \to \pi^+\pi^-$ candidates in PbPb collisions in the 30% - 40% ECAL energy activity class.

tion and assessing the preliminary performances of the detector through comparisons with the data. The process of validating and tuning the description of the sub-detectors in the simulation framework is actively ongoing. In addition, simulations were produced with the expected 2024 data taking conditions, in particular for different values of number of visible interactions, to be ready to promptly compare the evolution of the LHCb upgrade performances during the luminosity ramp up period. Finally, simulation productions are still needed to validate the measurements exploiting the Run 1 and Run 2 datasets and to evaluate accurately the associated systematic uncertainties.

# 6 2024 run: status and plans

During 2023 the LHCb experiment operated at an average number of $pp$ interactions per bunch crossing of $\mu = 1.1$, with all subdetectors included in the central

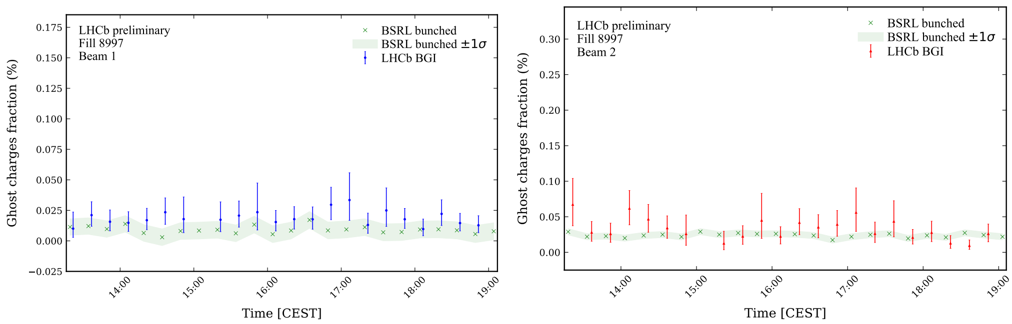


Figure 4: Comparison between LHCb and BSRL ghost charge measurements in fill 8997. The blue and dots are the LHCb measurements for beam 1 and beam 2, respectively. The green crosses are the BSRL bunched measurements integrated over 15 minutes, and the shaded area is the uncertainty window.

run control, except the UT, and with the VELO in a fixed position with a gap of 49 mm, due to the following reasons:

- Issues with front-end electronics stability reduced the data-taking efficiency to below 80%, motivating the initial operations at a lower instantaneous luminosity with respect to design. Weekly round tables between electronics experts started in 2023, and culminated with the setup of a new Detector Electronics Commissioning Task Force (DECTF) to address all the remaining issues as reported in Sec. 13.
- Given the late installation of the UT subdetector in early 2023, its commissioning was delayed compared to the other subdetectors, and the UT commissioning proceeded independently of the LHCb detector and software commissioning.
- The VELO opening was dictated by the mechanical deformation of the RF-foil and the damages to the motion system caused by the LHC vacuum incident at the beginning of the year.
- The increase of $\mu$ to the nominal value of 5.5 was interrupted by the LHC unscheduled stop for the repair of a vacuum leak between the cold mass and insulation vacuum in one of the triplets, which significantly shortened the *pp* run.

A total integrated luminosity of 150 $\text{pb}^{-1}$ has been collected for the *pp* run and a sample of approximately $250\,\text{pb}^{-1}$ for the PbPb run. Additionally the SMOG system routinely injected argon for the fixed-target physics programme during the whole PbPb run. The data taking efficiencies improved throughout the year, achieving during the last month of data taking typical values of 90%, similarly to Run 2.

## 6.1 Plans for 2024

The LHCb goal for Run 3 is to integrate 14 $\text{fb}^{-1}$ of *pp* collisions in order to achieve a sample corresponding to a total integrated luminosity of approximately 23 $\text{fb}^{-1}$ when including Run 1 and Run 2. The aim of 2024 is to record high-quality physics data in nominal conditions, *i.e.* at an instantaneous luminosity of $2 \times 10^{33}$ $\text{cm}^{-2}$ $\text{s}^{-1}$ with the VELO fully closed and all subsystems included, with a data taking efficiency higher than 90%. In addition, with the replacement of the VELO RF-foil box, the fixed target programme employing the SMOG2 system will be fully exploited.

The LHC preferred filling scheme is optimised for LHCb with 2327 colliding bunches in the LHCb interaction region, which would allow nominal instantaneous luminosity with a $\mu$ of about five to be achieved. If limited by the heat load, two alternative scenarios involving 1848 and 2260 colliding bunches at LHCb have been proposed by the LHC. Depending on the scenario, a larger pile-up may be required to reach the design instantaneous luminosity, needing further tuning of reconstruction and trigger sequences.

During the YETS most of the efforts focused on subdetector interventions (notably the RF-foil box replacement), on DECTF related activities, and on improving the low and high level monitoring infrastructure. The latter, involving several developments at the reconstruction, trigger and alignment level, also grew from the experience gained in operating the new LHCb detector in 2023. In order to have the required control over the online quality of data-taking, new technical triggers have been requested by subdetectors. The related software components are now coordinated by the newly established TBSC, as reported in Sec. 3.

Between the end of the YETS and the circulation of the first beams in the LHC, dry runs with all subdetectors included in the data-taking have been performed: stable running at 30 MHz was achieved while emulating physics collisions by injecting activity at the level of front-end or back-end electronics. A first iteration of new trigger sequences, including some of the required new features, has been successfully tested as well.

First stable beams at injection energy and collisions at 6.8 TeV in adjust beam mode (the latter not safe enough for VELO and UT to operate), have been also successfully exploited to perform the first subdetector local calibrations and global tests for reconstruction, trigger and alignment readiness.

The plan for the first fills with stable beams at 6.8 TeV consists of exploiting the intensity ramp-up of the machine to fully re-commission the detector and achieve nominal data taking conditions. Two phases are foreseen: the first few fills are dedicated to the calibration of the subdetectors, followed by fills dedicated to the global optimisation and a step-by-step increase of the number of collisions per bunch crossings. In parallel, the re-qualification of the VELO motion system as well as the automation of the per-fill closure procedure will be carried out. As part of the global optimisation, the bandwidth division between the physics lines at both levels of software trigger needs to be tuned and per-fill calibration and alignment procedures for all subdetectors are being automated. Already HLT1 has demonstrated to be able to handle a rate of about 20 MHz, corresponding to the number of colliding bunches at LHCb in 2023, and to perform selections at the design output rate (1-1.5 MHz). HLT1 will need to maintain the same performance at the input rate of about 25 MHz foreseen for 2024, while the HLT2 output throughput should lie within 10-15 GB/s as per design.

As part of the $\mu$ ramp-up procedure, subdetectors have prepared a list of checks to be fulfilled at every step, spanning from subdetector specific quantities such as occupancy and high-voltage currents, to observables commonly available and under the coordination of the DECTF, *e.g.* regarding Single Event Effects as reported in Sec. 13. On top of tracking these low-level performance figures, samples in stable running conditions will be acquired for the assessment of high-level performances. The plan requires a fast turnaround between data acquisition, data processing and feedback from performance experts. For this purpose, two layers of responses have been planned: a fast real-time response with dedicated high-level performance monitoring, and a slower, but more detailed and accurate, response (order a few days) with data processed through the offline chain.

The UT integration in the global data taking will proceed gradually. During April, local calibrations are being carried out with frequent tests included in the central run control. In the following couple of months the UT will be included for most of the time in the central run control to allow the development and validation of the reconstruction and alignment software. Eventually the UT will be exploited in the trigger decisions.

# 7 Physics

From October 2023 to March 2024 the LHCb collaboration submitted 27 new publications in physics, This brings the LHCb publications to a total of 712 at the time of writing, of which 691 are already published and 9 have been accepted. A further 19 publications are being processed by the LHCb Editorial Board and are close to submission. Three additional "Detector Performance" (DP) papers were also submitted. All papers relative to this period are listed in Table 1.

In the following some selected results from recent publications are briefly highlighted.

## 7.1 New studies on the $B_c^+$ meson and other $b$ hadrons

The $B_c^+$ meson is unique since its weak decay can proceed, with competing rates, through the $b$ quark or the $c$ quark. LHCb has already published many studies about this state, its properties and decay modes. In this period, interesting new results emerged. The first search for the rare decay $B_c^+ \to \pi^+\mu^+\mu^-$ was performed and upper limits at the order of $10^{-4}$ were set in bins of the dimuon squared mass (in regions outside charmonium resonances) [20] – the same work also updated the branching fraction of $B_c^+ \to \psi(2S)\pi^+$ relative to $B_c^+ \to J/\psi\pi^+$. In another publication, LHCb reported on the first observation of the decay $B_c^+ \to \chi_{c2}\pi^+$, and its branching fraction relative to the $J/\psi\pi^+$ mode was measured, with an upper limit set for the $\chi_{c1}\pi^+$ final state [21]. LHCb also made the first observation of the decay $B_c^+ \to J/\psi\pi^+\pi^0$ [22], showing that this decay proceeds mainly through the intermediate process $J/\psi\rho^+$. Interestingly enough, this process also appeared as a background contribution (with a missing $\pi^+$) of the decay mode $B^0 \to J/\psi\pi^0$, for which LHCb has performed an updated measurement of its branching fraction [23].

Other important first-time observations on b-baryon decay modes were obtained. The $\Lambda_b^0$ baryon was observed to decay to $\Lambda_c^+\bar{D}^{(*)0}K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ [24]. New decay modes for $\Xi_b$ baryons were measured, $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$, while improved measurements $\Xi_b^0$ and $\Xi_b^-$ were also obtained [25]. The decay mode $\Lambda_b^0 \to D^+D^-\Lambda$ was also observed for the first time [26] – although the statistics of Run 2 did not allow an amplitude analysis to be performed, the projections onto $\Lambda D^\pm$ and $D^+\bar{D}^-$ indicate the presence of resonances, where potential tetraquarks

Table 1: Full list of LHCb publications submitted for journal publication from October 2023 to March 2024. Detector performance papers with full LHCb author list are also displayed at the bottom.

| | Title | arXiv |
|---|---|---|
| 1. | Measurement of the CKM angle $\gamma$ using the B→ D*h channels | 2310.04277 |
| 2. | Enhanced production of $\Lambda_b^0$ baryons in high-multiplicity $pp$ collisions at $\sqrt{s} = 13$TeV | 2310.12278 |
| 3. | A measurement of $\Delta\Gamma_s$ | 2310.12649 |
| 4. | Observation of $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$ decays | 2310.13546 |
| 5. | Search for $CP$ violation in the phase-space of $D^0 \to K_S^0 K^\pm \pi^\mp$ decays with the energy test | 2310.19397 |
| 6. | Studies of $\eta$ and $\eta'$ production in $pp$ and $p$Pb collisions | 2310.17326 |
| 7. | Fraction of $\chi_c$ decays in prompt $J/\psi$ production measured in $p$Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV | 2311.01562 |
| 8. | Measurement of the $D^*$ longitudinal polarisation in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays | 2311.05224 |
| 9. | Observation of strangeness enhancement with charm mesons in high-multiplicity $p$Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV | 2311.08490 |
| 10. | Measurement of forward charged hadron flow harmonics in peripheral PbPb collisions at $\sqrt{s_{NN}} = 5$ TeV with the LHCb detector | 2311.09985 |
| 11. | A model-independent measurement of the CKM angle $\gamma$ in partially reconstructed $B^\pm \to D^* h^\pm$ decays with $D \to K_S^0 h^+ h^-$ $(h = \pi, K)$ | 2311.10434 |
| 12. | Measurement of $J/\psi$-pair production in $pp$ collisions at $\sqrt{s} = 13$ TeV and study of gluon transverse-momentum dependent PDFs | 2311.14085 |
| 13. | Observation of $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ decays | 2311.14088 |
| 14. | Measurement of associated $J/\psi - \psi(2S)$ production cross-section in $pp$ collisions at $\sqrt{s} = 13$ TeV | 2311.15921 |
| 15. | Determination of short- and long-distance contributions in $B^0 \to K^{*0}\mu^+\mu^-$ decays | 2312.09102 |
| 16. | Amplitude analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay | 2312.09115 |
| 17. | Search for $B_c^+ \to \pi^+\mu^+\mu^-$ decays and measurement of the branching fraction ratio $\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$ | 2312.12228 |
| 18. | Study of $B_c^+ \to \chi_c \pi^+$ decays | 2312.12987 |
| 19. | Multiplicity dependence of $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in $pp$ collisions at $\sqrt{s} = 13$ TeV | 2312.15201 |
| 20. | Prompt and nonprompt $\psi(2S)$ production in $p$Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV | 2401.11342 |
| 21. | Study of $CP$ violation in $B_{(s)}^0 \to DK^*(892)^0$ decays with $D \to K\pi(\pi\pi)$, $\pi\pi(\pi\pi)$, and $KK$ final states | 2401.17934 |
| 22. | Measurements of the branching fraction ratio $\mathcal{B}(\phi \to \mu^+\mu^-)/\mathcal{B}(\phi \to e^+e^-)$ with charm meson decays | 2402.01336 |
| 23. | Observation of the $B_c^+ \to J/\psi\pi^+\pi^0$ decay | 2402.05523 |
| 24. | Measurement of the branching fraction of $B^0 \to J/\psi\pi^0$ decays | 2402.05528 |
| 25. | Modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production in $p$Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV | 2402.14975 |
| 26. | First observation of the $\Lambda_b^0 \to D^+ D^- \Lambda$ decay | 2403.03586 |
| 27. | Amplitude analysis of the $\Lambda_b^0 \to pK^-\gamma$ decay | 2403.03710 |
| | Performance papers | |
| 28. | Tracking of charged particles with nanosecond lifetimes at LHCb | 2403.09483 |
| 29. | Momentum scale calibration of the LHCb spectrometer | 2312.01772 |
| 30. | Helium identification with LHCb | 2310.05864 |

or pentaquarks could be formed.

