Project LHCb Upgrade II at IN2P3

LHCb IN2P3 collaboration

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1 Overview of the LHCb Upgrade II project

1.1 Introduction

The LHCb collaboration plans a major upgrade of its detector to operate during the High-Luminosity phase of the Large Hadron Collider (LHC), called LHCb Upgrade II [1–3], and to maximize the outcome of the LHC physics program for Heavy Flavour Physics. A first version of the detector [4] collected about $9\,\mathrm{fb}^{-1}$ of data during Runs 1 and 2 (2011 – 2018). A first upgrade of the detector, Upgrade I [5], started operation in 2022 at the beginning of Run 3 (2022 – 2026) and will increase the collected statistics to $50\,\mathrm{fb}^{-1}$ at the end of Run 4 (2030 – 2033). The Upgrade II detector is expected to increase the recorded luminosity up to a total of more than $300\,\mathrm{fb}^{-1}$ at the end of Run 5 (2036 – 2041). The physics program of the experiment extends the original focus on the flavour physics sector described in Section 1.2 to include the study of Heavy-Ion physics, described in Section 1.3.

1.1.1 Detector design, timeline and challenges

In order to achieve the integrated luminosity goals, the instantaneous luminosity will be increased to a maximum value of $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ compared to the current value of $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. A new detector must be built to sustain higher multiplicities, and installed during the LHC Long Shutdown 4 (LS4, 2034 – 2035). Its geometry will be similar to the current detector, covering the forward region of the pp collisions. The various components are shown on Figure 1. The main technical requirement is to cope with the higher number of visible pile-up interactions (up to 40) by increasing the granularity of the detectors, by designing detector sensors capable of withstanding high radiation doses and by adding the ability to measure the time of the arrival of the particles in the detectors with an accuracy of the order of 10 ps. The latter is due to the size of the interaction region at LHCb, where the primary vertices distribution has a spread of the order of 100 ps.

The tracking and vertexing system is composed of

- the Vertex Locator (VELO), with 3D silicon sensors and 50 ps single hit time resolution.
- the Upstream Pixel Tracker (UP), made of four planes of silicon Depleted Monolithic Active Pixel Sensors (DMAPS) in the CMOS technology; it plays a critical role in tagging good tracks and rejecting mismatched associations between VELO and Mighty Tracker primitives, which, in the absence of UP, would result in an unsustainable number of ghost tracks.
- the Magnet Stations, a scintillating fibre detector installed inside the dipole magnet, on its sides, to reconstruct soft charged tracks with a momentum below $5\,\mathrm{GeV}/c$.

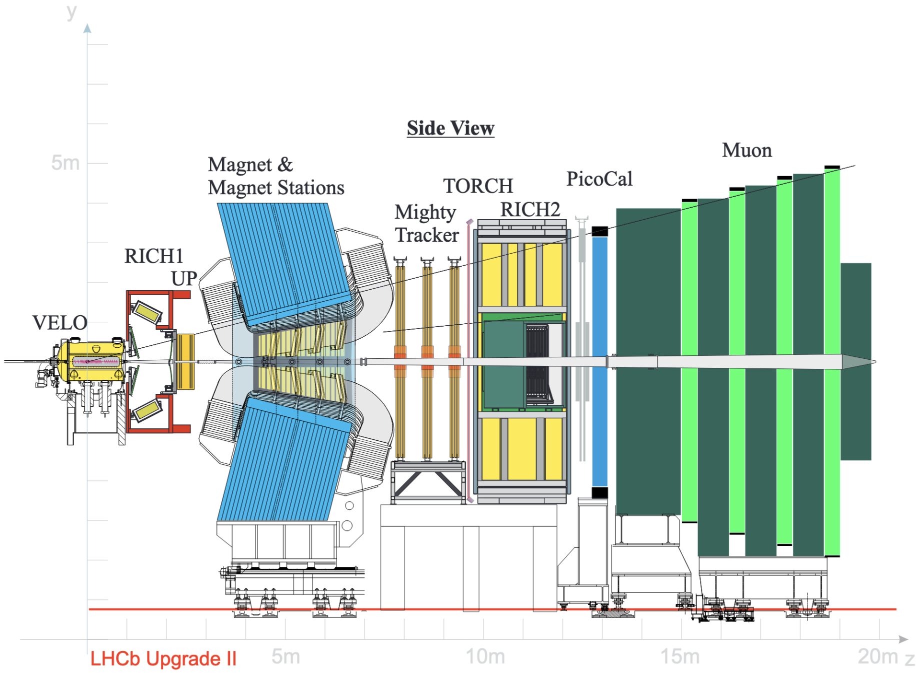

Figure 1: LHCb Upgrade II detector.

- the Mighty Tracker, consisting of three tracking stations, with mixed technology: scintillating fibres in the outer part and DMAPS silicon pixels in the inner part close to the beam pipe.

The Mighty Tracker Pixel part and UP share similar requirements. The LHCb collaboration is currently making concerted efforts to converge on the same DMAPS sensor for both sub-detectors. This helps to reduce the resources required for various aspects of the projects: module design and assembly, power supply, cooling system, data acquisition and concentration chain, test beams, etc.

The particle identification system is composed of

- the RICH1 and RICH2 detectors, imaging detectors based on the the Cherenkov effect, with high-granularity photo-detectors capable of time measurements of the order of 10 ps precision.

- the TORCH detector, for precise (15 ps) time-of-flight measurements and low ($< 20\,\mathrm{GeV}/c$) momentum particle identification.

- the PicoCal calorimeter, described in more details in Section 2.

- the Muon detector, made of 4 stations, equipped with Multi Wire Proportional Chambers (MWPC) and μ-RWELL chambers in the inner regions where the rates are very high.

In the LHCb Upgrade II baseline configuration, the design of the detectors will match or exceed the performances of the current detector while two new sub-systems, the Magnet Stations and TORCH, will enhance LHCb's capabilities in the low-momentum range. The requirements on the tracking systems, in particular on the UP, significantly benefit the Heavy-Ion program, providing access to the full centrality range of PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.5\,\mathrm{TeV}$ while centralities are limited to up 30% in PbPb collisions with LHCb Upgrade I.

The large number of channels and data rates from the detector put important constraints on the design of the readout and data processing chains, both online and offline. Following the success of the 2024 data taking, which met or exceeded the objectives set for LHCb Upgrade I, the same data processing logic will be used for the Upgrade II, with a full event reconstruction and selection in real time (RTA) at the 40 MHz bunch crossing rate. Details on the readout and RTA are given in sections 4 and 3.

A scoping document for LHCb Upgrade II [6] was submitted in September 2024 to the LHC experiments committee (LHCC) for review. The outcome of the review is expected in March 2025, with the final decision to approve the project taken by the CERN Research Board shortly thereafter. The next step will be the preparation of the Technical Design Reports (TDR) of the sub-systems at the end of 2026. The construction phase will take place between 2027 and 2033, when the installation will be done during LS4 (2034 – 2035). Exploitation of the new detector will start in 2036. Given the high complexity of the project, the experience gained for LHCb Upgrade I, concerning procurement of the components, ASIC and firmware developments and commissioning will be highly beneficial to the project.

The planning for the different detectors is shown in Figure 2. The installation period for LS4 is only two years. Therefore, as much infrastructure work as possible will be carried out during LS3 (2026 – 2029). In particular, the electromagnetic calorimeter mechanical and electronics infrastructure needed for Upgrade II will be installed at that time [7], where the LAPP, LPCA and IJCLab IN2P3 groups will be involved. A new version of the generic readout board, PCIe400 [8] is being designed and built for use by the enhanced RICH detector [7] and the Downstream Tracker (DWT) custom processor [8]. IN2P3, with the CPPM, LAPP, LPNHE, IJCLab and Subatech groups, is leading the PCIe400 project.

In several areas, the LHCb Upgrade II project requires challenging and ambitious developments that go beyond the state of the art: 10 ps precision measurements, highly integrated and radiation tolerant silicon sensors, high throughput data transfers with the most powerful FPGAs, heterogeneous computing for real time data processing, reconstruction with machine learning and artificial intelligence algorithms. These developments will be important to prepare the future generations of particle physics experiments and to maintain a high level of competences in the IN2P3 groups.

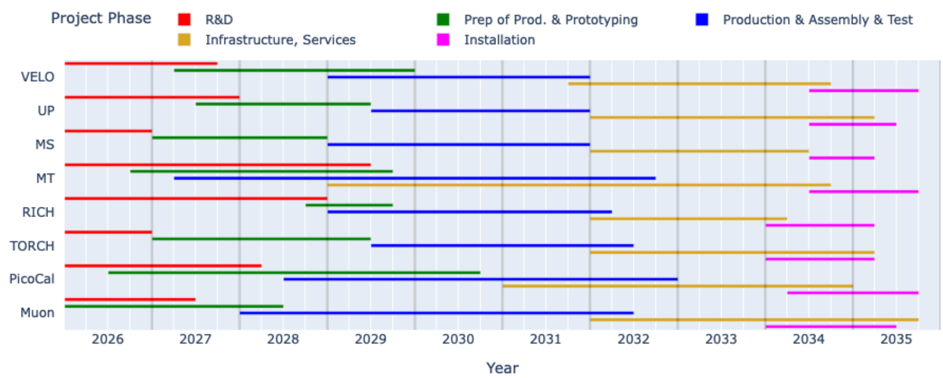

Figure 2: Outline schedule for the R&D, construction, near-detector infrastructure, and installation of the subdetectors.

1.1.2 Scoping options

Three scenarios (Baseline, Middle and Low) have been prepared [6]. Each has different options for each sub-detector, reducing costs and performance compared to the Baseline. The costs are shown in Table 1.

There are also two options for the LHC to provide collisions at the LHCb interaction point: round optics ($\beta_x^* = 1.5\,\mathrm{m}$, $\beta_y^* = 1.5\,\mathrm{m}$), similar to the one currently used and flat optics ($\beta_x^* = 1.5\,\mathrm{m}$, $\beta_y^* = 0.5\,\mathrm{m}$). The flat optics configuration allows the LHC to achieve a high potential instantaneous luminosity at LHCb. As the luminosity at LHCb is leveled, the duration of the leveling is longer with flat optics than with round optics, and the total integrated luminosity will also increase. The estimates given in the scoping document are based on the round optics, as the flat optics configuration requires further studies by LHC experts before it can be adopted as a solution.