Besides, the amplitude analysis of the radiative decay $\Lambda_b^0 \to pK^-\gamma$ was performed for the first time [27]. This is an important analysis since it aimed at characterising the $pK^-$ spectrum at the photon pole of the recoiling system, with unique access to the heavier $\Lambda$ states, and providing information that is valuable for BSM searches in $\Lambda_b^0 \to pK^-\ell^+\ell^-$ rare decays.

## 7.2 New results on CKM angle $\gamma$

Two new studies for measuring $\gamma$ using $B^+ \to D^*h^+$ decays were submitted for publication. The first used $B^\pm \to D^*h^\pm$ ($h = K, \pi$), with $D^* \to D(K_S h^+h^-)\pi^0/\gamma$. The measurement was performed by analysing the signal yield variation across the $D^0$ decay phase space, independent of any amplitude model [28]. The second uses the same final state but when the $\pi^0$ or $\gamma$ were not reconstructed [29]. The first obtains $\gamma = (69^{+13}_{-14})^\circ$ and the second $\gamma = (92^{+21}_{-17})^\circ$. They agree within each other (correlations taken into account) and also with the world average.

More recently, a new study of *CP* violation in $B^0_{(s)} \to DK^*(892)^0$ decays (with $D \to K\pi(\pi\pi)$, $\pi\pi(\pi\pi)$, and $KK$) was performed and the observables are used to constrain the parameter space of the CKM angle $\gamma$ and the so-called hadronic parameters $r_{B^0}^{DK^*}$ and $\delta_{B^0}^{DK^*}$ [30]. A combined analysis of these results with the measurement of *CP*-violating observables from $B^0 \to D(K^0_S h^+h^-)K^{*0}$ [31] was performed, resulting in the most precise measurements and provide the most stringent limits to date on $\gamma$ from $B^0$ decays, $\gamma = (63.3 \pm 7.2)^\circ$. For $B^0_s$ decays though, the results are found to be consistent with no *CP* violation.

## 7.3 Production of heavy hadrons in $pp$, $p$Pb and PbPb collisions

This was a particularly fruitful period for our heavy-ion programme, with many different results submitted for publication. Important studies have been performed on the effect of track multiplicity and nuclear matter effects in the production of different hadron species. For the latter, one such effect is recombination, that can lead to production enhancement at higher energies. To disentangle effects from different production mechanisms, it is important to have reference measurements, such as in proton-proton ($pp$) collisions, where nuclear matter effects do not apply. A few studies were recently performed to tackle this subject.

The production of $\Lambda_b^0$ baryons relative to $B^0$ mesons were investigated in $pp$ collisions as a function of the track multiplicity. and an enhancement is observed when compared to lower event multiplicity [25]. A significant dependence was found on both the transverse momentum and the measured multiplicity. At low multiplicity, the ratio measured at LHCb is consistent with the value measured in $e^+e^-$ collisions, and increases by a factor of $\sim 2$ within the measured multiplicity range. These results imply that the evolution of $b$ quarks into final-state hadrons is influenced by the density of the hadronic environment.

Multiplicity dependence for the cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in $pp$ collisions at $\sqrt{s} = 13$ TeV [32] was also studied. The results show correlation between the multiplicity and the charmonium production, while also presenting distinct behaviors of the prompt and non-prompt components, which again indicate the influence of interactions with other particles within the event in charmonium production.

The differential cross sections $\eta$ and $\eta'$ were used to calculate the so-called nuclear modification factors [33], which compare the cross-section for $pp$ with that for $p$Pb rescaled by the number of nucleons. These were obtained for both forward (Pb$p$) and backward ($p$Pb) beam configurations, showing also no significant evidence of mass dependence. These studies offered new constraints on mass-dependent nuclear effects in heavy-ion collisions, as well as $\eta$ and $\eta'$ meson fragmentation.

The fraction of $\chi_{c1,2}$ decays in prompt $J/\psi$ production was measured in $p$Pb collisions [34]. An increase of this fraction at low $J/\psi$ $p_T$ at backward rapidity is compatible with the suppression of the $\psi(2S)$ contribution to the $J/\psi$ yield. In-medium dissociation of the $\chi_c$ is not observed in this study, constraining the free energy available in these collisions to dissociate or inhibit charmonium state formation.

The production cross-sections of $D_s^+$ and $D^+$ are compared in high-multiplicity $p$Pb and Pb$p$ collisions [35]. The nuclear modification factors of these charmed mesons are determined as a function of $p_T$ and rapidity. An enhanced production of $D_s^+$ compared to that of $D^+$ is observed over the full range of $p_T$, constituting the first observation of strangeness enhancement in charm quark hadronization in high-multiplicity $p$Pb collisions.

For the first time, the production of the exotic hadron $\chi_{c1}(3872)$ is measured in proton-lead collisions [36]. When compared to that of $\psi(2S)$, different dynamics seem to be observed for $\chi_{c1}(3872)$ from $p$Pb production, while a comparison with $pp$ collision data indicates that the presence of the nucleus may modify $\chi_{c1}3872)$ production rates.

Other results include the measurement of $J/\psi$-pair production [37] and associated $J/\psi - \psi(2S)$ production [38] in $pp$ collisions; prompt and nonprompt $\psi(2S)$ production in $p$Pb collisions [39]; and measurement of forward charged hadron flow harmonics in peripheral PbPb collisions at $\sqrt{s_{NN}} = 5$ TeV [40].

## 7.4 New results in rare decays

Processes like $B \to K^{(*)}\ell^+\ell^-$ are rare decays involving $b \to s\ell^+\ell^-$ transitions that in the SM proceed through loops. BSM contributions can potentially modify this decay properties, such as branching fractions and angular observables. Previous analyses on this and other similar decays have shown intriguing tensions with some SM predictions.

An amplitude analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay was performed and, for the first time, the coefficients associated to short-distance physics effects, sensitive to processes beyond the SM, were extracted directly from the data through a

$q^2$-unbinned amplitude analysis, where $q^2$ is the $\mu^+\mu^-$ invariant mass squared. Long-distance contributions, originating from non-factorisable QCD processes, were investigated and the most accurate assessment to date of their impact on the physical observables was obtained. The pattern of measured corrections to the short-distance couplings is found to be consistent with previous analyses of $b \to s$ transitions, with the largest discrepancy from SM predictions found to be at the level of 1.8 standard deviations. These results led to two publications, just accepted, at PRL [41] and PRD [42].

Another important result was the measurement of $R_{\phi\pi}$, the cross-section ratio of $D^+ \to \phi(\mu^+\mu^-)\pi^+$ and $D^+ \to \phi(e^+e^-)\pi^+$ [43] – representing a valuable control measurement for lepton-flavor violation (LFV) studies. This was the first LFV test in $\phi$ meson decays at the LHCb experiment, probing a unique kinematic region crucial for understanding the experimental features of low-mass dileptons in the LHCb environment. Furthermore, the most precise measurement of $\mathcal{B}(\phi \to \mu^+\mu^-)$ was obtained.

# 8 Tracking detectors

## 8.1 Vertex Locator (VELO)

### 8.1.1 System overview

The VELO Upgrade is a pixel detector consisting of 52 modules, each equipped with four hybrid planar pixel tiles, arranged in thin walled radio-frequency (RF) boxes which form secondary vacuum enclosures within the LHC primary vacuum. It is cooled with evaporative $CO_2$ and provides a data push triggerless readout, with the total rate reaching 1.2 Tb/s.

### 8.1.2 Operation during the PbPb run

During the PbPb run, the firmware dedicated to reading out large events was tested and validated. The improvement brought to the VELO configurations and firmware allowed the detector to operate stably and efficiently. While improvements in the front-end stability were highlighted in the previous report, further improvements led to a better data acquisition efficiency reaching about 98% in the last ten days of operation.

### 8.1.3 Replacement of the RF Box during YETS 2023/2024

During the 2023/2024 YETS, the VELO detector was completely de-installed to allow for the replacement of the RF box that was deformed in the LHC-VELO vacuum incident in January 2023. The work schedule was spanning over 17 weeks and involved about 40 people from 13 institutes. The overall schedule with the key milestones are shown in Fig. 5. The work started in November with the dismantling of the support mechanics and $CO_2$ cooling system, and with the disconnection

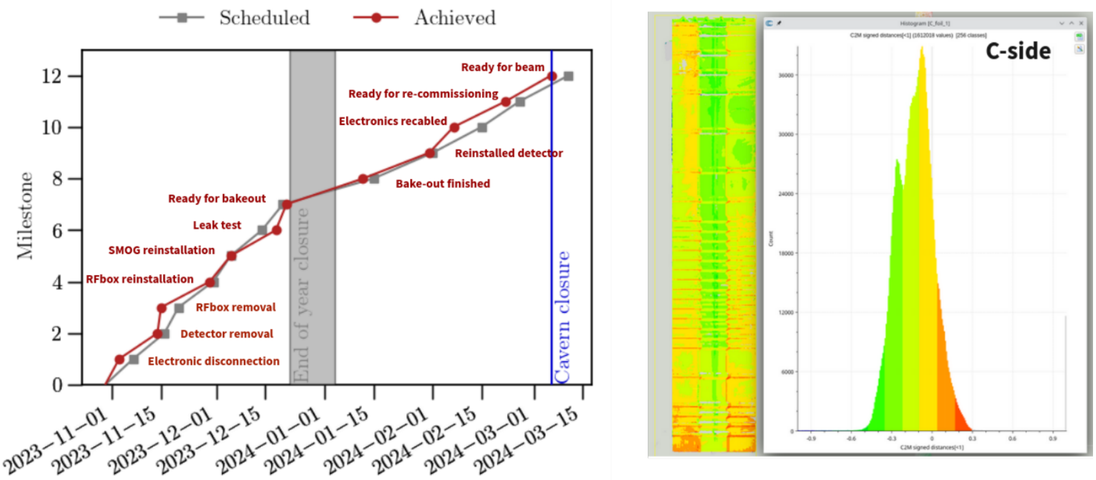


Figure 5: Left: Planned and achieved milestones of the VELO RF box replacement. Right: results of the in-situ metrology of the C-side RF box. The color shows the distance with respect to nominal RF box design.

of the electronics cables, from voltage supply and temperature monitoring to the optical fibres. During that period, the VELO was cleaned from silicon oil contamination that came from thermal pads of the opto-electronic boards, to allow working without having to wear full protection equipment. After removing all the other detectors from the VELO alcove (PLUME, BCM, RMS), the VELO halves were extracted from the deformed RF boxes. In the second half of November, the boxes, together with the SMOG2 cell, were removed from the VELO tank. The motion system was refurbished, in particular the coupling pieces that were damaged during the vacuum incident. The ion pumps were replaced by the TE-VSC group, who installed and recommissioning the new vacuum safety system after the spare RF boxes were re-installed mid December. A metrology campaign was performed in-situ on the new boxes to check their conformity and re-calibrate the motion system. The beam-pipe and new boxes were leak-checked, and their bake-out started during the second half of the Christmas break. After reinstalling PLUME, RMS and BCM, the VELO halves were reinstalled within the new boxes, with 0.5mm spacers on each side that will be removed during the first 2024 technical stop, once the clearance between the VELO modules and the RF boxes will have been validated by tomography measurements. Finally, the detector was recabled, the cooling system re-installed and commissioning could start. Figure 6 shows some of the re-installation steps. Once the detector itself was pumped down, a small leak was measured in the detector volume, leading to a vacuum at the level of $10^{-5}$ mbar instead of $10^{-7}$mbar. It was evaluated to be compatible with operation, not presenting safety concerns.

The beginning of March was used to perform the re-commissioning of the systems (cooling, voltage supply, slow control and data acquisition, ...), while the first collisions at 450 GeV were used to re-commission particle detection. The vertices

Figure 6: Left: The new boxes fixed to the trolley used to insert them in the vacuum tank. Centre: the A-side VELO half being re-inserted it the A-side box. Right: the control and data acquisition fibres reconnected to the opto-electronic boards.

of interaction region as recorded in these first data are shown in Fig 7 and illustrate the fact that the detector functions as expected, that tracks are made out of the registered clusters and $pp$ interaction vertices are reconstructed out of those tracks.

#### 8.1.4 Maintenance and developments over YETS

Beyond the RF box re-installation, the YETS period was used to further develop the various VELO systems towards better performances and stability. In particular the cooling system has been consolidated with the installation of a smaller-size heat exchanger in parallel of the existing one in order to allow operating the VELO without the use of an extra load when the UT and VELO are not on the same cooling plant. Closer to the detector, the $CO_2$ safety valves of the modules 8 and 10 that were observed in 2023 to be misbehaving at warm temperature were replaced. Those valves permit to prevent $CO_2$ pressure building up in the detector volume in case of $CO_2$ leaks in the modules.

High and low voltage systems underwent some maintenance during the YETS. The HV modules were sent to the producers for a modification of the circuit preventing current spikes during ramp, while the filters of the common supply of the LV crate were replaced. Alarm systems for over-current and over-voltages have been made easier to maintain.

A database application to store the detector calibration conditions as well as the extracted operation parameters allowed the bookkeeping during operation to be improved.

Finally, while new firmware developments were deployed earlier for large event, its maximal input rate was limited to about 20MHz. Further progress allowed to reach nominal conditions as illustrated in Fig. 7.

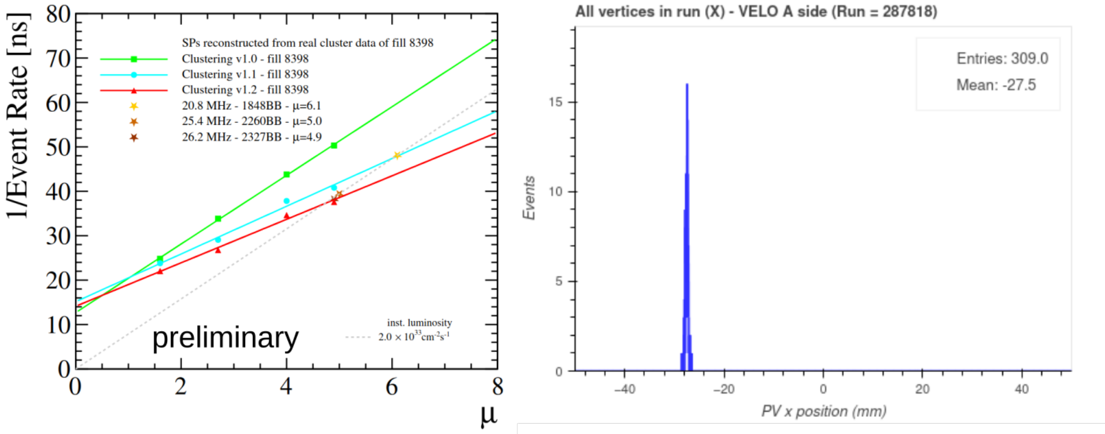


Figure 7: Left: The average processing speed of an event with various version of the VELO retina clustering firmware. The stars represent various running scenarios. The red line, which represent the performance of the new firmware on data from the fill 8398 shows processing speeds better than required can be achieved. Right: horizontal distance of primary vertices with respect to the A-side of the VELO as reconstructed during a fill with 450 GeV collisions.

## 8.2 Upstream Tracker (UT)

### 8.2.1 Introduction and overview

The UT is a silicon microstrip tracking detector located between RICH1 and the dipole magnet of LHCb. It comprises four planes of vertical columns called staves. Each stave is a carbon-fiber structure with embedded Ti pipes to provide evaporative $CO_2$ cooling that hosts silicon front-end hybrid modules attached to both sides to achieve full acceptance in the vertical direction. The dedicated (SALT) front-end ASICs, assembled on the 4 ASIC hybrids, feature 128 processing channels, including a low-noise preamplifier and shaper, and a 6 bit analog-to-digital converter (ADC). The digitised information is processed in a complex DSP, performing common-mode suppression and zero suppression for the normal data-taking operation.

The two-way communication between data acquisition boards (SOL40 for experimental control and TELL40 for data processing) is coordinated by data control boards (DCBs) located in crates on the top and bottom of the UT boxes. Regulated power to the DCBs and front-end hybrids is provided by dedicated boards (LVRs) that are based on the radiation hard ASIC LHC4913, hosted in crates located in the service bay area (SBCs).

The four UT detector layers are called UTaX, UTaU, UTbV and UTbX, with X indicating the vertical strip orientation, while U and V indicate $5^o$ stereo angles. The staves are staggered in the $x$ direction to achieve complete coverage of the LHCb acceptance. The staves are mounted on two separate boxes. The two halves can be retracted to allow for beam pipe bake-out and maintenance.

### 8.2.2 2023 Commissioning

The UT detector was installed in LHCb during 2022/23 YETS and closed around the beam pipe in March 2023. The initial tests with the TELL40 boards in "pass-through" mode showed that 96% of the channels were working well. In proper operations TELL40 boards accumulate data from many SALT ASICs, format them into Raw Banks which are then passed to Event Builder. Because of the large rate variation between the inner and outer region, the sensor/FE connections to TELL40 boards, and corresponding TELL40 firmware, varies across the detector. Five variations of UT TELL40 firmware are required for both normal data taking with zero-suppression (ZS) and non-zero-suppressed (NZS) mode used in electronic calibrations. Loss of synchronisation between various readout elements posed a serious obstacle to detector and firmware commissioning efforts throughout entire last year. Several partial improvements in SOL40 board communications with the Master GBTx residing in the DCBs were implemented in summer which allowed short data taking runs with high ZS ADC thresholds. The firmware flavour needed to operate the inner detector parts became available towards the end of the heavy-ion run. By that time DSS safety matrix was implemented, basic data monitoring infrastructure was in place, and digital pedestals determined from NZS calibration runs. A few short runs together with the rest of the LHCb detector were taken during the last day of the beam availability and analysed offline. The data showed that UT hits were arriving from 2-6 bunch crossings late (25ns per bunch crossing) with a pattern consistent with the differences in the outgoing fibre lengths. Merging proper bunch crossing frames allowed initial studies of space alignment of the UT inner sensors using long tracks reconstructed between VELO and SciFi subsystems. After adjusting individual UT sensor positions, the width of the unbiased UT-long track residual turned out to be only slightly larger than observed in the simulations, as illustrated in Fig. 8. The scope of these studies was limited by shortness of runs, low UT efficiency (about 5% per layer) induced by the high ZS thresholds (15-20 vs. signal peak $\sim$ 10), and harsh background environment due to the large track densities in heavy-ion collisions.

### 8.2.3 YETS 2023/2024

During the 2023/24 YETS, we recovered several sensors which had not been responsive after the installation by improving connectivity inside the box. At this point 98% of silicon sensors are operational. General and PEPI groundings were improved. We conducted several stress-tests of the DSS, including humidity, water, temperature, $CO_2$, $N_2$ and thermal switches. Thermal isolation of electronic boards was improved. New beam-pipe seal and new closing mechanism were installed.

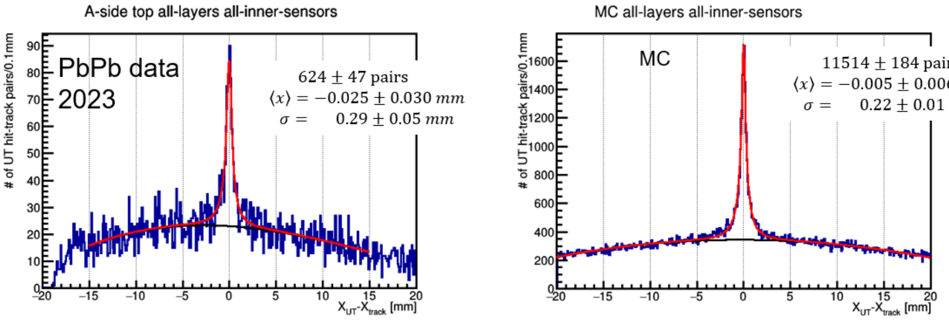


Figure 8: Distribution of the difference between measured UT cluster positions and VELO-SciFi long track projections onto UT sensors in (left) 2023 Pb+Pb data and (right) the simulations. The peak widths are an order of magnitude larger than intrinsic UT sensor resolution and is dominated by the track projection accuracy.

#### 8.2.4 2024 Commissioning

After closing the UT box the operating temperature was lowered to $-10^{o}$C. Further temperature lowering requires better sealing of the detector box to be accomplished during the next YETS.

SALT settings were significantly improved by tuning analog baselines. This made the dynamic range more uniform. Pedestal and ADC saturation values are now similar accross the detector, which is optimal for common mode noise subtraction in the SALT ASICs. Incoherent electronic noise is at the same level as measured during the installation, with an RMS of about 1 ADC count, with little variation across different parts of the detector allowing for uniform ZS threshold setting.

Desynchronisation problems between Master GBTx and SOL40 were significantly reduced by a new SOL40 firmware. Long data runs with low ZS thresholds are now possible. They were exercised with random triggers at 30 MHz without a beam first in local, then in global mode together with the other subdetectors. Occasional errors from individual links still occur with a rate less then one per hour. An automatic reset procedure has been developed and is now being tested.

Many improvements in ECS to automate data taking have been implemented. Error reporting and monitoring is now in place.

The first beam-beam collisions data were taken in local mode on March 21, with 450 GeV proton beams. Two isolated collision bunch crossings allowed for dedicated TAE trigger with $\pm 7$ surrounding bunch crossings recorded for time alignment studies. For the first time inner (p-type) and outer (n-time) sensors were read out with low ZS thresholds, and captured the peak of minimum ionising particles, as shown in Fig. 9. The data were used to determine coarse time alignment for the entire detector. Calibrating DCB level time offsets brought 94% of hybrids within the right bunch crossing; the rest required corrections by $\pm 1$ bunch crossing. Fine time alignment, in which ASIC level time constants are adjusted to maximize signal pulse-height, is in progress.

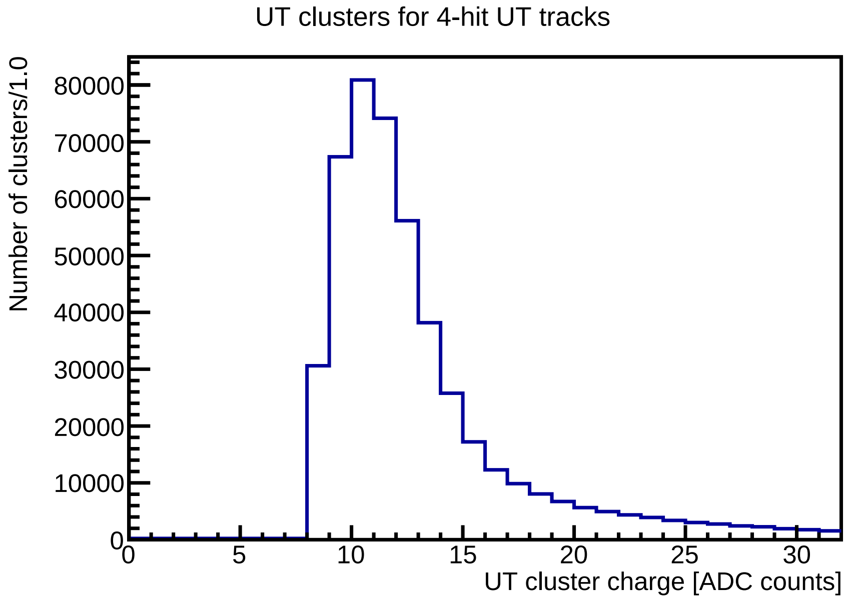


Figure 9: UT hit cluster charges in ADC counts obtained with UT operating during 450 GeV proton beam collisions in March 2024. The data were taken with the ZS threshold of $> 7$ ADC counts. Hits in all 4 UT layers matching the straight line pointing towards the beam-beam collision region have been selected.

Waiting for data taken with the rest of tracking detectors after they have been calibrated on their own, we have looked at the correlations between the four layers of the UT detector. Figure 10 presents the number of UT clusters detected in the second vs. first layers. The slope near 1 indicates that on average both layers have about the same efficiency. The space correlations among hits in different layers are clearly visible as illustrated in Fig. 11.

### 8.2.5 Plan for UT integration

Fine time alignment will be improved over the course of April. Even without it, the detector can be used for space alignment of its elements. The initial space alignment has been set to surveys of sensor position on staves during their installations, and surveys of staves after they were mounted on the detector frames. Further alignment has been exercised on simulation. Alignment on real data is awaiting the VELO and SciFi tracking detectors to have a good time and space alignment first, which is expected in late April. As the UT intrinsic space resolution is an order of magnitude better than precision with which VELO and SciFi can track particles through the UT detector, it is expected that the final space alignment will be performed with relevant degrees of freedom being adjusted to the data simultaneously.

After the space alignment is complete, use of UT in tracking will be first exercised in off-line environment. Then UT information will be added to global data

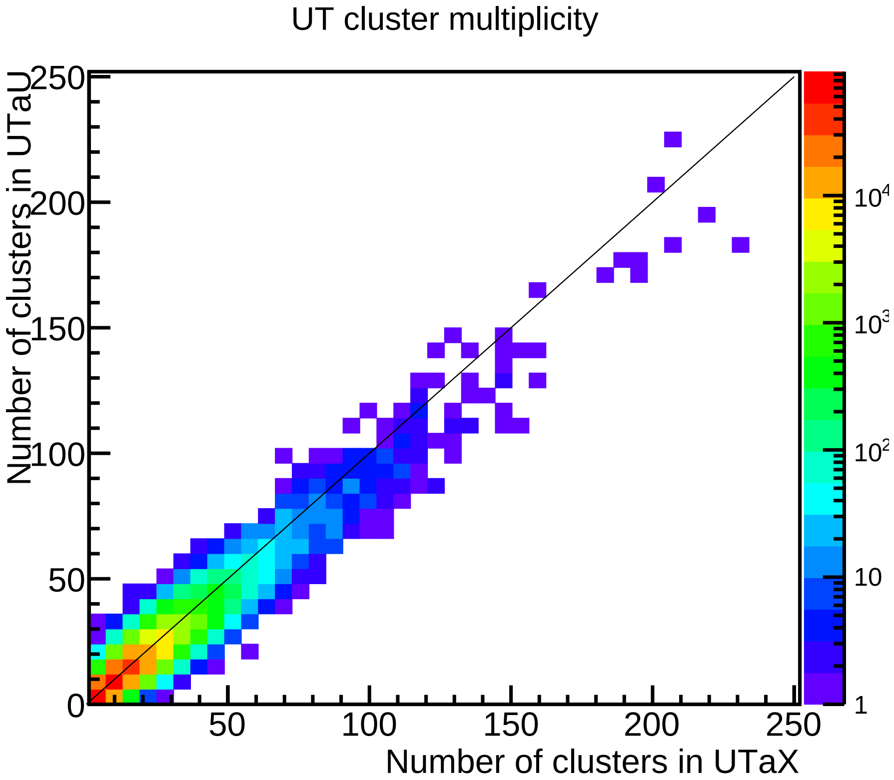


Figure 10: UT cluster multiplicity in the stereo layer (UTaU) versus UT cluster multiplicity in the first X layer (UTaX) obtained with UT operating during 450 GeV proton beam collisions in March 2024.

taking permanently, however not yet used in triggering. This will allow track-level monitoring to be set up and long term stability of its use to be observed in tracking by the monitoring farm, processing a fraction of data in parallel to data taking. In parallel, HLT1 and HLT2 production versions with use of UT will be prepared and tested offline. As a final step, these versions will replace the versions without use of UT. For planning purposes we anticipate that this will occur during the technical stop in mid June. However, if the detector and software are fully functional ahead of this schedule, the change may be performed earlier.

In addition to the steps outlined above, the UT DAQ system must be stable enough to deliver robust UT performance over long data taking periods at high luminosity. The process of the readout commissioning is not completed yet. Firmware still needs improvements for some of its flavors and the procedure for automatic resets is in its initial phase of testing. Beam induced SEUs in SALT chips were observed in the R&D phase, and mitigation strategies built into its design. Large system performance at high luminosity awaits to be tested with beam in April and May.