The reduced peak luminosity in the Middle and Low scenarios relaxes the detector requirements in terms of radiation tolerance and data rates. In particular, this leads to a reduction of the online trigger farm.

Compared to the Baseline scenario, the area covered by the silicon pixels in the Middle scenario can be reduced due to the lower occupancy and the granularity of RICH and MUON detectors. The acceptance of the TORCH detector is decreased by 25%. The VELO, UP and PicoCal specifications remain largely unchanged. Given the reduction in peak luminosity, the performances of the detector will still be similar to that of the Baseline ones, but with less redundancy.

The Low scenario does not include the two new detectors, TORCH and the Magnet Stations. Acceptance of the tracking detectors is reduced, and the VELO is built with an increased material budget to use simpler sensor designs. The RICH2 detector retains the current optical system of Run 3 and 4. The longitudinal segmentation in the PicoCal is removed in the outer areas, reducing the number of readout channels. While still maintaining good performances for important

Table 1: Cost estimates for the LHCb Upgrade II detector scenarios.

	Baseline	Middle	Low
$\mathcal{L}_{\text{peak}}$ ($10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)	1.5	1.0	1.0
Total recorded $\mathcal{L}_{\text{int}}$ (fb^{-1})			
round optics	297	262	262
flat optics	367	294	294
	(kCHF)	(kCHF)	(kCHF)
VELO	16672	15906	13753
UP	8077	7719	6887
Magnet Stations	2592	2234	0
Mighty-SciFi	21767	21273	17388
Mighty-Pixel	15994	11641	11061
RICH	21450	18415	14794
TORCH	12508	8756	0
PicoCal	27607	27607	21584
Muon	9785	8266	8266
RTA	18800	11700	9500
Online	11800	9467	8993
Infrastructure	14463	13284	12430
Total	181515	156268	124656

heavy flavour measurements, the degradation of performances and the reduction of acceptance in the Low scenario will affect a large fraction of the physics programme, such as the study of rare decays or lepton flavour universality studies, which require excellent tracking and PID performances. The ability to reconstruct the most central PbPb collisions in the Low scenario is also at risk.

1.1.3 LHCb at IN2P3

In 1998, five institutes from IN2P3 joined the collaboration during the initial construction of LHCb, before the start of the experiment in 2009, with an interest in the heavy flavour physics program: LAPP Annecy, LPCA Clermont-Ferrand, CPPM Marseille, IJCLab Orsay and LPNHE Paris. LLR physicists joined the collaboration at the beginning of Run 2. LLR Palaiseau became full member in 2020. The IN2P3 community currently comprises 34 permanent researchers (chercheurs du CNRS or enseignant-chercheurs des universités), 15 post-docs and 29 PhD students.

At the beginning of Run 2, due to the very good performances of the LHCb detector for the reconstruction of charm and beauty hadrons, a heavy ion physics program was initiated, in particular by physicists from the IN2P3 IJCLab and LLR. It uses collisions of Pb ions from the LHC and also fixed-target collisions with a gas target, as described in Section 1.3. The CEA Saclay, with physicists who were previously members of the ALICE Collaboration, joined this program as a full member in June 2024. Subatech Nantes also joined as a technical associate in June 2024. In addition, about 20 physicists from IN2P3, currently members of the ALICE Collaboration, have expressed interest in participating in LHCb Upgrade II at the end of Run 4. They come from LPCA Clermont-Ferrand, IJCLab Orsay and Subatech Nantes.

Based on historical involvements, the IN2P3 community has proposed contributions to the LHCb Upgrade II project:

- Calorimeters with the contribution to the PicoCal project described in Section 2;

- Data acquisition and real time analysis, with the contributions to the Online project described in Section 4 and to the RTA project described in Section 3;

In addition, the LLR and Subatech teams, together with the CEA Saclay group propose to contribute to the UP detector, starting from a common R&D phase on Mighty Tracker and UP projects. The UP detector is crucial for carrying out the proton-proton at high pileup and the Heavy-Ion physics program with LHCb Upgrade II.

The Subatech laboratory has historical contributions to the design, development, construction, maintenance and operations of the tracking detectors of STAR (SSD) and ALICE (ITS-SSD, muon chambers, muon trigger, MFT) experiments at RHIC and LHC. This experience and expertise, with the full support of the technical services, will be a strong asset to this R&D phase. In addition to its contributions to the PicoCal, PCIe400 and RTA projects, Subatech aims to play substantial role in the R&D and in the construction of the LHCb Upgrade II tracking system. This involvement follows the interest of the group, and more globally the interest of the French Heavy-Ion community, for the LHCb physics program, and the demonstrated necessity of a new MAPS-based tracking system.

The contribution of Subatech to the R&D of the module conception for the future MAPS pixel tracker shall cover mechanical, thermal, electrical, electronics and readout design aspects. The design and exploitation of a mechanical test bench to explore cooling solutions is foreseen, as well as the design and production of a test bench for the readout chain from the sensor to the PCIe400 readout board. For the laboratory, this major contribution to the R&D will be the opportunity to acquire the knowledge and the equipment to be part of the production phase. In close collaboration and synergy with the other actors of the LHCb Pixel Tracker Project, the Subatech group is willing to contribute to the qualification of the detector modules, to ensure the design of the detector's mechanical structure and the integration of the modules in the detector and to contribute to the commissioning phase. This would ensure an important and durable involvement of Subatech into LHCb operations in the Upgrade II phase.

LLR has expressed particular interest in contributing to the implementation of a functional testing platform, including characterization studies that could lead to performance evaluations of ASIC solutions proposed for this project. The LLR laboratory has demonstrated its expertise in this area through the work on the CMS/HGCAL experiment, where it characterized HGCROC ASICs, and the HK experiment, where it characterized HKROC ASICs. Additionally, the LLR group could potentially participate in the validation of chip production before their integration into the front-end electronics of the detector.

1.2 Heavy flavour, spectroscopy and electroweak physics case

The vastly increased data sample together with the improvements in the Upgrade II detector will provide access to several new observables and reduce the uncertainties of other key measurements to levels comparable to their theoretical predictions. The expected future uncertainties for a large number of key flavour observables are expected to be the best in the world. The sensitivity to quantum imprints of new particles will extend the discovery potential of New Physics (NP) to energy scales of 10 TeV and far beyond what is currently possible at the energy frontier. This section describes the physics potential for flavour physics, as well as hadron spectroscopy and electro-weak physics for Upgrade II. As the full physics case is quite broad not all topics are covered in this section, however they are extensively documented in Ref. [3]. The topics presented here cover the interests of the IN2P3 groups.

1.2.1 Standard Model benchmarks

The only source of *CP* violation in the Standard Model (SM) arises in the Cabibbo–Kobayashi–Masakawa (CKM) quark-mixing matrix. Matter-antimatter asymmetries arising from this source are observable only in a limited and clearly predicted set of decays of heavy flavour hadrons. The size of *CP* violation in the SM is insufficient, by several orders of magnitude, to explain the observed matter-antimatter asymmetry of the Universe. Consequently, there must be additional sources of *CP* violation in nature beyond the SM. Moreover, many NP models predict new *CP*-violating processes. This motivates searches for *CP*-violating NP effects in as wide a range of decays as possible.

Searches for *CP*-violating NP processes require precise determination of the SM benchmarks, *i.e.* measurements that can be related to the fundamental SM parameters with minimal theoretical uncertainty. The total amount of *CP* violation in the quark sector of the SM is governed by the position of the apex of the CKM unitarity triangle which can be constrained using several complementary measurements. This apex can be determined using only tree-level processes (CKM angle γ and magnitudes of the CKM elements V_{ub} and V_{cb}) or instead, using flavour-changing neutral-current (FCNC) loop-level processes (CKM angle β and measurements of neutral B-meson oscillation frequencies, Δm_d and Δm_s). By over-constraining the CKM model, *CP*-violating NP processes can become manifest through tensions between tree- and loop-level determinations.

The golden SM benchmark is the CKM angle γ, which can be determined with negligible theoretical uncertainty entirely from tree-level processes such as $B^- \to DK^-$ decays. Several complementary methods for determining γ involve different intermediate neutral D meson decays, including decays with π^0 mesons in the final state, and their dominant systematic uncertainties arise from different sources. This provides robustness against systematic uncertainties that may affect particular analyses. Current estimates of the relevant effects indicate that systematic uncertainties will remain subdominant even with the full LHCb Upgrade II sample size.

The latest data from LHCb give a "direct" measurement of γ with a precision better than 3° [9, 10]. This can be compared to the precision obtained by predicting the value from other measurements of the CKM matrix elements, which is 1°. With LHCb Upgrade II, the precision of the "direct" determination from $B^- \to DK^-$ and similar decays will be improved down to 0.35°. Along with direct measurements the family of $B \to K_S hh$ decays which are dominated by loop-induced transitions offer additional sensitivity to the angle γ. The Belle II precision on γ is foreseen to be $\mathcal{O}(1°)$ with the full anticipated dataset of 50 ab^{-1} [11]. This will make γ the most precisely determined SM benchmark of the CKM paradigm against which all other CKM observables can be compared. This unparalleled level of precision will open up completely new areas of study allowing, for example, probing NP at tree level.

There are also excellent prospects for measurements of $|V_{ub}|$ and $|V_{cb}|$ with the Upgrade II detector. Several modes currently inaccessible, *e.g.* those involving decays of B_c^+ mesons, will become feasible with the large Upgrade II dataset. Furthermore, the planned detector improvements will greatly enhance opportunities for V_{ub} extraction with the $B_s^0 \to K^-\mu^+\nu_\mu$ decay.

1.2.2 New Physics in *CP* violation

The *CP*-violating weak phase associated to B_s^0–$\overline{B}{}_s^0$ oscillations, ϕ_s, is a particularly sensitive probe of NP models as it is both extremely small and very precisely predicted in the SM, so that subtle NP contributions can be detected. The SM prediction, $\phi_s = 37 \pm 1\,\text{mrad}$, comes from the SM benchmarks mentioned in the previous section. The latest LHCb ϕ_s measurement [12] is approaching the sensitivity needed to observe a non-zero value, and this milestone may be achieved with data available before the end of Run 4. The improvement in uncertainty to the $\mathcal{O}(1\,\text{mrad})$ level made possible by Upgrade II will provide the ultimate test of compatibility of this phase with its SM prediction. Importantly, this includes studies of a number of different $b \to c\bar{c}s$ decay modes, including polarisation-dependent measurements in $B_s^0 \to J/\psi\phi$ decays, as well as processes related by flavour symmetries, for example $B_{d,s}^0 \to J/\psi\pi^+\pi^-$ decays. This will allow the origin of a deviation from the prediction to be disentangled as being due to either NP or a subleading SM amplitude.

The phase ϕ_s can also be extracted from decays to final states that proceed only through loop processes such as $B_s^0 \to \phi\phi$ and $B_s^0 \to K^{*0}\overline{K}^{*0}$. These decays are highly sensitive to NP, since virtual particles contribute to both the mixing and decay amplitudes. Furthermore, flavour symmetry relations between $B_s^0 \to K^{*0}\overline{K}^{*0}$ and $B^0 \to K^{*0}\overline{K}^{*0}$ can be used to constrain precisely contributions from subleading SM amplitudes, greatly reducing the theoretical uncertainty in interpretation of the results. *CP* violation in both B^0–$\overline{B}^0$ and B_s^0–$\overline{B}_s^0$ mixing is also expected to be extremely small in the SM, and therefore provides an excellent null test through which NP can be searched for. The measurements are typically made using semileptonic decays, with observables denoted $a_{\rm sl}^{d(s)}$ for the $B_{(s)}^0$–$\overline{B}_{(s)}^0$ systems. The existing LHCb results [13, 14] are already world-leading, and a significant improvement in sensitivity can be achieved with Upgrade II.

1.2.3 New Physics in charm

Charm hadrons provide a unique opportunity to study *CP* violation in FCNC transitions involving up-type quarks. These can be affected by NP contributions in fundamentally different ways than the down-type quarks in the kaon and beauty systems are. Since the level of *CP* violation expected in the charm system is extremely small, $\mathcal{O}(10^{-4})$, it potentially provides a very sensitive NP probe, but uncertainties related to long-distance QCD interactions limit the precision of the theoretical predictions. LHCb has made the first observation of *CP* violation in charm decays [15] with a measurement of the asymmetry difference $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$ consistent with, but at the top end of, the range of SM predictions. Further measurements with other processes, also including π^0 mesons in the final state, are necessary to understand whether the observed *CP* violation can be explained within the SM.

In particular, measurements of *CP* violation in the D^0–$\overline{D}^0$ mixing, which is expected to be at the $\mathcal{O}(10^{-5})$ level [16], are crucial. The non-zero value of ΔA_{CP} shows clearly that there are two amplitudes with different weak and strong phases contributing to at least one of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays. Determination of individual *CP* asymmetries [17] helps to pin down where the effect comes from, but further input is essential to understand to what extent each *CP* asymmetry is driven by a larger-than-expected ratio of the magnitudes of the two amplitudes or by the strong phase difference, and thus to establish whether the observed value of ΔA_{CP} can be explained by the SM or not.

LHCb Upgrade II is the only experiment, existing or planned, that can achieve the necessary precision to understand whether charm *CP* violation is caused by NP.

1.2.4 New Physics with lepton flavours

The absence of tree-level FCNC transitions is a feature that is highly specific to the SM. There is no fundamental necessity for the cancellation of these processes, and consequently generic NP models often provide sources of FCNCs. Decays which can proceed only through FCNCs are therefore highly sensitive probes of NP, as the NP amplitudes are potentially large compared to the small SM contribution.

Historically, the golden channel for NP searches in FCNC b-hadron decays has been $B_s^0 \to \mu^+\mu^-$. LHCb was the first experiment to observe independently this extremely rare ($\mathcal{B} \sim 10^{-9}$) decay and in the latest analysis [18, 19] it appears that a hint of the even-further suppressed, 30 times rarer, mode $B^0 \to \mu^+\mu^-$ is starting to emerge. Together, measurements of these two branching fractions provide extremely powerful tests of the SM with ability to discriminate between different NP models, in particular testing the minimal flavour violation NP scenario. Recently, LHCb set limits on the branching fraction of $B_s^0 \to \mu^+\mu^-\gamma$, where the photon is reconstructed. This channel offers sensitivity to a different range of short distance effects [20].

With the Upgrade II dataset, LHCb will additionally have capability to measure the parameters $A_{\Delta\Gamma}^{\mu\mu}$ and $S_{\mu\mu}$ of the $B_s^0 \to \mu^+\mu^-$ decay-time distribution. These are considered smoking gun observables that, if different from their SM expectations of unity and zero respectively, would provide unambiguous evidence for NP.

An enticing possibility is that NP may be causing these deviations exclusively in $b \to s\mu^+\mu^-$ and, perhaps, $b \to d\mu^+\mu^-$ processes while leaving the corresponding $b \to se^+e^-$ and $b \to de^+e^-$ transitions at their SM rates. This would provide striking violations of lepton flavour universality, which could not be caused by any SM process. Although the hints seen in early LHCb measurements of the branching fraction ratios R_K and R_{K^*} were not confirmed in improved analyses with larger data samples [21, 22], this remains a powerful way to probe for NP in which LHCb Upgrade II has unparalleled precision.

The chiral structure of the weak interaction is a further distinctive feature of the SM that is not necessarily replicated in NP scenarios. New right-handed currents that appear at high energy scales could, through quantum-loop effects, leave an imprint on the polarisation of the photon emitted in $b \to s\gamma$ processes. This can be probed through several different methods, including studies of the angular distribution in $B^0 \to K^{*0}e^+e^-$ decays at low e^+e^- invariant mass, studies of the decay-time distribution in $B_s^0 \to \phi\gamma$ decays, and studies of the angular distributions in $\Lambda_b^0 \to \Lambda\gamma$ decays. The last two of these methods are unique to LHCb, and with the Upgrade II data sample the former will also be measured more precisely than at any other experiment.

Lepton-flavor universality in the charged-current $b \to c\tau^-\overline{\nu}_\tau$ decays will be comprehensively explored across all b-hadron species at LHCb Upgrade II. To fully explore and identify potential NP contributions requires much higher precision in the core lepton universality ratios, particularly in the much-rarer B_c^+ system, as well as exploration of differential decay distributions to access short distance information via Wilson coefficients. Such multiply-differential measurements require large datasets as expected in Upgrade II, due to the high dimensionality involved. A full understanding of the SM itself and the exclusion or understanding of NP suggests also the exploration of the related $b \to u\tau^-\overline{\nu}_\tau$ decays.

1.2.5 Hadron spectroscopy

The enormous production rates for heavy quarks in LHC collisions mean that an unprecedented range of hadrons are formed, making it the ideal laboratory to study spectroscopy, in particular of the so-called exotics, *e.g.* pentaquarks. Whilst the existence of hadrons with exotic quark content was suggested in the original formulations of the quark model, there is not yet a clear understanding of how these states interact and decay. Many states appear near the mass thresholds, suggesting a possible molecular or hadron rescattering interpretation. However some exotic states cannot be explained in this way, indicating that models involving tight binding may play a role. Experimental measurements of the properties of these new states are of the utmost importance because it is extremely difficult to make first-principle predictions of the excitation spectrum and widths of such multi-quark states due to the nonperturbative nature of QCD at low energies.

LHCb Upgrade II has unique potential to study hadron spectroscopy. With the significantly increased data sample, the main limitation on which states can be observed are due to detection capability, and therefore the improved performance of the detector will have a direct impact on the physics output in this area. Among a huge number of possible discoveries, it is anticipated that observations of many doubly heavy hadrons ($\Xi_{bb}^{+,0}$, Ω_{bb}), both conventional and exotic, will become within reach.

In addition to studies of prompt production, it will become possible for the first time to study production of exotic hadrons with open or hidden charm in B_c^+ meson decays, extending the mass range that is currently accessible in B^0, B^+, B_s^0 or Λ_b^0 decays. Many other approaches will also become within reach with the Upgrade II dataset.

1.2.6 QCD and Electroweak physics

LHCb's geometry and momentum coverage provide access to a kinematic region that is not accessible at other LHC experiments. This has enabled a unique programme of electroweak and QCD measurements, particularly in muonic W and Z decays, at the current experiment that were not foreseen in its original design. For example, determination of the W mass in the forward acceptance can strongly suppress the uncertainty related to knoweldge of the parton distribution functions (PDFs) in the LHC W mass average, due to geometry of the LHCb detector being complementary to that of ATLAS and CMS [23, 24]. The forward geometry also allows increased sensitivity in determinations of the weak mixing angle from pp

collisions [25, 26]. Such measurements play an important role in both direct measurement of electroweak quantities but also in reducing uncertainties relating to knowledge of gluon PDFs, which are important inputs to Higgs analyses and NP searches at ATLAS and CMS. Indeed, PDF related uncertainties are expected to become the limiting factor on the weak mixing angle determination [27].

These various measurements will continue to be important into the Upgrade II era. With the Upgrade II dataset LHCb is projected to measure the W mass with a precision of a few MeV.

1.3 Heavy Ion Physics case

The field of ultra-relativistic nuclear collisions has seen enormous progress since its inception in the mid-eighties, from the first signals of colour deconfinement at the SPS to the evidence, at RHIC, for a strongly-coupled QCD medium that quenches hard partons. Nuclear collisions at the LHC offer an ideal environment for a broad program of characterisation of the properties of this unique state of matter. Besides providing access to the highest-temperature, longest-lived experimentally accessible QCD medium, they also offer an abundant supply of self-calibrating heavy-flavour probes. In addition, the very low net baryon density eases significantly the quantitative connection between experimental measurements and lattice QCD calculations.

Full completion of the LHC heavy ion program will require running heavy ion collisions at the LHC until the end of the LHC operation. LHC experiments will pursue the exploration of the strongly interacting matter phase diagram (QCD matter) with better precision, new observables (like multi-charm hadrons, high precision beauty, P-wave quarkonia, ...) and varying collisions systems.