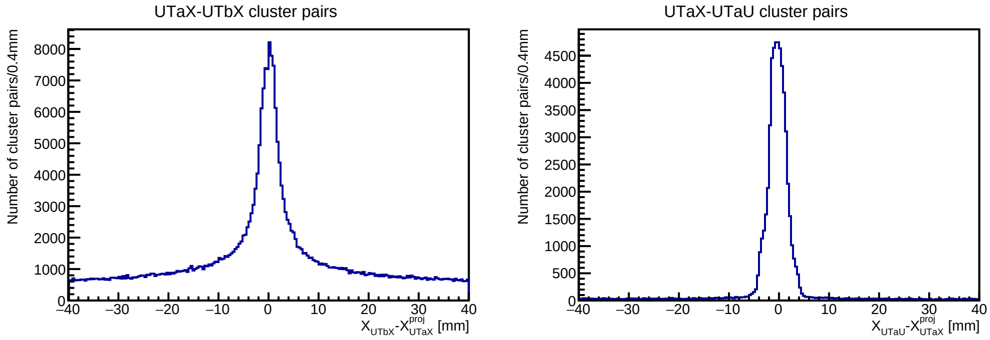


Figure 11: Space correlations among UT clusters in various layers obtained with UT operating during 450 GeV proton beam collisions in March 2024. (Left) Difference between the measured UTbX x-position and the projected one from the UTaX hit position. The straight line projection from the LHCb detector origin (near the beam-beam collision region) to UTaX hit are used, with $x$ coordinate well determined by Si strips and $y$ coordinate set to the centre of 10cm wide sensor. The observed width of the coincidence peak is affected by bending in residual magnetic field and deviations of the beam-beam interaction points from the detector origin. (Right) Difference between the measured UTbU x-position and the projected one from the UTaX hit position after the UTbX hit position agreed with the projected one from UTaX within 2mm. The width of the distribution is affected by poorly determined $y$ coordinate of the UTaX hit preventing exact correction for the stereo angle of UTaX hit.

## 8.3 Scintillating-Fibre Tracker (SciFi)

### 8.3.1 System overview

The technology and design of the SciFi system are described in the LHCb Tracker Upgrade TDR [5]. The active element of the SciFi consists of 250 $\mu$m thick and 2.5 m long scintillating fibres arranged as hexagonally close-packed six-layer mats of 131 mm width. Eight of these mats are joined to form 5 m long and 52 cm wide modules. The fibres are read out from the outer ends by 128-channel arrays of silicon photomultipliers (SiPM), which can be cooled to -40°C to limit the single-pixel dark-count rate after irradiation. It is composed of a total of 524,288 read-out channels.

The fibre modules together with the readout electronics are mounted on 6 m $\times$ 4 m large support frames (C-frames). These frames provide the necessary services (low voltage and bias voltage, optical connections, SiPMs cooling) including water cooling of the electronics. The necessary cooling of the SiPMs is achieved with a separated cooling system operated at temperatures as low as $-50$°C.

The detector is divided in half with 6 C-frames arranged in 3 stations of X-U V-X layers installed on each side of the beam-pipe; there are 12 C-Frames in total. A survey system (BCAM) is used to monitor the movements of the C-frames over time in addition to the alignment with tracking data.

We have reached a stable operation of the SciFi Tracker in 2023 and an average hit detection efficiency of all SiPMs close to 98%. Our aim is now to achieve an average hit detection efficiency of all SiPMs greater than 99%. To do this, we took advantage of the last few months to improve SciFi in terms of detector stability, operations and hit efficiency for the ongoing data taking period.

### 8.3.2 Maintenance activities

The YETS has allowed access to the detector to perform some maintenance work and to improve the stability of the detector during operation.

**SiPM cooling system**

The cooling plant for the SiPMs (including the common chiller) has been upgraded during the period without beam in the summer of 2023. It was seen previously that some of the thermal transfer oil in the heat-exchanger at the plant was jelling, coating the walls, and reducing the efficiency of the heat-exchanger, such that the detector temperature increased to -42°C. Unfortunately, this was not sufficient to maintain a stable setpoint of -50°C for a long period. To try to fix this issue, EN-CV in addition to the yearly maintenance of the cooling plant has made a change of the oil in the exchangers. If the goal is not met, further upgrades will be performed during the LS3.

For the monophase cooling fluid circulated to the detector, a different cooling liquid was studied as a better replacement, called NOVEC 7100, with a lower greenhouse warming potential (GWP=300), was positively evaluated to replace the current $C_6F_{14}$ (GWP = 10,000). Its purchase is ongoing, and the exchange of the fluid will be done in the next YETS. It will be used for the remaining operation of the SciFi.

**The Condensation Prevention System (CPS)**

In general, the CPS is performing well, in particular considering it was built as a late compensation measure not planned in the original design in order to solve water condensation observed on systematically under-insulated locations during SciFi assembly when the SiPMs were actively cooled.

To avoid condensation on the SciFi detector, a system of heating wires is wrapped around the cold locations. They are powered by rebuilt MARATON Power Supply Units, PSU. Several failures, which are most likely related to the age of the PSU units, have been observed. For every failure, it has been necessary to heat up the system to avoid condensation and then replace the PSU at the next access. Since the SiPMs have not yet received a large dose, this only had minor consequences for operation in the form of higher but tolerable noise (dark count rate), but in the future the consequences will grow and potentially lead to significant downtime for SciFi and LHCb. To make the system more reliable, the PSU system has been upgraded to use 2 PSUs redundantly per channel. Four diode boxes have been designed by EN-DT and installed to allow automatic switching between the PSUs and to separate the PSUs (such that a failure on one should not affect the other). New cables were installed in the cavern to power these four additional MARATON power supplies. The automated control software has been updated according to this and the system is fully commissioned. The new units are not yet delivered and only one spare MARATON is currently in use, but they will be installed as soon as they arrive, since a short access to the cavern is sufficient for this.

There are other dependencies in the system that are also desirable to get rid of; *e.g.* if one temperature sensor is disconnected, the reading of several sensors will be lost. Another example is that when a heating wire is shorted to a C-frame, the reading of many frames is affected. Therefore, an upgrade of some electronics boards is being prepared. These new boards were designed and produced. They are being tested and will be installed on the C-frames at the next YETS.

**On-detector electronics**

Five half-FEB (Front-End Board) and 4 data links were not fully functional in 2023. This corresponded to 5632 channels out of a total of 524 288 channels (less than 1%). Two problematic FEBs were replaced on the detector, and some optical inspection/cleaning for a handful of problematic links was done. In addition, two broken fibres in the long distance trunk were identified and repatched to spare ones. Only two data links (out of 5120 data and control links) were not fixed during this YETS due to time constraints and the risks associated with accessing their location in the lower occupancy part of the detector. More than 99.95 % of the channels are now functional.

There were also minor repairs of malfunctioning temperature sensors, flow metres, etc. and usual maintenance like the cleaning of water filters, etc.

### 8.3.3 Commissioning activities

In parallel with the hardware activities in the cavern, we carried out some commissioning activities to improve the operation of the detector and prepare 2024 data taking.

**Control and Data link stability improvements**

The major source of instability for SciFi during commissioning and 2022/2023 data taking was nailed down to an unexpected feature of the GBTx ASIC itself. Previous to the mitigation of this problem, we faced a high number of decoding errors appearing in the DAQ, which led to the DAQ no longer sending physical data but only error fragments. Last year, we established a clear correlation of FEC (Forward Error Correction) counts with the payload of the TFC Frame delivered to the MasterGBT. In collaboration with the CERN ESE group, LHCb Online group, and in collaboration with the other sub-detectors within the DECTF, we found a way to mitigate this problem by modifying the TFC frame sent to the SciFi by the SOL40 (applying an unused bit in the GBT frame). This allowed us to take data in a stable and efficient way since September 2023. The issue was tracked down to the GBTx ASIC itself, and a more robust mitigation method in the SOL40 firmware has been proposed and is currently in place.

We have at our disposal a setup to test our Front-End Boards (so-called FE-tester) that we use extensively. We upgraded its software/firmware in order to have an environment as close as possible to that of the detector. Thanks to this, we were able to reproduce a separate problem encountered on a FEB on the detector in the same way when the FEB was mounted on the FE-tester. This will enable us to further investigate and study the relevant problems over the lifetime of the detector.

We carried out extensive 12-hour control link tests without counting any errors for SciFi's 512 bi-directional control links. We also performed a very long (24h) run of 56 billion events without any control links failure, and negligible data loss. Currently, the major sources of errors experienced in 2022 and 2023 are no longer an issue, though some less frequent errors still appear and are being monitored and studied.

**Control software improvements**

New functionalities were added to the control software. They allow for reaing back registers in a scan with a small increase in duration (around 10%) and a new beam scan method was implemented for a finer scheme of the fine time alignment with beam. We are now able to shift the readout phase around a given reference for the entire detector, helping to find the optimal hit efficiency.

**Other improvements**

Each PACIFIC ASIC features two charge injectors that allow three different amounts of charge release. This is a powerful tool for debugging the FE and BE systems on-detector. We used it when we commissioned the C-frames just after they had been assembled. The control software and firmware have been updated so we can now use it for the detector in the cavern.

SciFi is equipped with a Light Injection System (LIS) consisting of small auxiliary boards with two drivers and laser diodes controlled by the FEBs. This system sends light which is distributed by plastic optical fibres over the fibre mats and is used to determine the electronic signal gain vs delay time for each of the 524k channels such that the thresholds can be set correctly with respect to the peak gain and the efficiency of the detector is more uniform. A campaign was conducted to well adjust the latency in bunch crossings between the calibration trigger and the data, as well as the fine delay between the calibration trigger and the light injection to maximise the signal. This was used to improve the calibration of the detector and to optimise the threshold settings to reconstruct clusters.

In addition, the SiPM bias voltage was fine-tuned. The complete system consists of over 500,000 SiPM channels, and the HV power supply system is organised into channels of commercial devices. Each channel biases 4 SiPM, corresponding to one fibre mat. But each SIPM has a slightly different breakdown voltage per channel, and this can be compensated in the PACIFIC chip of the Front-End electronics which is used for the readout of 64 SiPM channels. This PACIFIC per channel bias compensation was completed and studies of the dependence of the gain with temperature have been carried out. We expect to obtain a more uniform detector in terms of efficiency and noise and, therefore, better performance for the individual channels.

# 9 Particle identification detectors

## 9.1 Cherenkov detectors (RICH)

### 9.1.1 System overview

The RICH system of LHCb is composed by two detectors, RICH1 and RICH2, designed to provide charged hadron identification in the momentum range 2.6-100 GeV. The upgrade of the RICH system consists of new optics and mechanics for the RICH1 detector and new opto-electronics chain in both RICH1 and RICH2. The new opto-electronics chain is composed of multi-anode photomultipliers (MaPMTs) as photon detectors, read out by a custom ASIC, the CLARO chip, designed to digitise the signal at 40 MHz. Finally, a FPGA-based digital electronics takes care of the interface with the PCIe40 for both the trigger and fast control and the data transmission. The full installation of the upgraded RICH system was achieved during LS2 so that both detectors were ready to be operated at the start of Run 3.

### 9.1.2 Maintenance and YETS activities

During the YETS period, the RICH team performed regular maintenance on the RICH detectors. Particular care was devoted towards the beampipe and Velo bake-out at the beginning of the year. A dedicated cooling system was installed around the bellow at the interface between RICH1 and the Velo vessel, to keep the temperature of the RICH1 gas enclosure under control (Fig. 12 left). Furthermore, a dedicated ventilation system was installed at the entry window of RICH2. The bake-out was controlled profiting from the existing temperature monitoring system, enhanced with further sensors for this specific phase, validating the conditions of the RICH system throughout the entire period.
During the month of February, the RICH team performed regular maintenance on the opto-electronics chain of few elements RICH2. The illumination system used for calibration in RICH1 was upgraded (Fig. 12 right) and minor interventions were performed on the RICH1 columns, benefiting from the Upgrade design which greatly simplifies the accessibility to the photon detector enclosure for maintenance.
As usual, during the YETS, the RICH1 gas enclosure was emptied from $C_4F_{10}$ and filled temporarily with $CO_2$. The gas group at CERN performed a global maintenance, including the consolidation of the full piping system. Towards the end of the YETS, the gas enclosure was refilled with $C_4F_{10}$ (Fig. 13) and the RICH system has been made ready for the start of the data taking.

### 9.1.3 Performance and readiness for data taking

In 2023, the RICH group devoted particular effort in validating the performance of the RICH system concerning both the Cherenkov angle resolution [44] and the

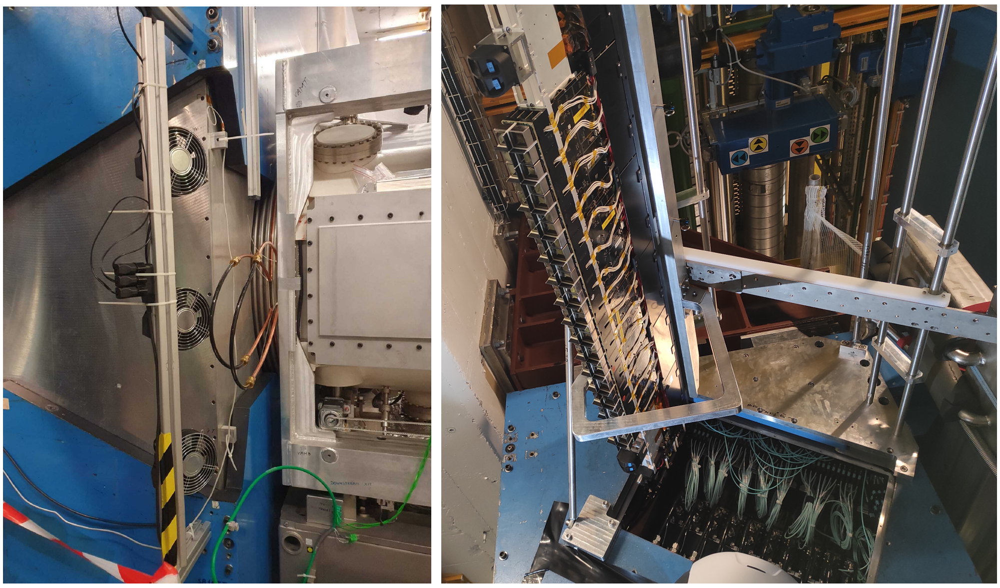

Figure 12: Left: cooling system installed during the bake-out phase to keep under control the temperature of the RICH1 detector; Right: intervention on the Up box of the RICH1 system for regular maintenance.