In particular Run 5 will be crucial in understanding the onset of collectivity in small systems [28] and its evolution with the size of the system. The origin of the collective-like phenomena observed to date in very light systems such as high-multiplicity pp collisions can be studied in detail by measuring intermediate systems between pp and PbPb collisions, such as the pA, OO, ArAr or XeXe systems or with other species that can be accelerated in the LHC.

Experimental research of the Quark-Gluon Plasma (QGP) at RHIC and LHC Runs 1 and 2 during the last 20 years, has established a convincing paradigm describing key features of heavy-ion collisions as flow, energy loss, and quarkonium physics at colliders as due to the formation of a strongly coupled QGP. However, this picture remains in key areas qualitative. A deeper understanding of the inner workings of the emergence of QGP, its properties and its transition to hadrons, *i.e.* the microscopic picture behind the initial state, the thermalisation, deconfinement and hadronisation is required.

LHCb is the only detector at the LHC containing a set of sub-detectors for vertexing , tracking, particle identification and energy reconstruction in the phase space region $2 < \eta < 5$. It offers excellent capabilities in separating "prompt" charm hadrons coming from the collisions from those coming from b decays, since this is crucial for the Heavy Flavour physics program described earlier. Its tracking detectors provide reconstruction of charged tracks down to transverse momentum $p_T = 0$ with good resolution. Beauty and charm decays can then be reconstructed also in purely hadronic final state in contrast to measurements performed with muons from semi-leptonic decays where the momentum of the particles cannot be measured fully. Finally, the LHCb detector is the unique detector at LHC capable in running in a fixed-target mode, which, since the beginnig of Run 3, consists in a storage cell (SMOG2) installed upstream of the VELO in which several gases can be injected (H_2, D_2, He, Ne, Ar). Among the various physics case for heavy ion physics, achievable with the LHCb detector, IN2P3 and CEA teams are particularly interested in the topics detailed in the following sections.

1.3.1 Bulk properties

Bulk physics refers to the study of collective phenomena in ultra-relativistic nucleus-nucleus collisions. These phenomena are sensitive to the non-perturbative QCD interactions between soft particles and can be used to infer the quantities that characterize the system such as the temperature or the velocity field which are related to other quantities, such as the entropy density via the Equation of State (EoS). At the LHC, most theoretical calculations assume longitudinal symmetry of the initial temperature profile, meaning that T is independent of rapidity y. However, the rapidity density of prompt charged particles $\mathrm{d}N/\mathrm{d}y$ is not constant [29]. The final multiplicity is smaller at large rapidities for the same transverse interaction region. Therefore, since different temperatures can be accessed by solving the hydrodynamic equation for different values of $\mathrm{d}N/\mathrm{d}y$ the unique forward acceptance of the LHCb experiment allows the study of the QCD EoS at different temperatures. Within the LHCb acceptance, the effective temperature range is about $T_{\text{eff}} \in [190, 225]$ MeV [30]. Some of the quantities that can be studied as a function of temperature for the first time are the speed of the sound, medium viscosity and quarkonia suppression.

In addition to the thermodynamics of the equilibrium QGP, the out-of-equilibrium phase of the collision prior to the hydrodynamic regime is of major interest since it is the only thermalisation of a non-abelian standard-model matter observable in the laboratory. So far, this phase is difficult to access experimentally, since any hadronic observable only decouples to a later time. Electromagnetic probes living at the scales of these early times of a few GeV and in particular dileptons are sensitive to the isotropisation of the energy-momentum tensor and of the chemical equilibration from a gluon-dominated system to a QGP. LHCb offers excellent opportunities for the detection of prompt dimuons in the mass range of 1.5 to 8 GeV with the excellent secondary vertexing (rejection of heavy-flavour background), muon-PID (rejection of hadronic backgrounds) and mass resolution (rejection of quarkonium resonances) [31, 32].

1.3.2 Heavy-quarks

Heavy Flavour (HF) production has long been recognized as a key probe for exploring both QCD and the QGP properties. Open HF states such as D^0, Λ_c^+, B^0 are often used as tomographic probes of the deconfined medium [33]. With the first two LHC runs, the coalescence mechanism at constituent quark level has become increasingly popular to describe HF production in heavy-ion collisions, despite not yet completely understood. While some models let quarks coalesce when they are close in the phase space, other approaches use colour strings, such as the string Colour Reconnection implemented in PYTHIA. Alternative approaches [34], which also succeed in explaining data, replace coalescence or colour reconnection possible effect by contribution with feed-down from excited states.

Owing to its unique design optimized specifically to study HF decays, the LHCb detector already stands as a major contributor to HF production studies, especially in *pp* and *p*Pb collisions. For instance, LHCb has pioneered the measurements of double charm production in *p*Pb collisions [35] and has made substantial contributions to the investigation of exotic states such as the $\chi_{c1}(3872)$ hadron [36]. The extended capabilities of the detector in Run 5 will enable measurements of the charm and beauty baryon-to-meson ratios in the very central PbPb collisions, where the QGP is the hottest. The increased reach in centrality together with the high statistics will open new possibilities for tomographic studies of the QGP. Moreover, charm and beauty quark density varies strongly winthin the LHCb acceptance. This variation of the "QGP-heavy-quark-doping" has proven to be decisive to iron out qualitatively different scenarios at RHIC and at LHC. Together with the centre-of-mass energy provided by the LHCb fixed-target (see section 1.3.5), it is the most important lever arm to discriminate between different production mechanisms of heavy quarkonium [37]. The measurement of the production of multi-heavy-flavor hadrons, like B_c mesons and Λ_{cc}, Ξ_{cc}, and Ω_{cc} baryons, is an additional and powerful handle to understand the interplay between thermalization and hadronization of charm quarks in particular the prominent role of coalescence or regeneration mechanisms. The excellent vertexing and particle identification capabilities of LHCb and its forward large acceptance are crucial here.

1.3.3 Quarkonia

Bound states of heavy quark-antiquark pairs have long been studied as a probe of the QCD medium formed in heavy-ion collisions. Due to their large masses, $c\bar{c}$ and $b\bar{b}$ pairs are created at the early stages of the collision before QGP formation and are affected by the deconfined medium. Colour-charge screening and medium-induced dissociation can prevent the formation of quarkonium bound states [38]. Excited states with lower binding energies and larger radii should be more suppressed as they are expected to dissociate more easily in the QGP. So far, all quarkonium measurements performed in ion-ion collisions at the LHC are for S-wave vector states $(J/\psi, \psi(2S), \Upsilon(1S), \Upsilon(2S), \Upsilon(3S))$ [39–42], because they have significant branching fractions to dilepton final states that can be easily reconstructed. However, their prompt productions include contributions from direct production and feed-downs from excited state decays which are not necessarily S-waves vector states. $1P$-wave states such as χ_c and χ_b constitute a large fraction of the total production. To have a quantitative understanding of quarkonium production in medium, measurements of $\chi_{c/b}$ feed-downs to S-wave vector states in ion-ion collisions are mandatory. LHCb Upgrade II with its upgraded calorimeter offers great potential to provide new and unique measurements of $\chi_{c/b} \to (\psi/\Upsilon)\gamma$ decays. Moreover, thanks to its extended capabilities in reconstructing very central PbPb collisions, LHCb will offer the opportunity to thoroughly explore the interplay between charmonium suppression and regeneration mechanisms at TeV scale energies.

1.3.4 Saturation

At high collision energy, the phenomenon of gluon saturation has been predicted to occur in hadrons at small fractional longitudinal momentum. The search for saturation is one of the major motivations for hadron structure measurements at the LHC, in particular at forward rapidity. This is key motivation for the study of Drell–Yan, the study of quarkonium photoproduction and other channels to be explored in ultra-peripheral collisions, or the study of electroweak bosons, where LHCb will provide unique measurements in its rapidity coverage with an excellent momentum resolution. The availability of hard exclusive and inclusive production in hadro- and photo-production over a broad kinematic domain, highly complementary to the upcoming electron-ion collider, using collider and fixed-target mode data, complements the hadron structure physics case.

1.3.5 Fixed-target physics program

Starting from 2015, under the initiative of IN2P3 teams, LHCb has been using its unique capability to inject gas in the LHC beam pipe with the System of Measuring Overlap with Gas (SMOG) to function as a fixed-target experiment, studying beam-gas data at a $\mathcal{O}(100)$ GeV energy in the nucleon-nucleon centre of mass frame. Thanks to the LHCb rapidity coverage and to the boost induced by the incoming beam with several TeV energy, the fixed-target setup allows to explore a large part of the negative rapidity hemisphere in the centre-of-mass frame, providing unique inputs to theoretical models in several fields of research in the poorly explored high-x and moderate Q^2 kinematic region. During LS2 (2019 – 2021), the fixed-target system has been upgraded to SMOG2 [43], a 20-cm-long storage cell installed 31 cm upstream of the nominal LHCb interaction point. With respect to the previous system, this offers instantaneous luminosity up to two orders of magnitude larger for the same gas flow and more gas possibilities, including non-noble gas like hydrogen and deuterium. The tracking system of the LHCb Upgrade I detector is able to reconstruct tracks in central PbAr collisions, and those will be extensively studied with data collected during Run 3 and 4. However, as a result of the high detector occupancy, the track reconstruction efficiency at the most central collisions is expected to be degraded, limiting the statistical power to study the rarest probes (such as Drell-Yan or Upsilon). With Upgrade II, LHCb will be able to dramatically increase signal yields in central beam-gas collisions as a results of the improved performance. Additionally, the detector will be capable of coping with multiplicities of larger systems such as PbKr and PbXe, extending physics studies, such as quarkonium suppression, to higher densities, a key pathway towards the unambiguous test of the quarkonium sequential suppression pattern as a consequence of the color screening mechanism expected to be at play in a fully deconfined medium. In parallel to the exploitation of the data acquired with the SMOG2 system, an R&D project (LHCspin) is ongoing aiming at the installation of all the equipment needed to polarize the injected gas, opening a new window on several experimental observables sensitive to quark and gluon TMDs and Generalised Parton Distribution, complementing previous results from semi-inclusive deep inelastic scattering experiments and from future facilities such as the EIC.

2 PicoCal

The LHCb electromagnetic calorimeter (ECAL) is a critical element of the experiment, enabling the reconstruction of electrons and photons with transverse energies ranging from a few MeV to 40 GeV. A large part of the physics case of the Upgrade II program of LHCb depends on the continuation of the good reconstruction efficiency and energy resolution ($\sigma(E)/E = 10\%/\sqrt{E}$) the LHCb ECAL has achieved in the past 15 years of operation [44]. In order to maintain its current efficiency and momentum resolution in the challenging conditions of High-Luminosity LHC, the ECAL will be largely redesigned. A key aspect of the ECAL upgrade will be the introduction of precise time measurement with 15 ps resolution at high energies, which is necessary to mitigate the increased pile-up. This brings the future LHCb calorimeter, PicoCal, into the cutting-edge era of 5D calorimetry.

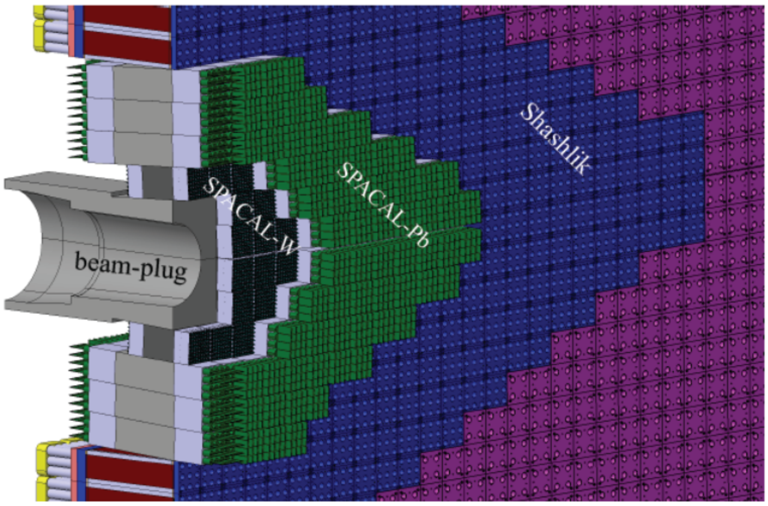

Figure 3: Schema of inner part of the PicoCal for the new modules installed during LS3 [7].

The geometry of the inner region of the LHCb PicoCal will need to be adapted, in order to mitigate the accumulated radiation damage and higher occupancy. While the existing Shashlik modules are retained in the outer region, the inner region will be replaced with new SpaCal technology modules, in which scintillating fibers are inserted into dense absorbers (tungsten or lead), and act both as active material and light transporters [7].

A schematic of the new geometry is shown in Figure 4. The outer part of the PicoCal is organized into 3 Shashlik-instrumented regions, with cell sizes of $12{\times}12\,\text{cm}^2$, $6{\times}6\,\text{cm}^2$ and $4{\times}4\,\text{cm}^2$. The region closest to the beam-pipe is equipped with $1.5{\times}1.5\,\text{cm}^2$ SpaCal-W modules, followed by $3{\times}3\,\text{cm}^2$ SpaCal-Pb modules. Various radiation-hard materials were investigated for the active material, and GAGG crystals and polystyrene fibers were selected for the innermost and next-to-innermost regions, respectively. The SpaCal and Shashlik modules will be longitudinally segmented and read from both the front and back to improve the time measurement and provide electron/hadron separation capabilities. The modules in both the Shashlik and SpaCal regions will be arranged in a rhombic shape to better follow the occupancy and irradiation profile of *pp* collisions. The Baseline and Middle scenarios are identical for what concerns PicoCal, with 31 000 channels. In the Low scenario, only the most central modules are segmented longitudinally, and the detector contains 20 000 channels.

The replacement of the innermost region with the SpaCal modules will occur during LS3, as the existing Shashlik inner modules will be at the end of their life. Timing and longitudinal segmentation will be introduced during LS4 in preparation of the instantaneous luminosity increase planned for Run 5.

The upgraded ECAL readout must provide a measurement of the deposited energy and the time of arrival of the signal to the reconstruction and high-level trigger software, at the full LHC bunch crossing rate (40 MHz). In particular, the introduction of the timing information with a precision of 15 ps at high energies is a new challenge and requires a redesign of the PicoCal readout chain. As shown in Figure 4, in Upgrade II, each Front-End Board (FEB) will contain two separate application-specific integrated circuits (ASICs) for the energy and timing information, called ICECAL65 and SPIDER, respectively. The ICECAL65 ASIC is an upgrade in 65 nm CMOS technology of the current ECAL ASIC and is currently under development by the Spanish LHCb Valencia and Barcelona groups. The SPIDER ASIC is fully under the responsibility of IN2P3, specifically the IJCLab, IP2I, LPC, LPCA and Subatech groups. The separation of the two ASICs, and the efforts to implement flexible design choices during the R&D phase open up the possibility of using the SPIDER technology for other applications requiring precise timing determination, both within and outside the field of collider physics. It could then be used in other experiments such as Belle-II at superKEKB in Japan, or for the cameras of the CTA astro-particle observatory. This in itself represents a real impact and natural spin-off benefits for our IN2P3 community. While timing accuracies below a few tens of picoseconds are expected in routine mode and in the next few years, in the longer term, the SPIDER concept suggests the possibility of designing calorimeters or other detectors offering timing measurements on the order of a few picoseconds. More details on the SPIDER ASIC technology, development status and project organization are given in the following sections.

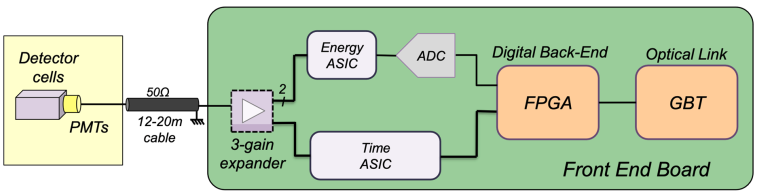

Figure 4: Schematics of the readout chain of PicoCal.

In addition to the development of the SPIDER ASIC, the IJCLab and LPCA groups intend to contribute to the upgrade of the front-end electronics for LS3 and LS4. For LS3, 110 FEBs have to be produced to equip the new modules installed during this long shutdown [7]. These boards are identical to the ones now used in Run 3, except for a minor modification to the power supply components. The groups have also taken on the responsibility of designing, characterizing, producing and participating in the operation of 500 cards for LS4. They will also provide the dedicated backplanes for LS4 and the associated power supplies. The LAPP group in Annecy is involved in the mechanics design and installation during LS3 of a new modified platform on top of the calorimeter, where the Front-End racks and crates are located.

The energy and timing information from the FEBs will arrive at the common back-end board, PCIe400, or its evolution. The FPGAs of the back-end board will format and pack the events, before sending them to the online farm for event building. To reduce the data rate coming from the detector and to speed up the real time processing, these FPGAs could combine the information from the different FEBs to perform clustering and apply sparsification as well as zero suppression. The addition of high-level calorimeter reconstruction algorithms in the back-end processing, including machine learning approaches, is a possibility that has recently started to be explored by the IJCLab and LAPP groups. This work will be done in close collaboration with similar developments that are being explored in the high-level trigger reconstruction.

2.1 Genesis

The IN2P3 LHCb teams have been responsible for the calorimeter electronics since the beginning of the experiment design. In the initial version of the experiment, this included the Front-End Boards of the PreShower, ECAL and HCAL detectors as well as the trigger boards for the L0 Calorimeter system that was used during Runs 1 and 2. For LHCb Upgrade I, while the PreShower and L0 Calorimeter were removed, a new version of the ECAL and HCAL FEBs adapted to the 40 MHz readout was designed, built and installed.

Based on the extensive experience gained since the start of the experiment, the IJCLab and LPCA groups propose to lead the design and fabrication of the new Front-End boards required for the operation of PicoCal during Upgrade II. The design of these boards will follow the main principles of the two previous versions: the boards will be housed in crates and racks installed in the LHCb cavern, above the PicoCal detector, in an area exposed to modest radiation doses. The existing infrastructure will be improved during LS3 to provide sufficient space, electrical power and cooling is available for the Upgrade II Front-End electronics.

While the details of the FEB specifications are still under discussion, they will follow the design of the previous versions. The boards will contain the ICECAL65 and SPIDER ASICs as well as radiation hard FPGAs from the MicroSemi PolarFire family. The latter will perform the digital processing of the signals from the ASICs and format the information to send it through the lpGBT [45] components via optical fibers to the back-end electronics. The other major function of the board is to receive the LHC clock as well as the fast and slow commands distributed to the detector readout. One FEB will handle 64 channels, so a total of 500 FEBs will be needed for PicoCal. The FEB project also includes the associated power supplies and the design of custom crate backplanes.

Precise time measurement has been a major area of research for several years at LAL, then IJCLab Orsay, initiated by Dominique Breton in collaboration with CEA Saclay. This led to the production of the WaveCatcher system [46] or the SAMPIC ASIC [47], establishing the team as world experts in this field. In parallel, several groups of microelectronics experts collaborated in the Fastime and Lojic130 IN2P3 R&T projects to develop Phase-Locked Loops (PLLs) and Time-to-Digital Convertors (TDCs) in ASICs. Based on this experience, it was proposed to design a new ASIC, called SPIDER, based on the SAMPIC principles to perform the precise time measurement required for PicoCal.

The requirements for the ASIC are to measure the time with a precision of 15 ps at high energies, in a wide dynamic range, from 50 MeV to 5 GeV transverse energies. The signals from the PMTs used in PicoCal have a rise time between 1.5 ns and 4 ns depending on the area. The typical occupancy of channels with a measured transverse energy above 50 MeV, is less than 10% but rises up to 50% in the busiest areas. The technology used by the SAMPIC ASIC is particularly well suited to these requirements. It uses a combination of a waveform digitizer based on analog memories and a DLL-based TDC. This allows to be less affected by time-walk effects than traditional methods (TDC) for such a wide dynamic range. However, this design is affected by a large dead time, so the need arose for a new ASIC, SPIDER, that would be optimized for high rate conditions, close to 40 MHz.