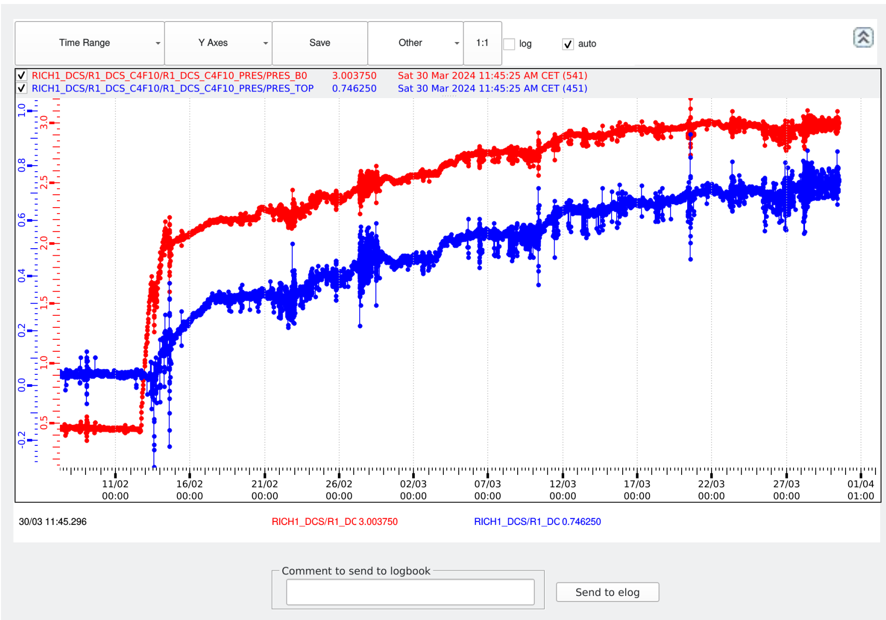


Figure 13: Pressure variation within the RICH1 vessel during the phase of filling with $C_4F_{10}$ at the end of the YETS.

charged hadron identification [45]. The RICH system has proven to be already very close to the design performance and ready to provide excellent PID to the LHCb physics production phase. In preparation for the 2024 data taking, the online monitoring system of the RICH has been upgraded to provide particle iden-

tification variables per run in real time, to check the overall stability of the LHCb performance. Furthermore, the synchronous running of HLT2 will allow to access in depth studies of PID concurrently to the run, to fully exploit the potential of the RICH system.
A full set of calibration runs was acquired in 2023 and has been acquired in 2024. The analysis of this data set showed that no ageing of the photon detectors system has been observed after the first two years of data taking in Run 3. The gain equalisation across the photon detector planed was performed during 2023 and will be the baseline setting for the 2024 data taking. Finally the RICH variables to provide an online measurement of the luminosity will be put in production as backup system during the regular LHCb operations.

## 9.2 Calorimeters (ECAL and HCAL)

### 9.2.1 System overview

The upgrade of the LHCb calorimeters consisted in replacing the electromagnetic (ECAL) and hadronic (HCAL) calorimeter readout electronics and upgrading the high-voltage, monitoring and calibration systems. The detector modules of the original LHCb were retained. The gain of the photomultipliers (PMT) has been reduced by a factor up to five in order to keep them operational throughout the higher luminosity runs of the upgrade. The new analogue electronics partially compensates for the gain reduction by boosting the signals by a factor of 2.5. The remaining factor of two is used to extend the dynamic range of the calorimeter system and thus to extend the physics case to some new topics.

The construction of the electronics, for the front-end, the high-voltage, the monitoring and the calibration of the calorimeters was completed in 2021. After the productions, the installation started in parallel with the tests of the hardware, so that the installation was achieved the same year. The final firmware versions to ensure a proper processing of the electronics have been written and loaded also in 2021.

The ECAL and HCAL detectors are fully operational and are used routinely in the global LHCb acquisition since Spring 2022. The calorimeters took part in the first high-energy collisions in stable beams in July 2022.

### 9.2.2 Latest activities

Since July 2022, the main hardware activities for the calorimeter system consisted in consolidating the electronics and performing adjustments. In parallel, our group worked on the decoding of the data, the calibration, the time alignment, writing the monitoring tools, adapting the simulation to the DD4Hep, etc.

The quality of the data stored by the calorimeter has become the priority during the last months.

**Maintenance** We benefited from the latest shutdown of winter 2023-2024, to replace 40 HCAL PMTs which were suffering from ageing. This is a regular operation, and we bought, from Hamamatsu, a couple of years ago, the necessary spares. Some other individual malfunctioning Cockcroft-Walton bases or PMTs from the ECAL and HCAL have also been replaced, and a couple of FEB connectors bringing the PMT signals to the boards have also been fixed.

**Tuning of the LED system** Another activity consisted in modifying the calibration and monitoring LED pulse shape. In 2023, we noticed that the clipping of the channels was leading to an undershot after the pulses. The new pedestal subtraction method which has been implemented into the FEBs for the Run 3, in order to mitigate the higher occupancy expected, does not cope with such an undershot and was leading after the subtraction to a positive tail that could extend out of the collision gap where the LED pulse is triggered. The shape adjustement was foreseen on the ECAL LED drivers and could be easily done. For the HCAL the tuning required a physical operation on the driver circuits. Fig 14 shows the HCAL LED pulse amplitudes, and the effect of the pedestal subtraction on the next samples. A couple of channels still exhibit a positive tail that can be removed by better timing the LED pulse, and is harmless for the physics collision data.

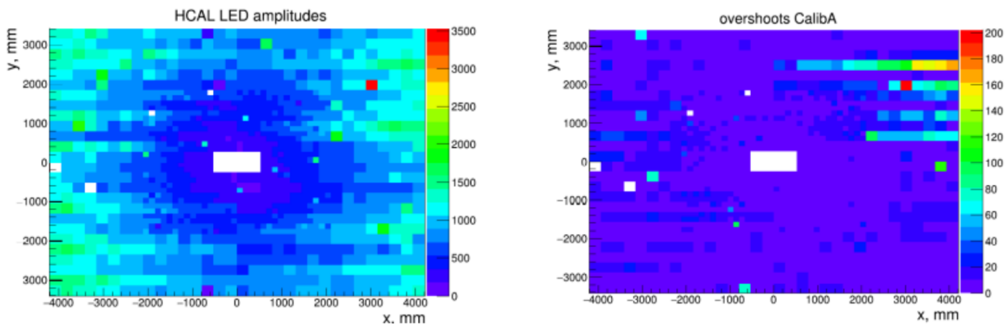


Figure 14: Left, the HCAL LED pulse amplitude in ADC counts on the calorimeter front-face. Right, The positive tail, in ADC counts, induced by the LED pulse shape and the FEB pedestal subtraction technique.

**Calibration and monitoring** The overall LED system for the ECAL and HCAL has been tuned in term of signal amplitude and timing. Some problems had been identified in 2023, with the Cesium source used to calibrate the HCAL cells. The garage and the source have been cleaned by the Radioprotection group at CERN. And the water used to push the source in the pipes that cross the volume of the HCAL has been replaced.

We had planned originally to pulse the LEDs of the calorimeter system 3 times per orbit. Twice to pull current from the PMTs in order to stabilize their response and once to monitor it. Since, we checked that one pulse was enough for the stabilization of the PMT response and now only two triggers are used per orbit.

This required a modification of the FPGA firmware the 3CU boards that receive and propagate all the slow and fast signals in the calorimeter crates.

The software for the monitoring of the calorimeter system has been reviewed and improved. New quantities are now determined and provided to get a faster and more precise diagnostics of the potential failures.

**Simulation** The MC simulation had to be upgraded to the new DD4Hep framework. This was done in the last two years. Recently, some corrections on the geometry or on the generation of the signal response have been implemented. Moreover, the new HCAL beam plug was has been added to the simulations properly.

## 9.3 Muon chambers (MUON)

### 9.3.1 System overview

The Muon detector has performed exceptionally well in Run 1 and Run 2 of the LHC. The main changes for Run 3 are the removal of M1, the redesign of the off-detector electronics, and the installation of a new shielding in front of the inner region of M2 to reduce by about a factor two the low energy background rate in this region.

The electronics of the Muon detector upgrade consists of a new readout board (nODE), equipped with four custom ASICs (nSYNC) redesigned to be compliant with the 40 MHz readout of the detector, and of new control boards, the Service Board (nSB) and the Pulse Distribution Module (nPDM), redesigned to be compliant with the new ECS/TFC system.

All interventions done during YETS 2023 were successful and the system is ready to take data in 2024.

### 9.3.2 Commissioning

All the activities needed for the commissioning of the Muon system are progressing well. All Muon Tell40 and SOL40 boards are connected and in use, and the firmware is updated to the latest version. The ECS project is almost completed in all its sub-projects: the DAQ project, the HV project and the DCS one, a new project which now includes the low voltage control, the temperature monitor, and the gas flow and gain monitor projects.

The Muon system is successfully taking part in the Run 3 LHCb data taking. The detector has been working well. The experimental control system (ECS) has been in daily use to operate and control the Muon system. A lot of effort has been put on the optimization of the DAQ and in its interaction with the Tell40 firmware. A suite of new ECS panels have been developed to help this optimisation and to serve as tools for the piquets and the experts in the management of the system. The new version of the online monitoring of the Muon system has been enriched with a suite of new histograms and with the activation of the automatic analysis. The monitoring is currently in use by the experts and the central shifters, and helped in the optmisation of the Muon DAQ stability. The Muon Tell40 desynchronisation caused large inefficiencies in 2022. The root cause of the desynchronisation is still being investigated, but many tests allowed a working configuration for power supply, firmware, and software to be found, such that in the Muon system the issue is reduced to a negligible level, no longer affecting either the DAQ or MuonID performance. The Muon system has been easily aligned to the LHC clock, and the procedure for the fine time alignment of the electronics within the 25ns bunch has been completed. To deploy the effective alignment, we will need to acquire special Time Alignment Events (activity already planned for the first days of *pp* collisions in stable beams).

A lot of effort has been also put to update the Run 1 and Run 2 Muon software to the Run 3 detector and environment. The readout cabling is much changed and required a new raw data decoding and simulation encoding software. The Muon reconstruction and identification algorithms have been adapted to the tight time constraints of the full software trigger. The first measurements of MuonID performance in Run 3 data showed good results, albeit to reach the full efficiency the Muon system the deployment of the fine time alignment and the expected improvement of the tracking system performance will be needed. The removal of M1 and the new shielding required to modify the detector description and all the geometry has been ported to DD4HEP, while the work to port to DD4HEP all methods is close to be completed. Finally an improved modelling of the detector response to low energy background and to spillover is ready to be used in the simulation.

# 10 PLUME and luminosity

For Upgrade I, LHCb has developed and equipped its interaction region with dedicated systems whose goals are to continuously monitor luminosity and beam induced background conditions. Moreover, other LHCb sub-detectors started to provide ECS counters to monitor the luminosity, increasing the redundancy of the whole system.

## 10.1 System overview

The luminosity and beam/background monitors at LHCb are composed of a set of hardware and software systems. The PLUME detector is a new detector in LHCb, based on quartz sensors and using the calorimeter front-end readout electronics, specifically developed and adapted for Run 3. PLUME is fully dedicated to continuously monitor in real-time the instantaneous luminosity, averaged and per bunch, and to provide a direct measure of the average number of visible *pp* interactions per bunch crossing ($\mu$). PLUME is synchronised with the LHC clock and in addition it is included in the LHCb Data Acquisition (DAQ) system providing such measurements for offline purposes included in the event bank.

The Beam Conditions Monitor (BCM) directly measures beam losses around the LHCb interaction region and acts as the LHCb primary safety interlock, dumping the beams when such losses are above specified thresholds. The BCM consists of two stations (Upstream and Downstream), each composed of 8 diamond sensors interfaced to current-to-frequency converter (CFC) cards providing continuous running sums (RS) over 40 μs (short RS) and 1280 μs (long RS).

The Radiation Monitoring System (RMS) continuously estimates the amount of beam induced losses observed around the LHCb interaction region. The RMS is composed of 4 stations, with each composed of 2 metal foil detectors connected to charge-to-frequency converters. The change in frequency is linearly proportional to the number of minimum ionizing particles (MIPs) providing an estimate of the amount of particles lost by the beams around LHCb.

PLUME, BCM Upstream and RMS are located around 1.5 m from the interaction point in LHCb, in the zone of the LHCb cavern between the VELO and the cavern wall, commonly referred to as the VELO alcove. The BCM Downstream system is located between the Upstream Tracker and the LHCb dipole.

## 10.2 Commissioning, maintenance and operation

The PLUME, BCM and RMS detectors all completed their initial commissioning phase during the first months of data taking in Run 3. Since then, they all have been operating continuously throughout 2022 and 2023. Improvements in stability and robustness were added throughout 2022 and 2023, and studies on detector efficiency were also performed. The online measurement of instantaneous luminosity showed a non-linear dependence at higher values of pileup. This was demonstrated by dedicated tests where LHCb took data at different values of pileup, from 0.1 to roughly 7. This issue was not problematic during 2022 and 2023, as LHCb took data at a maximum value of pileup of roughly 2.5. A solution has been studied during the 2022 YETS and has been successfully deployed in time for the first PbPb collisions in 2023. The validation of the new approach for high pileup will be performed by dedicated tests ongoing in April 2024.