2.2 Technical achievements

The principle of the time measurement with the technique proposed for SPIDER was tested in test beams with PicoCal module prototypes and the WaveCatcher system, which uses the same technology. The required accuracy for time measurement was achieved, validating this approach.

The R&T project LHCb-ECAL2 funded by IN2P3 allowed the interested groups (IJCLab, IP2I, LPC and LPCA, now joined by Subatech) to start the development of SPIDER. The 65 nm TSMC technology was chosen as it is the one expected to last at least until the start of Upgrade II and is available through CERN. A first prototype was submitted in December 2024 and will be produced before the summer 2025. This prototype contains the main functionalities of the chip and can handle two channels, compared to 8 for the final version. It samples the input signal from the PMTs in a configurable time window. The start of the time window can be set in steps of 200 ps. The sampling period is also adjustable between 50 ps and 600 ps, which is sufficient to cover a variety of signal rise times from 250 ps to

4 ns, making this ASIC also well suited for other applications beyond LHCb. The signal is sampled in 32 samples. The ASIC implements a *peak finder* algorithm to locate the maximum of the signal optimizing the selection of samples sent by the ASIC to a companion FPGA where the time is computed by extrapolating from these samples. Several analog memory banks are implemented and used in parallel in the ASIC. This reduces the dead time to the required level. More details about the technical implementation can be found in Refs. [48, 49].

After this first prototype is manufactured and tested, another version with 8 channels will follow shortly. The radiation hardness of the ASIC will then be increased and tested with beams in subsequent versions of the design. From the end of 2025, the ASIC will also be used in test beams organized to characterize the detector modules.

Concerning the FEBs for LS4, a first simplified prototype will be designed during 2025. Other more complex prototypes will be produced, in particular to handle the communications with the two ASICs, until the end of 2030 when the production will start.

2.3 Project organization

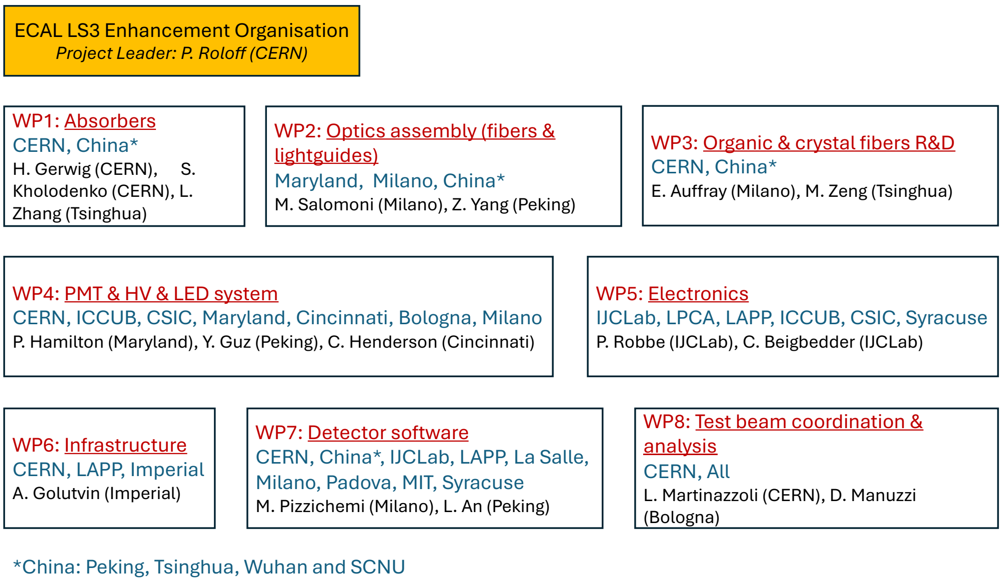

Figure 5: Work packages for the ECAL LS3 enhancement project

The ECAL project organization is summarized in Figure 5. The project leader of the ECAL Upgrade II project since July 2024 is Philipp Roloff (CERN). The work is divided into eight Work Packages (WPs) with the following activities and participating institutes:

- WP1 - Absorbers: CERN & China
- WP2 - Optics assembly (fibers & lightguides): Mayryland & Milano & China
- WP3 - Organic & crystal fibers R&D: CERN & China
- WP4 - PMT & HV & LED system: CERN, ICCUB (Barcelone), CSIC (Valencia), Maryland, Cincinnati, Bologna, Milano
- WP5 - Electronics: IJCLab, LPCA, LAPP, ICCUB (Barcelona), CSIC (Valencia), Syracuse
- WP6 - Infrastructure & cabling: CERN, LAPP, Imperial
- WP7 - Detector software: CERN, China, IJCLab, LAPP, La Salle (Barcelona, Milano-Bicocca, MIT, Syracuse
- WP8 - Testbeam coordination & analysis: CERN, all

The French contribution to the ECAL project is mainly focused on *WP5 - Electronics* and *WP6 - Infrastructure*, while contributions to *WP7 - Software* and *WP8 - Testbeam* could be envisaged in the future.

In France, the work is organized in four main work packages, as shown in Figure 6: the design of the SPIDER ASIC, the design of the Front-End electronics, the development of the firmware and software for the back-end electronics, the associated reconstruction algorithms, and the adaptation of the infrastructure (mechanics and services) for the new detector. The activities are supervised by Vincent Tisserand (LPCA Clermont-Ferrand) and Patrick Robbe (IJCLab Orsay). The work on the electronics is coordinated by Christophe Beigbeder (IJCLab Orsay), while the developments for the SPIDER ASIC are carried under the supervision of Philippe Vallerand (IJCLab Orsay) and Baptiste Joly (LPCA Clermont-Ferrand).

The IN2P3 laboratories that have expressed interest in participating in the project are:

- LPCA Clermont-Ferrand: SPIDER ASIC, Front-End electronics design and infrastructure adaptation,
- IJCLab Orsay: SPIDER ASIC and Front-End electronics design, reconstruction algorithms developments and infrastructure adaptation,
- LAPP Annecy: mechanics and Back-End electronics firmware developments,
- IP2I Lyon (not member of the LHCb collaboration but part of the R&T LHCb-CALO2): SPIDER ASIC developments,
- LPC Caen (not yet member of the LHCb collaboration but part of the R&T LHCb-CALO2): SPIDER ASIC developments,
- Subatech Nantes: SPIDER ASIC developments.

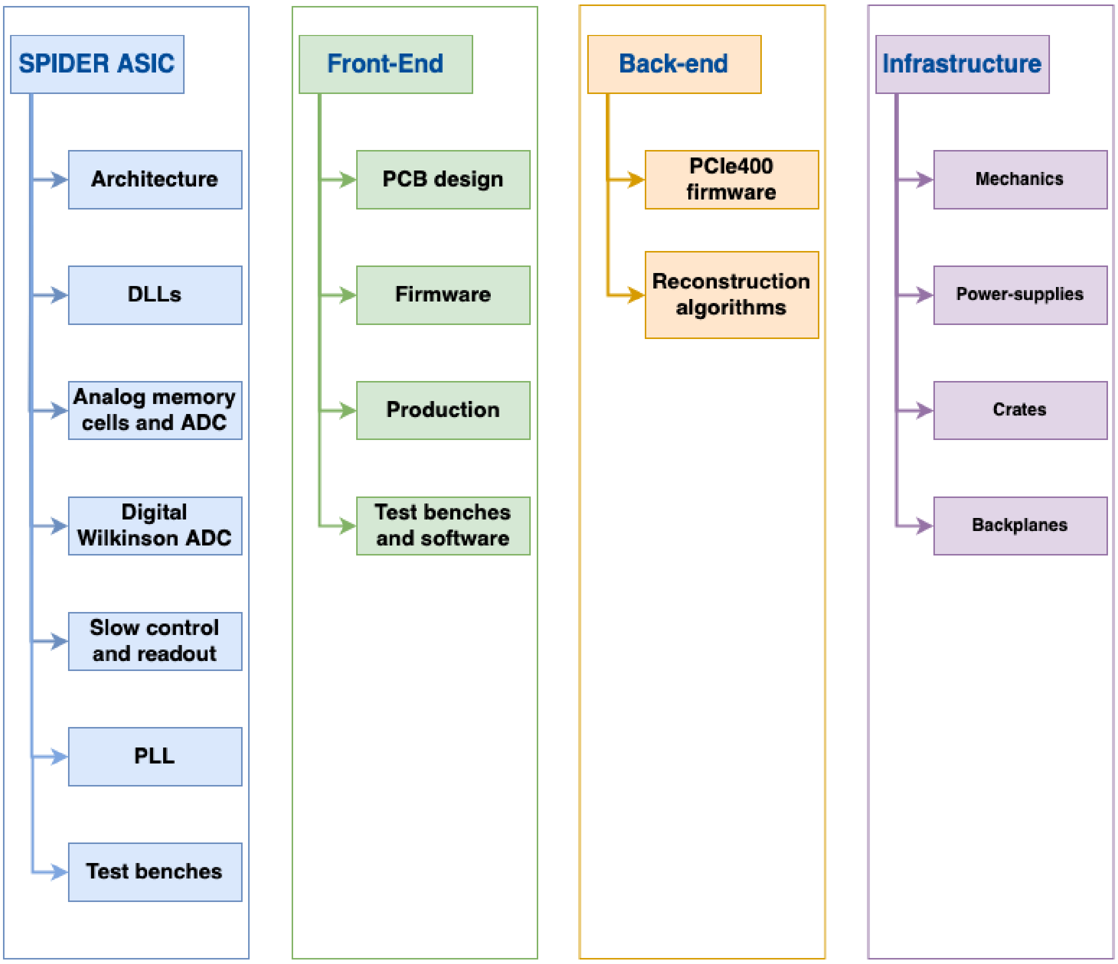

Figure 6: French work packages for the PicoCal project

2.4 Schedule and costs

The ECAL upgrade will take place in two phases. The first phase is to consolidate new modules into LS3, but with front-end electronics identical to the current one, and the second, to develop new electronics for installation in LS4.

2.4.1 LS3 enhancement

The LS3 enhancement will consist in 10 control boards (3CU) identical to the Upgrade I version, and 110 Front-End boards slightly modified from the Upgrade I version, since the DC-DC converters used then are no longer available.

Figure 7 shows the planning for the production, installation and commissioning of the 3CU and FEB for LS3.

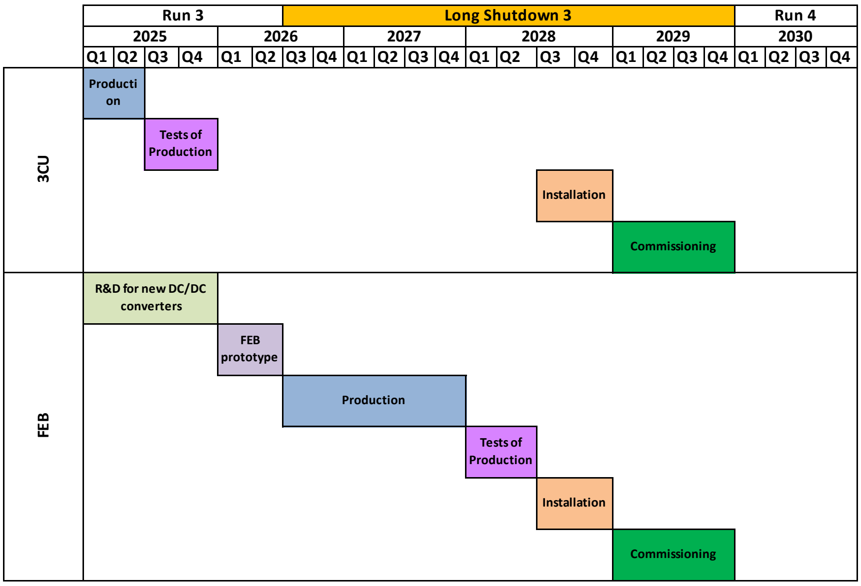

Figure 7: Schedule for the production of 3CU and FEBs for LS3

2.4.2 LS4 upgrade

The work for the LS4 upgrade consists of the development and production of the SPIDER ASIC and the development and production of new Front-End boards. For all scopping scenarios, the requirements for the electronics are identical, meaning that the developments are the same in all scenarios. In the Basline and Middle scenario, 4 000 ASICs and 500 FEBs, both including spares, are needed. For the Low scenario, 2 600 ASICs and 350 FEBs have to be produced. The new readout architecture eliminates the need for a controller board.

The planning for prototyping and production of the SPIDER ASIC and the FEB is shown in Figure 8.

Five SPIDER prototypes and one pre-production are expected, with a unit price of 39 k€. For the FEBs, the unit price is assumed to be 10 k€ for the prototype and 3.5 k€ for the production. The latter takes into account the price increase of the FPGAs compared to the production of the Upgrade I boards.

The backplanes for LS4 are expected to cost 5 k€ for a prototype and 1 k€ per backplane for production. Including spares parts, the total production cost of the backplanes is expected to be 35 k€. The price of each power supply price is 15 k€ and the total amounts to 240 k€.

The project costs include estimates for building the test-bench setups to characterize the SPIDER ASICs and LS4 FEBs, as well as contributions to the test beam material. Mission costs during the installation period prior to Run 4 and Run 5 are also included. The total cost of the project is 3 065 k€, in a 10-year period between 2025-2035, for the Baseline and Middle scenarios, and 2 500 k€ in the Low scenario.

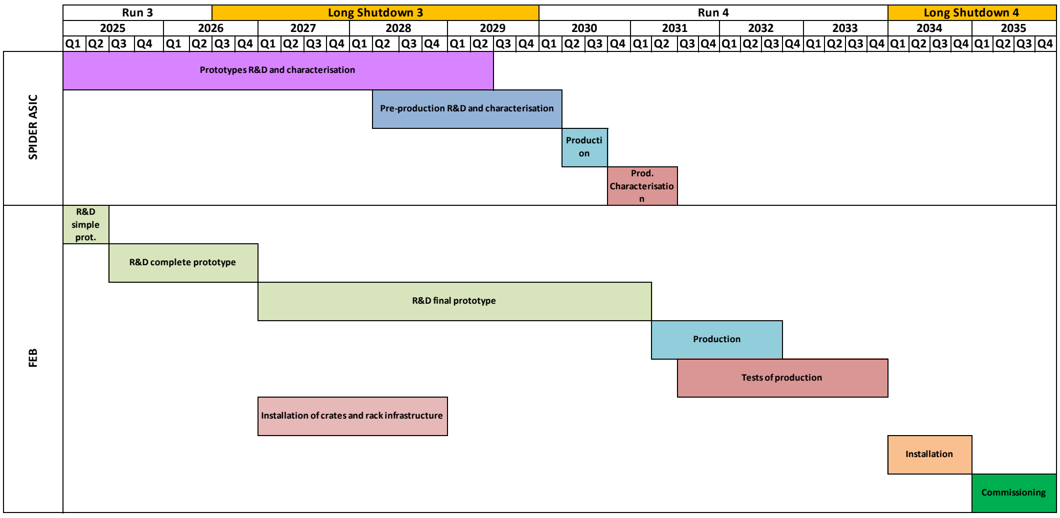

Figure 8: Schedule for the SPIDER ASIC and FEB R&D and production for LS4

The total cost of the ECAL upgrade for LS3 and LS4 is shown in Table 9. It is based on reliable quotes for components and on estimates from past production for the assembly. The 10 control boards for LS3 and the first SPIDER prototype production have already been funded in 2024, and are therefore not included in this table.

Item	Run 3	LS3				Run 4				LS4		Total
	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	
LS3 FE production		385										385
LS3 installation mission					15							15
SPIDER protytpes	39	39	39	39								156
SPIDER production						39	360					399
LS4 FE prototypes		10	10	10								30
LS4 FE production							875	875				1750
LS4 Power supplies			120	120								240
LS4 Backplane boards						5	35					40
test bench material	1	8	4	4	4							21
test beam material		2	4	4	4							14
LS4 installation mission											15	15
Total per year	40	444	177	177	23	44	1270	875	0	0	15	3065

Figure 9: Cost of ECAL upgrade for Run 4 and of the PicoCal upgrade for Run 5 and beyond, in k€.

The estimated number of FTEs needed to complete the project is shown in Table 10, while the currently available FTEs (as of December 2024) per institute are shown in Table 11.

While the available person-power matches well the estimated needs of the project until 2026, the successful completion of the project requires that this trend continues until the installation of LS4 in 2035. The current estimate shows a shortage of person-power, especially towards the end of the project. It could possibly be filled with additional PhD, postdoc or engineer positions and more effectively

	Run 3	LS3				Run 4				LS4		Total
	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	
Management	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	3,3
Microelectronics	5	5	4	4	4	3	2	2	1	0,3	0,3	30,6
Electronics	3	3	3	3	3	3	2	2	1	0,3	0,3	23,6
Mechanics	1,7	1,4	0,7	0,3								4,1
Computing/Software	0,85	0,7	0,5	0,5	0,5	0,5	0,5	1	1	2	2	10,05
Instrumentation	0,3	0,3			0,3	0,3	0,3					1,5
Cabling/Installation			2	2	1				1,6	5	5	16,6
Total	11,15	10,7	10,5	10,1	9,1	7,1	5,1	5,3	4,9	7,9	7,9	89,75

Figure 10: Estimated number of FTEs needed for the PicoCal project.

	Run 3	LS3				Run 4				LS4	
Physicists	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
IJCLab	1.5	1.75	1.7	1.7	1.2	1.2	1.2	1.2	1.2	2.5	2.5
LAPP	0.25	0.5	0.5								
LPCA	1	0.7	0.7	0.7	0.7	1	1	1	1	1	1
Total	2.75	2.95	2.9	2.4	1.9	2.2	2.2	2.2	2.2	3.5	3.5

	Run 3	LS3				Run 4				LS4	
Engineers	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
IJCLab	3.55	2.8	2.8	2.2	2.2	2.2	1.2	1.2	1.2	2	2
LAPP	0.7	0.8	0.9	0.8							
LPCA	3.25	3.25	3.25	3.25	3.25	2.7	1.5	1.5	1.5	2	2
LPC Caen	0.2	0.2	0.05	0.05	0.05	0.05	0	0	0	0	0
SUBATECH	0.5	0.5	0	0	0	0	0	0	0	0	0
IP2I Lyon	0.2	0.2	0.05	0.05	0.05	0.05	0	0	0	0	0
Total	8.4	7.75	7.05	6.35	5.55	5	2.7	2.7	2.7	4	4

Figure 11: Estimated FTEs available for the ECAL enhancement for Run 4 and of the PicoCal upgrade for Run 5 and beyond. *LPCA to be reviewed*

with the newcomers from the ALICE groups that will join the IJCLab and LPCA LHCb groups before LS4.

2.5 Risks

The risks associated with the choice of technology for the ASIC (65 nm process, analog memories) were addressed during the R&T phase. TSMC's CMOS 65 nm technology is sustainable for the next 10 years. Simulations show that the various elements needed for SPIDER are functional and with satisfactory performances with the 65 nm technology. Test beams using the WaveCatcher system have also shown that analog memories allow us to achieve the required timing accuracy. Having several prototypes (5 in total) will allow us to solve the remaining problems and gain expertise with working with the 65 nm technology.

There are significant risks associated with the availability and price of the components required for Front-End board production (FPGAs or components provided by CERN). The price of FPGAs has increased in recent years, and the estimated costs above take this into account. The CERN components are being produced for the ATLAS and CMS Phase II upgrades (LS3) and will need to be ordered also by LHCb relatively soon. The mitigation of these risks is to order these components as soon as the design is frozen.

Another risk is associated with the retirement of the current electronics experts in the next few years, and the strong need to transfer their knowledge to newcomers in the project. This is especially the case for the engineers at IJCLab who have the main expertise in the Front-End Board design and in analog memories. To mitigate this risk, an IR (Research Engineers) position has been opened in IJCLab, and a new engineer has been hired to start in March 2025. She will be trained during the prototyping phase of the FEB design for Upgrade II and eventually take over a position of expertise in the project.