In addition, PLUME worked in improving the recipes for the front-end boards, improving pedestal subtraction, and substantial work has gone into the development of the readout board firmware. These activities allow a quasi-online measurement of the bunch clock phase shift with a precision of about 100 ps to be performed, as well as an online pedestal determination from empty events directly in the Tell40 readout board. The online luminosity determination by PLUME has been made quasi-independent from the LHCb detector status, allowing PLUME to run even if the LHCb run is stopped. This feature has been successfully deployed with the first collisions in March 2024. The measurement of the luminosity per bunch has been implemented in the Tell40 readout board and is currently available, even if it has to be validated before being transmitted to the LHC. This validation is ongoing.

The BCM system had its readout board updated, exchanging the Tell1 board with a custom one named MIBAD. The operation was successful and after a first validation period in which both boards were used in parallel, the BCM system is now running with the new readout without issues. The RMS did not undergo interventions during the YETS.

During the last months, the VELO, SciFi and RICH sub-detectors deployed different ECS counters that have been or will be added to the luminosity panels in the control room. These counters could be used in the future to obtain independent determinations of the online luminosity after a calibration performed with Van-der-Meer scans.

### 10.3 Offline luminosity determination

Two dedicated luminosity lines have been added to the pool of trigger lines contained in the HLT1 framework. The first one, running at a rate of 30 kHz, contains around 60 counters from different sub-systems that will be used for the determination of offline luminosity. The second one, with a rate of 1 kHz, contains additional counters not included in the first due to event size constraints. The output of the 1 kHz line, propagated to HLT2 and processed by sprucing, is also exploited to count the number of luminosity events contained in physics streams. This information is then propagated to the analysts' ntuples via the Final State Report (FSR) mechanism. This will allow the integrated luminosity to be determined from the ntuples, by counting the number of events stored in the FSRs and matching it with the offline luminosity determined per run contained in an online server deployed on GitLab and running on a CERN virtual machine.

This mechanism has been first deployed in September 2023 and will be finalised when an estimate of the offline luminosity collected by the experiment will be available, possibly before Summer 2024. A first preliminary analysis of the data collected during the September 2023 vdM scan is being performed. First results are expected for Summer 2024. This will allow the offline luminosity collected during 2023 to be calibrated with a precision of few percent.

## 11 Real time analysis

The Upgrade trigger [6] is fully implemented in software. Collisions are reconstructed in real time with the best possible quality; candidates and event-level information are then selected and written to offline storage. This process is done in two steps. In the first, HLT1, a fast reconstruction sequence is run on about 350 GPGPUs to reduce the rate to about 1 MHz. Data are then stored in a disk buffer, enabling detector calibrations and derivation of alignment constants. Once ready, the second step, HLT2, performs the full reconstruction using CPUs on about 4000 nodes and either selects full events or individual particle candidates to be analysed further offline. In this scheme, the full reconstruction is performed online and not redone later.

## 11.1 First trigger stage

Most work in HLT1 in the last months focused on the preparations of the 2024 data taking under nominal conditions, *i.e.* a collision rate around 26 MHz and a (visible) pile-up of about 5.5. Significant effort was dedicated to study the different reconstruction sequences to achieve the optimal working point between throughput of HLT1 and efficiency of the reconstruction. All technical components of HLT1, *i.e.* components not directly selecting physics events of interest were reviewed to understand and improve their computing performance, resulting in a significant gain in HLT1 throughput. The optimal settings for the physics trigger lines were determined with an automated procedure called "bandwidth division", the final result largely profiting from a newly introduced, neural-net based rejection of fake tracks in the HLT1 track reconstruction. Several new components for monitoring and commissioning the trigger system, but also other subdetectors have been introduced. These include the possibility to select events based on activity during the collisions of isolated bunches, needed for the time-alignment of subdetectors, an improved monitoring of error data from the detectors, and trigger lines to ease the mapping for the VELO material distribution. Progress has also been made on the inclusion of the UT in the software chain, with finalisation of the geometry description for the use in HLT1 and the convergence of several software components between the two trigger stages. In addition, the reconstruction of tracks from long-lived particles has been implemented in HLT1 and is ready to be used as soon as the UT becomes part of the trigger decisions.

## 11.2 Alignment and calibration

Significant progress has been made in the understanding of the alignment and calibration of the detector using the data collected during 2023. Improvements in the alignment of the SciFi detector include the introduction of new degrees of freedom to consider thermal effects affecting the position measurements of the SciFi detector and an improved procedure to select events for the determination of the alignment constants, resulting in more uniform results. The global track reconstruction efficiency has been determined with a better understanding of the hit efficiencies of the individual subdetectors and their operating conditions, achiving a better agreement between the results in data and simulation. The high quality performance of the RICH detectors, already observed with 2022 data, has been confirmed with the 2023 data set. Moreover, electron identification efficiencies have been determined from b-hadron decays. The results with 2023 data have limited precision due to the available statistics, but the procedure has been developed an automatised to ensure a fast turn around in 2024.

A new procedure to determine the position of the beamline in an automated way was implemented, improving on the situation in 2023. The position is now automatically determined, validated and written to the detector conditions, such that the reconstruction algorithms automatically use the updated values.

A new monitoring framework is being set up, running as an online monitoring task after HLT1. Interesting events are selected by filtering on relevant HLT1 decisions and high-level quantities, such as track and particle identification efficiencies, are determined in quasi-real time by a series of automatic analysis tasks. This tool provides a direct monitoring of the physics quality provided by the detectors and real-time analysis software, and will be crucial to ensure high quality data is collected during the intensity and pile-up ramp up at the start of the 2024 data taking.

## 11.3 Second trigger stage

Together with the physics working groups, many HLT2 trigger lines, comprising the full physics programme, were implemented. A campaign to bring the amount of data to be written out in accordance with the guidelines in the LHCb computing TDR [17] was carried out, significantly reducing the output bandwidth of HLT2 without sacrificing signal efficiency. Detailed tests of the expected output bandwidth are carried out on a daily basis, thanks to a newly integrated procedure. Additionally, new functionality for the luminosity measurement in HLT2, and also lines for calibrations and technical purposes were set up. A new inference framework for the various machine learning applications in HLT2 was deployed, simplifying the training and deployment of neural nets across the software trigger. Several improvements in the persistence of events and candidates have been implemented, leading to either additional functionality, or a better and more failsafe structure of the software. Studies have been carried out to determine the optimal settings for the initial running conditions in 2024 that balance the efficiency of the data being written out, its purity, and the fact that non-negligible differences between and simulation are expected during the early running period.

## 11.4 Data processing

All *pp* data from 2023 has been processed by the end of January 2024. The majority of the data had been processed in late 2023, including most of the *pp* data after the June 2023 technical stop, and the PbPb data, taken during the heavy-ion runs in October 2023. The processing of the PbPb was an excellent test for the reconstruction of the upgraded LHCb experiment, as for the first time centralities down to 30% could be reached with acceptable reconstruction performances despite the high occupancies. The remainder of the *pp* data after the June 2023 technical stop, exhibiting the need for a special treatment due to a technical shortcoming, was processed in January 2024, together with the BGI and vdM data from 2023.

# 12 Online

At the heart of the data acquisition is the event-builder, which assembles the events at a rate of 40 MHz, aggregating 40 Tb/s. It is composed of 163 PC-servers interconnected through a 200 Gb/s bi-directional network. The event-builder is fully connected to the sub-detectors and has been extensively used in commissioning and data-taking. It is the biggest and highest throughput system of its kind in the world today.

The event-builder software is working well. The reliability of the system in case of hardware failure has been improved, reaching almost no loss of throughput in case of multiple link or hardware failures on the network.

All computers in the Online system have been migrated to the latest version of the RedHat Linux OS without disturbing operations activities.

New readout firmware has been deployed in all PCIe40 boards. It successfully addresses all known issues and has been extensively tested in long, stable runs. Many more monitoring and diagnostic counters and features have been added to facilitate detailed understanding and tuning of front-end electronics and readout.

The experimental control system as well as the Run Control are fully operational. Both systems are continuously improved and automated, in order to optimise the data-taking efficiency and facilitate the quality control of the data. New panels are now available in order to identify quickly uncommon errors in the data acquisition flow and to raise alarm to the shift crew. A new version of the underlying SCADA software WinCC OA has been successfully deployed with minimal disturbance to subdetector activities.

The central monitoring and storage systems are working very well and significantly above the original requirements without the need for additional hardware.

The dataflow between HLT2 and the CERN Tier-0 has been improved with new features such as compression and is now entirely automated, with extensive monitoring.

# 13 Electronics

At the end of the 2023 period of data taking, a Task Force, called Detector Electronics Commissioning Task Force (DECTF) was put in place to address and solve all remaining issues related to the electronics, in view of obtaining a successful and efficient data taking in 2024. The DECTF was quickly set up at the beginning of November 2023 with a few experts from each sub-system. Regular meetings and follow-ups were organised and all remaining issues were tackled. Action lists and names were assigned to each action for tracking.

At that time, a total of 17 major issues were identified. In particular, one serious issue was discovered in the control links to the front-ends which had a major impact on the data-taking stability of the SciFi and UT systems in particular. This was also experienced by the ATLAS New-Small-Wheels detector. A detailed investigation was launched by CERN-EP-ESE using data and hardware provided by LHCb and ATLAS. The issue was successfully identified as a periodic disturbance of the down-links to the front-ends resulting in a corruption of TFC commands and corresponding data packets, and in some cases loss of the link synchronisation. The underlying cause is a combination of the GBTX link architecture and how it is used in the LHCb and ATLAS environments. The investigation also identified mitigation steps which were implemented and tested by the LHCb Online and detector groups. Since then, data-taking instability due to this issue has been entirely eliminated.

All other issues were mostly related to the quality control of the clock transmission, firmware robustness and improvements and de-synchronisation related to un-optimised settings in the readout chain (Front-End electronics or Back-End electronics).

Today, all issues are either solved or sufficiently mitigated in order to have minimal effect on data taking efficiency. The current detector and electronics is ready for efficient data taking, having been commissioned regularly for sustained periods of time with little or no inefficiency during the winter shutdown. One aspect remains to be studied, and it relates to the sensitivity of the detector and electronics to beam induced effects (for example, Single Event Effects). These effects were never studied as LHCb never ran continuously at the nominal pileup. The DECTF however has made all necessary preparations to be ready to study these effects.

# 14 Software and computing

## 14.1 Data processing

Following the trigger reconstruction and selections, with the last step of the trigger being HLT2, the data is required to be Spruced – meaning skimmed and trimmed – and streamed before it is made available to analysts. The centralised Sprucing processing step on the HLT2 Turbo, TurCal and FULL streams had been fully and successfully commissioned in 2023. This comprised both the validation of the software application itself and the validation of the Spruced outputs with the results of the physics working group selections in a set of streams. Several Sprucing campaigns took place, and were delivered successfully and timely; details are given in Section 5 on Operations.

The operational aspects of exploiting WLCG resources for the execution of Sprucing jobs have been consolidated during the said campaigns, in collaboration with the Computing team. The continuous monitoring and validation of the relevant software has also been enhanced, ensuring a better physics performance (and application throughput) across the board.

Analysts create their reduced data samples starting from the Spruced samples in the Turbo and FULL streams. A significantly larger number of analysts has been executing Analysis Productions. Analysis Productions are the by-now-well-commissioned centralised way of producing ntuples that are subsequently utilised for physics measurements by working groups and users. "Early analysts" have been seen to create ntuples within days after the completion of Sprucing campaigns, as samples became available in the bookkeeping system, stress-testing the continuous-integration system that relies on the reviews and approvals from working group liaisons to ensure the best quality of the production requests and the minimisation of issues on WLCG sites.

On the side of the analysis software stack, the DaVinci offline analysis application with state-of-the-art software engineering tools got further consolidated and stress-tested with the 2023 data samples produced by the many analysts. The comprehensive test suite in place since the early development days has been enhanced according to needs to follow the evolution of the stack, from core components to trigger and offline specific code. The test suite continues to be effective in preventing issues with the software and the data. Complex integration tests chaining HLT2, Sprucing and ntuple-making jobs have also been enhanced to verify the correctness of the full processing chain.

## 14.2 Simulation

The simulation software continues to support the needs of the collaboration for physics analysis of Run 1 and Run 2 legacy data. Extensive work is ongoing to fine-tune the simulation of the Run 3 detector to be ready for exploitation of Run 3 data to allow timely analysis of data to be taken in 2024. Furthermore, significant work has gone into support of future upgrades with the short-term aim of supporting necessary studies for the scoping of the LHCb Upgrade 2.

The description of the detector geometry based on the DD4Hep received significant attention. Improvements have been made to bring the current Run 3 detector geometry description close to the actual detector and the remaining differences are being identified and fixed. The sub-detectors regularly provide feedback and improvements, many based on the data taken during 2023. Along with the improvements of the Run 3 detector geometry descriptions, refactoring of the code allows the use of different detector geometries and provides versioning of the existing geometry descriptions. This was not only crucial for the Run 3 support, but also to allow us to build a coherent simulation of the Upgrade 2 detector for global studies. The first integration tests of the possible Upgrade 2 geometry were performed and feedback from the sub-detectors is being incorporated into the next version.

Over the past few months, there has been progress in exploiting possible machine learning models for the calorimeter simulation arising from the Fast Calorimeter Simulation Challenge 2022 initiative. An interface to one of the models based on variation auto-encoder has been implemented in the Gaussino framework and successfully tested in the multi-threaded version of the LHCb simulation, which is being developed. Initial tests on relevant physics decay modes show very good agreement with detailed simulation based on Geant4, while providing a significant speedup of the simulation. The machine-learning-based models are also interesting as they can be easily used to exploit GPU resources. Another available avenue to use GPU resources consists of developments like Adept or Celeritas, which implement electromagnetic physics to replace Geant4 and are designed specifically for GPUs. Work is ongoing to interface such models in our multi-threaded framework to evaluate their performance.

The beta version of Gauss based on the Gaussino multi-threaded core simulation framework has been released and infrastructure has been adapted for its use on the grid. First tests on the grid in a single-threaded mode were successful and we are currently in the process of rerunning tests in the multi-threaded mode. In addition, the beta version has also been compiled and released for ARM processors and the first tests to use it on the grid and validate its performance are ongoing.

On the operational side, it has been about a year since LbMCSubmit, the tool for submission of simulation production, was put into production. One of its aims was to simplify operations by minimising problems in production and to automatise repetitive tasks which required significant time from experts. After one year of use, the expectations were fulfilled with almost all issues being discovered in the testing phase before submission to the production system with only a small number of cases when a problem appeared only when requests were handed to production managers. Over the year, over 95% of requests were handled through the LbMCSubmit without the need for dedicated action from experts.

## 14.3 Offline computing

The offline computing infrastructures are running smoothly. An ARM slot in the nightly build system has been used to test the simulation software. A validation campaign of the simulation on ARM test facilities at Glasgow and at CERN is imminent. The detector description for Run3, based on DD4hep, has been put in production for the reconstruction of real data; its implementation in simulation applications is at an advanced stage; support for the description of the detector in Run4 and Run5 has been provided as well. The LHCb software stack has been upgraded to newer versions of the LCG release and Gaudi core software framework, thereby allowing the usage of more recent Root and compiler versions.

In the distributed computing domain, work is ongoing to integrate the existing NCBJ (Poland) and IHEP (China) Tier2 centers as new Tier1 sites. The NCBJ site was officially endorsed as a Tier1 by the WLCG Overview Board in December 2023. The IHEP site is successfully configured; it is connected to LHCONE through a shared 100Gbps optical link, a dedicated LHCOPN link is being deployed.

A modernization of the DIRAC system for workload and data management on distributed computing resources is currently under way; agents and services will be migrated one at a time, thus guaranteeing service continuity. In February 2024, LHCb participated in the joint data challenge in view of the high-luminosity LHC program (DC24). The target metrics for transferring data from the Tier0 to the

Tier1 sites (including the new NCBJ site), writing to tape and reading back from tape, were reached successfully; operational experience was gained, and a fruitful collaboration between the LHCb operations team and remote site managers further improved performance.

The distributed computing resources pledged to LHCb were efficiently used, although the average CPU power was at about 90% of the pledged resources. Most resources (85%) were used for simulation productions; 6% was used for physics analysis and 6% to process the data sets taken in 2022 and 2023 *pp* and heavy ion collisions.

The lower utilization of CPU resources is due to a lower demand for simulation. A long tail of Monte Carlo productions corresponding to Run1+Run2 data taking conditions is still present, whereas only small samples of simulation with Run3 conditions were produced, mainly for commissioning and performance studies. As the year 2023 has been mostly a commissioning year of the LHCb detector, the bulk of simulation production corresponding to Run3 conditions was delayed, as LHCb is very sensitive to the experimental conditions and the corresponding simulations start only after data taking has been completed. The pressure on compute was therefore lower than expected.

The activities related to real data included centralized processing of the proton and heavy ion collision datasets collected in 2022 and 2023, and an incremental stripping cycle of the Run2 proton collision datasets. Opportunistic resources were used, in form of computing clusters at LHCb institutions and HPC centers, contributing to a few percent of the total compute work. Russian sites continue to contribute in an opportunistic way; no custodial storage is archived on those sites.

A dedicated document [46] has been prepared to present the final requests for the computing resources in 2025. The resource increase with respect to the revised 2024 needs is at the 60% level on average. The estimation of the computing resources needed by LHCb until the end of Run4, prepared in Spring 2023, has been subsequently updated; CPU needs stay within a 15%-20% yearly increase; storage is also compatible with the same level of increase, with the exception of 2025. A report has been prepared which describes the utilization of computing resources in the 2023 calendar year [47].

The LHCb Computing Model for the Upgrade era and the associated computing requirements are presented in Ref. [17]. The 2024 WLCG year is going to be the first year where this model will be exercised in full. The pledged resources for 2024 are sufficient to sustain the activities of a nominal data-taking year. However, a recent decision to shift the 2024/2025 YETS by four weeks has an impact on the offline resources requirements; in particular, a 10-15% increase is expected on storage requirements, which is difficult to be accomodated by the existing 2024 pledges and may need additional resources to be put in place in the course of the year.

# 15 Infrastructure

The modification to the shared chiller has enabled the testing of operational capabilities using a single heat exchanger within the SciFi cooling plant. Following the test, it was determined that the cooling capacity provided by a single heat exchanger is insufficient to maintain the required setpoint of -50°C. As a result, further modifications are necessary to meet the operational demands. During the YETS 2023/24, a further consolidation of the shared primary chiller took place, along with the introduction of an additional heat exchanger flushing system to enhance performance recovery. To address concerns regarding oil distribution, a decision was made to switch the refrigeration coolant from R449a to R448a, offering improved oil miscibility at lower temperatures.

Partial replacement of the insulation in MAUVE cooling plants has been carried out and the Velo cooling plant has been outfitted with a new heat exchanger. Completion of the mechanical and electrical installation now permits operation of the new circuit in manual control mode. However, the system will undergo long-term testing in its original configuration to evaluate the performance of the new coolant.

Regarding NOVEC products, the validation studies for using NOVEC 7100 in the cooling system of SciFi have been finalized. A sufficient stock of the fluid has been procured. The RICH system will continue to utilize NOVEC 649 with the existing stock originally from SciFi.

The insulation and temperature regulation system for the gas pipes of RICH1, which run through the technical galleries from the SG8 building to the PM85 shaft, were refurbished.

# 16 LS3 enhancements

## 16.1 Particle identification

A Technical Design Report (TDR) has been submitted to the LHCC in September 2023 with the proposal of enhancing the ECAL and RICH detectors during LS3 [48]. Both projects will anticipate key features of LHCb Upgrade II, which will be installed during LS4, thus facilitating the successful deployment of this challenging project. These proposed enhancements will also improve the physics capability of LHCb during Run 4, when the majority of the Upgrade I data sample will be acquired, without introducing substantial additional commissioning time at beginning of Run 4. The LHCC review was completed successfully during early 2024, and the TDR was approved by the CERN Research Board in March 2024. Discussion will now concentrate on securing the needed funding, before the enhancement projects can be carried out. The main elements of the proposals are as follows.

For the ECAL, replacement of the innermost modules, which will be severely affected by radiation damage by the end of Run 3, is foreseen, using the same design and SpaCal technology of Upgrade II. In addition, the existing Shashlik modules will be rearranged to better match the occupancy map. Significant improvement in performance is expected, which will be reflected in better sensitivity for a wide spectrum of physics channels. Several prototypes of the new SpaCal modules have already been built, which in test-beams have been demonstrated to meet the required energy resolution performance. At the moment, activity is concentrating on preparing the module and front-end electronics production lines, on adapting the detector software, and on expanding the detector infrastructure at CERN.

For the RICH system, a new time-sensitive front-end readout with a novel ASIC (FastRICH) directly connected to newly developed optical link components (lpGBT/VL+), is proposed for installation. The RICH detectors will thus become the first part of LHCb to provide the timing capability that is the crucial feature of Upgrade II. In Run 4, the time resolution will be limited to $\sim 150\,\text{ps}$ due to the MAPMT transit time spread, but nevertheless substantially improved background rejection can be achieved by applying a time gate on the Cherenkov photons, thus improving the hadron PID capabilities. The design phase for the FastRICH ASIC is presently well advanced, with the goal of targeting the Upgrade II time resolution specification (few tens of picoseconds).

Each of the two proposals presented in this TDR are relatively minor in scope compared to their counterparts for the Upgrade II project, and their cost, 5.3 and 2.6 MCHF for ECAL and RICH, respectively, represents $\sim 20\%$ of the total investment proposed for these detectors in Upgrade II. In addition, the cost of reused elements, which constitutes the major fraction of the total investment, will be accounted for in the core cost of the Upgrade II detector.

## 16.2 Online system

In addition, in February 2024 the LHCb Collaboration submitted to the LHCC a TDR on Data Acquisition Enhancement during LS3. The review is expected to develop during the next months. The main elements of the proposed enhancement are given below.

The data acquisition architecture and most of the technologies will be kept during LS3 and through LHC Run 4, adding more nodes to handle new front-end channels. An example of this is given by the aforementioned upgrades of ECAL and RICH detectors. New data acquisition nodes will, however, rely on a new readout board, named PCIe400. The development of this generic board is a stepping stone to keep pace with the latest generation of FPGAs and take advantage of them to build, in the future, a very large readout system running at over 200 Tbits/s. This development also fits perfectly with the learning path toward mastering clock distribution at the ultimate precision of $\mathcal{O}(10)\,\text{ps}$ as well as state-of-the-art high speed links in PCB, over 100 Gbit/s.

In Upgrade II, LHCb will need to perform real-time reconstruction of complex detector data at a luminosity an order of magnitude higher than in Run 3. In these conditions, it should be advantageous to perform low-level reconstruction at the subdetector readout level, using custom processors to produce intermediate, more compact data structures. Using these primitives rather than raw data as the starting point of the HLT reconstruction can save both bandwidth and precious computing resources for the higher-level physics selection tasks. We propose to explore this approach by designing and operating a Downstream Tracker processor in Run 4. This standalone custom processor will search for track segments in the T-stations taking advantage of the powerful FPGA available in the PCIe400. Implementing it during LS3 will allow both useful operational experience and improved physics sensitivity to be obtained during Run 4, when the majority of the LHCb Upgrade I data sample will be collected.

The proposed enhancement of the data acquisition system is essential to gain experience on key technologies for Upgrade II, validating the future design and preparing an efficient commissioning and exploitation phase for this project. The cost is modest, and most of the developed hardware can be reused in the final detector. It also opens the door to new computing architectures which can be considered for optimisation of the ultimate physics performance.

# 17 Upgrade II status

The total integrated luminosity of the LHCb Upgrade I phase is expected to reach $\sim 50\,\text{fb}^{-1}$ by the end of Run 4. Further data taking with the Upgrade I detector beyond Run 4 will not be attractive, on account of the excessive 'data-doubling' time, and also due to the fact that many of its components will have reached the end of their natural lifespan in terms of radiation exposure. There is therefore a strong motivation to perform a second upgrade, Upgrade II, of the detector, in order to realise fully the flavour-physics potential of the HL-LHC. Upgrade II will be installed during LS4, and will operate at a maximum instantaneous luminosity of $1.5\times10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$, with the target of integrating $\sim 50\,\text{fb}^{-1}$ per year, and of increasing the total LHCb data set to $\sim 300\,\text{fb}^{-1}$ by the completion of the HL-LHC. The data sample for flavour physics will at this point be significantly larger than that of any other planned experiment, and will allow for improvements in the precision of a large number of key observables without being limited by systematic uncertainties [15]. The Upgrade II plan of LHCb received strong support in the 2020 Update of the European Strategy for Particle Physics [49], which was approved by the CERN Council that year. Achieving this ambitious goal will be highly challenging, and will necessitate improved granularity and radiation tolerance beyond the specifications of Upgrade I, and the equipping of certain subdetectors with a timing resolution of $\mathcal{O}(10\,\text{ps})$ in order to mitigate the effects of pileup. The project components, cost-envelope for the baseline detector and options being investigated for descoping are defined in the Framework Technical Design Report (FTDR) [16], which was approved by the LHCC in 2022. The LHCC has recommended that the collaboration performs "the R&D necessary to complete technical design reports on the proposed schedule". The R&D phase is presently being actively pursued, with major contributions from all of the LHCb supporting institutes.

A multi-step process to scrutinise and approve the Upgrade II project and secure the needed funding has been proposed by the LHCC at the June 2022 RRB meeting [50]. The next stage in the process is the presentation of a Scoping Document, which will complement the FTDR by adding information on detector scoping options matched to the established cost ranges of approximately 100%, 85% and 70% of the baseline cost outlined in the FTDR. Preliminary scenarios will be discussed with the LHCC and presented at this RRB meeting, with the final scoping document, containing information on the financial envelope and physics performance in each of the descoped detector scenarios, on person-power and funding profiles, and on project organisation and milestones, to follow in September 2024. A list of sub-detector TDRs will also be provided, with expected dates for their review within the LHCC. In the next section, the main characteristics of the baseline Upgrade II detector will be briefly presented.

## 17.1 Detector overview

Performing flavour physics in the forward region at peak instantaneous luminosity of $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ presents significant experimental challenges. The expected number of interactions per crossing is around 40, producing $\sim 2000$ charged particles within the LHCb acceptance. Radiation damage also becomes a greater concern for most detectors. On the other side, the physics programme requires that the Run 3 detector performance is maintained, and even improved in certain specific domains. The design proposed in Ref. [16], which is shown in Fig. 15, is based on the present spectrometer footprint, with all detector components being upgraded in order to meet the desired specifications.

Among the distinctive features of the new design is the capability of providing fast-timing information with a resolution of few tens of ps per particle, which at very high pile-up becomes an essential attribute for suppressing combinatorial background. As an example, a new VELO detector will be designed to provide a similar spatial resolution as the Upgrade I detector, but adding a 50 ps resolution time-stamp per hit, thus becoming the first 4D-tracking device of this type.

For the tracking system, high granularity silicon pixel sensors appear to provide a solution to cope with high particle density in the UT, which is located upstream of the magnet, and in the central region of the Mighty Tracker (MT in the following), which is located downstream of the magnet. The emerging radiation hard DMAPS technology is a strong candidate for the above detectors. The outer region of the MT will be still covered by scintillating fibres, as in Run 3, with significant developments required to cope with the increased radiation damage. As a new feature with respect to Upgrade I, additional tracking stations will cover the magnet side walls, thus increasing the acceptance for low-momentum particles.

The excellent performance of the PID detectors of the current experiment will be maintained for Upgrade II, and in some cases enhanced. The RICH system will be a natural evolution of the current detectors, with SiPMs considered as potential

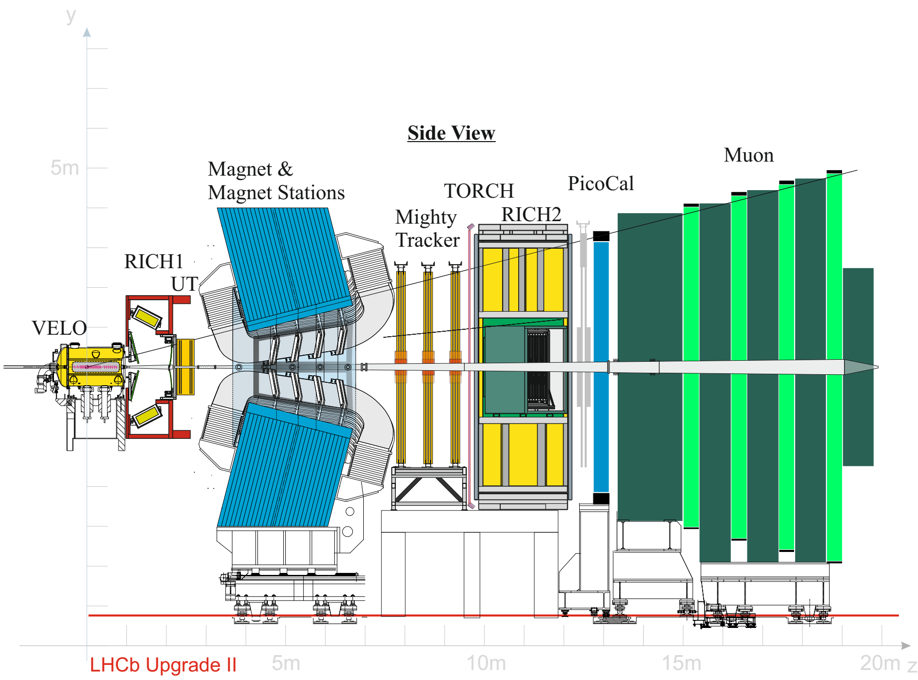


Figure 15: Schematic side view of the Upgrade II detector.

replacements for the existing multi-anode PMTs due to their higher granularity and excellent timing performance. In particular, a single photon time resolution of a few tens of picoseconds is required to obtain significant suppression of the combinatorial background. To meet the required performance it will also be necessary to achieve a Cherenkov angle resolution of $\sim 0.2\,\text{mrad}$, a factor of three better than in Run 3. As an additional feature to boost the PID performance at low momenta, a time-of-flight detector (TORCH) is proposed, to be installed in front of RICH2. The new electromagnetic calorimeter, named PicoCal for its picosecond timing capabilities, will make use of SpaCal modules (also proposed for installation during LS3, see Sec. 16.1) in the innermost highly irradiated region, while keeping Shashlik modules for the outer part. A combination of tungsten absorber and novel radiation-hard garnet crystal fibres or lead absorber and polystyrene fibres will be used for the SpaCal modules with expected doses above and below 200 kGy, respectively. With respect to the LS3 enhancement proposal, a double readout with longitudinal segmentation of the modules is proposed for the whole calorimeter, in order to achieve a timing resolution of the order of a few tens of ps, which will guarantee the needed background reduction. Finally, for the muon system new detectors will be needed to replace MWPCs in the innermost region of all stations, with a design possessing both high granularity and high rate capability. A promising candidate for this purpose is the $\mu-$RWELL, a new type of Micro-Pattern Gaseous Detector based on the same principle as the GEM and exploiting a very similar manufacturing process.

The above detector scenario is presented as the baseline option in Ref. [16], with an estimated cost of $\sim$ 175 MCHF. In preparation of the Scoping Document, additional scenarios are being studied with envelopes reduced by $\sim$ 15% and $\sim$ 30%, respectively. This is very relevant in terms of a global optimisation of resources, but also to demonstrate the physics performance slope as a function of cost. The main directions which have been explored for descoping are:

- A reduction of peak instantaneous luminosity in a range comprised between the nominal value, $1.5 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$, and a minimum value of $1.0 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$, This approach would of course reduce, together with the integrated luminosity, also the requirements in terms of sub-detector granularity and maximum data throughput.
- A reduction of sub-detector features, with impact on specific aspects of the physics programme.

A further important aspect, which is being considered in the optimisation, is the detector complexity, as it is strictly related to the possibility to deliver the project within the specifications required while respecting the global timeline constraints.

Comprehensive studies have been carried out in the last months, with the goal of optimising the detector for each of the three cost envelopes mentioned above, and comparing the expected performance. Preliminary results from these studies will be presented at this RRB meeting, while additional studies targeting the expected sensitivities on specific physics channels are expected for the final version of the Scoping Document in September 2024.

# References


[1] LHCb collaboration, *Letter of Intent for the LHCb Upgrade*, CERN-LHCC-2011-001. LHCC-I-018, 2011.

[2] LHCb collaboration, *Framework TDR for the LHCb Upgrade: Technical Design Report*, CERN-LHCC-2012-007, 2012.

[3] LHCb collaboration, *LHCb VELO Upgrade Technical Design Report*, CERN-LHCC-2013-021, 2013.

[4] LHCb collaboration, *LHCb PID Upgrade Technical Design Report*, CERN-LHCC-2013-022, 2013.

[5] LHCb collaboration, *LHCb Tracker Upgrade Technical Design Report*, CERN-LHCC-2014-001, 2014.

[6] LHCb collaboration, *LHCb Trigger and Online Upgrade Technical Design Report*, CERN-LHCC-2014-016, 2014.

[7] LHCb collaboration, *LHCb Upgrade Software and Computing*, CERN-LHCC-2018-007, 2018.

[8] LHCb collaboration, *Computing Model of the Upgrade LHCb experiment*, CERN-LHCC-2018-014, 2018.

[9] LHCb collaboration, *LHCb SMOG Upgrade*, CERN-LHCC-2019-005, 2019.

[10] LHCb collaboration, *LHCb Upgrade GPU High Level Trigger Technical Design Report*, CERN-LHCC-2020-006, 2020.

[11] LHCb collaboration, *LHCb PLUME: Probe for LUminosity MEasurementt*, CERN-LHCC-2021-002, 2021.

[12] LHCb collaboration, *Addendum No. 1 to the Memorandum of Understanding for Collaboration in the Construction of the LHCb Detector. The Upgrade of the LHCb Detector: Common Project items* CERN-RRB-2012-119A, revised April 2014, CERN, Geneva, 2012.

[13] LHCb collaboration, *Addendum No. 2 to the Memorandum of Understanding for Collaboration in the Construction of the LHCb Detector Upgrade of the LHCb detector Sub-Detector Systems*, CERN-RRB-2014-105, 2014.

[14] LHCb collaboration, *Expression of Interest for a Phase-II LHCb Upgrade: Opportunities in flavour physics, and beyond, in the HL-LHC era*, CERN-LHCC-2017-003, 2017.

[15] LHCb collaboration, *Physics case for an LHCb Upgrade II — Opportunities in flavour physics, and beyond, in the HL-LHC era*, `arXiv:1808.08865`.

[16] LHCb collaboration, *LHCb Framework TDR for the LHCb Upgrade II Opportunities in flavour physics, and beyond, in the HL-LHC era*, CERN-LHCC-2021-012, 2022.

[17] LHCb Collaboration, *Computing model of the Upgrade LHCb experiment*, CERN-LHCC-2018-014. LHCB-TDR-018, CERN, Geneva, 2018.

[18] LHCb collaboration, *First invariant mass spectra and performance figures of the 2023 ion run*, LHCb-FIGURE-2023-030, 2023.

[19] LHCb collaboration, *Ghost charge measurement with beam-gas imaging for fills 8997 and 8999*, LHCb-FIGURE-2024-001, 2024.

[20] LHCb collaboration, R. Aaij *et al.*, *Search for $B_c^+ \to \pi^+\mu^+\mu^-$ decays and measurement of the branching fraction ratio $\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)$*, arXiv:2312.12228, to appear in Eur. Phys. J. C.

[21] LHCb collaboration, R. Aaij *et al.*, *Study of $B_c^+ \to \chi_c\pi^+$ decays*, JHEP **2024** (2024) 173, arXiv:2312.12987.

[22] LHCb collaboration, R. Aaij *et al.*, *Observation of the $B_c^+ \to J/\psi\,\pi^+\pi^0$ decay*, arXiv:2402.05523, to appear in JHEP.

[23] LHCb collaboration, R. Aaij *et al.*, *Measurement of the branching fraction of $B^0 \to J/\psi\,\pi^0$ decays*, arXiv:2402.05528, to appear in JHEP.

[24] LHCb collaboration, R. Aaij *et al.*, *Observation of $\Lambda_b^0 \to \Lambda_c^+\bar{D}^{(*)0}K^-$ and $\Lambda_b^0 \to \Lambda_c^+D_s^{*-}$ decays*, arXiv:2311.14088, submitted to Eur. Phys. J. C.

[25] LHCb collaboration, R. Aaij *et al.*, *Observation of $\Xi_b^0 \to \Xi_c^+D_s^-$ and $\Xi_b^- \to \Xi_c^0D_s^-$ decays*, Eur. Phys. J. **C84** (2024) 237, arXiv:2310.13546.

[26] LHCb collaboration, R. Aaij *et al.*, *First observation of the $\Lambda_b^0 \to D^+D^-\Lambda$ decay*, arXiv:2403.03586, submitted to JHEP.

[27] LHCb collaboration, R. Aaij *et al.*, *Amplitude analysis of the $\Lambda_b^0 \to pK^-\gamma$ decay*, arXiv:2403.03710, submitted to JHEP.

[28] LHCb collaboration, R. Aaij *et al.*, *Measurement of the CKM angle $\gamma$ using the $B^\pm \to D^*h^\pm$ channels*, JHEP **12** (2023) 013, arXiv:2310.04277.

[29] LHCb collaboration, R. Aaij *et al.*, *A model-independent measurement of the CKM angle $\gamma$ in partially reconstructed $B^\pm \to D^*h^\pm$ decays with $D \to K_S^0h^+h^-$ $(h = \pi, K)$*, JHEP **02** (2024) 118, arXiv:2311.10434.

[30] LHCb collaboration, R. Aaij *et al.*, *Study of CP violation in $B_{(s)}^0 \to DK^*(892)^0$ decays with $D \to K\pi(\pi\pi)$, $\pi\pi(\pi\pi)$, and $KK$ final states*, arXiv:2401.17934, submitted to JHEP.

[31] LHCb collaboration, R. Aaij *et al.*, *Measurement of the CKM angle $\gamma$ in the $B^0 \to D^0K^{*0}$ channel using self-conjugate $D^0 \to K_S^0h^+h^-$ decays*, arXiv:2309.05514, to appear in Eur. Phys. J. C.

[32] LHCb collaboration, R. Aaij *et al.*, *Multiplicity dependence of $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in pp collisions at $\sqrt{s} = 13$ TeV*, arXiv:2312.15201, submitted to JHEP.

[33] LHCb collaboration, R. Aaij *et al.*, *Studies of $\eta$ and $\eta'$ production in pp and pPb collisions*, Phys. Rev. **C109** (2024) 024907, arXiv:2310.17326.

[34] LHCb collaboration, R. Aaij *et al.*, *Fraction of $\chi_c$ decays in prompt $J/\psi$ production measured in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV*, Phys. Rev. Lett. **132** (2024) 102302, arXiv:2311.01562.

[35] LHCb collaboration, R. Aaij *et al.*, *Observation of strangeness enhancement with charm mesons in high-multiplicity pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV*, arXiv:2311.08490, submitted to Phys. Rev. Lett.

[36] LHCb collaboration, R. Aaij *et al.*, *Modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV*, arXiv:2402.14975, submitted to Phys. Rev. Lett.

[37] LHCb collaboration, R. Aaij *et al.*, *Measurement of $J/\psi$-pair production in pp collisions at $\sqrt{s} = 13$ TeV and study of gluon transverse-momentum dependent PDFs*, JHEP **03** (2024) 088, arXiv:2311.14085.

[38] LHCb collaboration, R. Aaij *et al.*, *Measurement of associated $J/\psi - \psi(2S)$ production cross-section in pp collisions at $\sqrt{s} = 13$ TeV*, arXiv:2311.15921, submitted to JHEP.

[39] LHCb collaboration, R. Aaij *et al.*, *Prompt and nonprompt $\psi(2S)$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV*, arXiv:2401.11342, to appear in JHEP.

[40] LHCb collaboration, R. Aaij *et al.*, *Measurement of forward charged hadron flow harmonics in peripheral PbPb collisions at $\sqrt{s_{NN}} = 5$ TeV with the LHCb detector*, arXiv:2311.09985, to appear in Phys. Rev. C.

[41] LHCb collaboration, R. Aaij *et al.*, *Amplitude analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay*, Phys. Rev. Lett. **132** (2024) 131801, arXiv:2312.09115.

[42] LHCb collaboration, R. Aaij *et al.*, *Determination of short- and long-distance contributions in $B^0 \to K^{*0}\mu^+\mu^-$ decays*, Phys. Rev. **D109** (2024) 052009, arXiv:2312.09102.

[43] LHCb collaboration, R. Aaij *et al.*, *Measurements of the branching fraction ratio $\mathcal{B}(\phi \to \mu^+\mu^-)/\mathcal{B}(\phi \to e^+e^-)$ with charm meson decays*, arXiv:2402.01336, submitted to JHEP.

[44] LHCb collaboration, *RICH Performance Plots - Cherenkov Angle Resolutions for RICH 1 and RICH 2*, LHCb-FIGURE-2023-007, 2023.

[45] LHCb collaboration, *Charged hadron identification performance with early Run 3 data*, LHCb-FIGURE-2023-019, 2023.

[46] C. Bozzi, *LHCb Computing Resources: 2025 requests* , CERN, Geneva, 2024.

[47] C. Bozzi, *LHCb Computing Resource usage in 2023* , CERN, Geneva, 2024.

[48] LHCb collaboration, *LHCb particle Identification Enhancement TDR*, CERN-LHCC-2023-005, 2023.

[49] European Strategy Group, *Deliberation document on the 2020 update of the European Strategy for Particle Physics*, CERN-ESU-014, 2020.

[50] Large Hadron Collider Committee, *LHC Experiments Phase IIb Upgrades Approval Process*, CERN-LHCC-2022-012, 2022.