The R&T project has also allowed micro-electronics groups from other laboratories (LPCA Clermont-Ferrand, IP2I Lyon, LPC Caen and Subatech Nantes) to learn about the analog memory architecture. As the IP2I and LPC Caen laboratories are not members of LHCb, there is a risk that the engineers currently working on the SPIDER project will not be able to commit themselves to the project in the long term. This has been taken into account in the development plan, where the blocks (DLL and PLL) for which they are responsible are expected to be ready soon in the project planning, but their participation must be ensured at least until the end of 2026.

3 Real Time Processing

3.1 Overview

3.1.1 State of the art

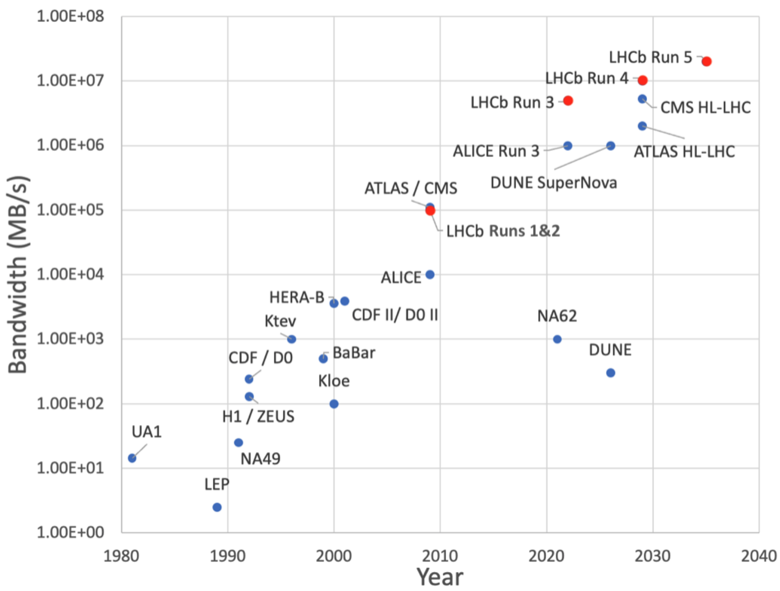

Figure 12: Data bandwidth processed in software for various HEP experiments across time. Red data points show the bandwidths processed by LHCb.

The Real-Time Analysis (RTA) project is responsible for the real-time reconstruction of the LHCb detector data, its near-real-time alignment and calibration, and online selection. The input bandwidth of the system is compared with other HEP experiments in Figure 12 which shows that LHCb's RTA system is at the leading edge of real-time processing in the HEP community.

Since Run 3 of the LHC, LHCb uses a triggerless readout to send the raw data for the full 30 MHz of non-empty bunch crossings to a custom data processing center. Using off-the-shelf components, the bunch crossing fragments from each sub-detector are first assembled into *events* and then reconstructed into higher-level physics objects. The latter system is called a High Level Trigger (HLT).

The HLT is divided into two stages, called HLT1 and HLT2, separated by a disk buffer that stores events while the detector is being aligned and calibrated in near real time with offline precision. HLT1 performs a subset of the full offline reconstruction (*L1 reconstruction*) selecting events by searching for a range of inclusive physics signatures. This reduces the data volume by about 30. HLT2 then uses the full offline quality detector reconstruction (*L2 reconstruction*), alignment, and calibration to select a subset of high-level physics objects, relevant to any of the hundreds of physics analyses, for permanent storage.

To achieve its objectives, RTA contributes to the development and maintenance of the LHCb software. In particular, the Allen framework [50] has been proposed and developed by LHCb France researchers and their international collaborators over the last six years. It enables complex processing pipelines to operate efficiently on heterogeneous architectures at extreme throughputs of 5 TB/s. Allen is designed to first optimize performance. Code portability across architectures is ensured by a thin compatibility layer that currently supports x86 and GPU architectures, but can be extended to others as required.

Allen has enabled LHCb to run the full HLT1 on GPUs since 2022 [51]. This was more cost effective than the CPU alternative [52] and contributed to an improvement of around $\times 16$ in the energy efficiency of LHCb's high-performance software compared to 2015–2018 data taking [53]. This is the first time GPUs have been used in a high-throughput environment in High Energy Physics (HEP).

Other LHC experiments using GPUs for real-time reconstruction are CMS and ALICE. Since the primary goal of ALICE is to study the quark-gluon plasma in PbPb collisions, the event size is orders of magnitude larger than for other LHC experiments, but the events occur at a lower rate. ALICE has being using GPUs since Run 1, evolving to a fully software-triggered scheme processing 0.9 TB/s of data in Run 3. In preparation for the HL-LHC in Run 4, CMS has introduced heterogeneous computing to the HLT in Run 3, processing 100 kHz of events. Pixel reconstruction and part of the calorimeter reconstruction are offloaded to GPUs in a heterogeneous computing farm.

The ALICE O2 framework [54] allows for the implementation of heterogeneous code. For CMS, the offloading of parts of the reconstruction is implemented in the CMSSW [55] framework and intertwined with the processing on CPUs. Similar code portability methods are used as in LHCb. However, due to the different event size and rate in ALICE, and the only partial offloading in CMS, the scheduling requirements in LHCb are unique. Therefore, the further development of a dedicated software framework for LHCb will be essential.

3.1.2 Proposed RTA project for LHCb Upgrade II

While in Run 3 LHCb processes 5 TB/s of data with more than 1 MHz of signal rate, in Upgrade II LHCb has to process 25 TB/s with more than 5-7.5 MHz of signal rate. Therefore, it is no longer sufficient to select events inclusively in an HLT1, but a more fine-grained selection is required already at the first level. Consequently, the L1 reconstruction should be close to offline quality. Given that the output of the HLT1 is signal dominated, and that each selected event will be more complex due to the increased pile-up, the L2 reconstruction algorithms will be the biggest computational challenge in Upgrade II.

Therefore, the only currently known viable option for Upgrade II is to perform both the L1 and L2 reconstruction on GPUs, as stated in the framework TDR for Upgrade II [3]. However, given the long timescale and the ongoing rapid changes in computing architectures, it is essential to remain flexible with respect to emerging architectures. In particular, energy efficiency will become an increasingly important criterion over the coming decades. It is therefore crucial to maintain the ability to use particularly energy-efficient architectures such as FPGAs, ARM processors, or the emerging RISC-V family of open-source microprocessors.

In order to meet the Upgrade II requirements, the objectives of RTA are the following:

1. Obtain the same physics performance for *pp* collisions as in Run 3;
2. Improve the physics performance for most central heavy ion collisions;
3. Improve both the cost performance and the energy efficiency of the system;
4. Remain flexible with respect to computing architectures and languages.

The current software frameworks used in LHCb, GAUDI[1] and ALLEN, provide a strong foundation for Upgrade II: GAUDI currently supports offline and HLT2 processing on CPUs, while ALLEN is optimized for HLT1 processing on GPUs. No major technical obstacles have been identified in adapting and integrating components of both frameworks for Upgrade II data processing.

Within LHCb France, we will focus on two key pillars: 1) algorithmic and methodological developments within ALLEN, and 2) the evolution of the ALLEN software framework to enable the deployment of these innovations.

The algorithm development will be closely linked to the sub-detector projects. The RTA project will focus on designing reconstruction algorithms for parallel computing architectures within ALLEN, designing global reconstruction using information from different sub-systems, and performing alignment and calibration. The RTA France project will focus on algorithms involving the Upgrade II sub-detector projects proposed in France, such as the calorimeter and the pixel tracker. This will allow us to benefit from the strong competences of the French groups in this area.

As computer architectures are increasingly optimized for AI applications, the use of AI methods for tasks such as pattern recognition and classification will be essential to scale both physics and computational power with increasing detector occupancy. This approach is particularly important for improving the reconstruction of heavy ion collisions. This is one of the main goals of the project, which is supported by the growing heavy-ion community in France participating in LHCb.

Data processing and reduction should take place as early as possible in the processing chain, ideally already before the HLT. For example, clustering and calorimeter reconstruction are obvious candidates for algorithms to be processed locally on the PCIe400 cards to save throughput during the L1 and L2 reconstruction in software, if the FPGA resources of the card allow it. A strong collaboration with the DAQ and PicoCal projects in France is therefore foreseen.

[1] GAUDI is LHCb's main framework for x86 based processing and physics analysis. Its development is shared with ATLAS.

3.1.3 Allen applications beyond LHCb

Allen is more than just an application for the LHCb experiment. It is a general-purpose software framework designed for high-throughput heterogeneous processing. Its ability to compile as a standalone application was critical to its rapid development in the early stages. Maintaining this standalone functionality remains essential for two main reasons: first, it enables rapid prototyping of new and emerging computing architectures in a lightweight environment; second, it facilitates the reuse of Allen beyond LHCb. This broader applicability has already attracted the interest of other experiments with similar high-throughput processing requirements, such as the ePIC experiment at EIC, which involves several French laboratories. Maintaining this flexibility will ensure that Allen continues to support both innovation and cross-experiment collaboration.

One of the unique features of Allen which may be of particular interest for non-LHCb use cases is the ability to combine a mixture of classical and AI algorithms in a single processing pipeline. Such mixtures have been shown to give optimal results, for example in the TrackML HEP particle tracking challenge [56]. Three key features of Allen make it particularly well suited to such use cases: 1) Compile mixed pipelines for execution on different computing resources: CPU, GPU, etc.; 2) Optimized for batched execution, Allen is well suited to saturate available computing resources; 3) Minimizing communication between the host server and accelerator resources, Allen can run efficiently without having to be fine-tuned to the precise composition of the data centre in question. The French LHCb teams, in collaboration with colleagues from the SKA observatory and industrial partners, are pioneering the exploration of such uses of Allen as part of the recently funded EU infrastructure project ODISSEE.

3.2 Genesis and timeline

The involvement of French institutes in LHCb's real-time reconstruction has a long history, ranging from the authorship of most of the track and calorimeter reconstruction algorithms for Runs 1-3, the calorimeter calibration in Runs 1-3, the development of the Allen framework and the co-development of most HLT1 reconstruction algorithms for Run 3. Table 2 gives an overview of the involvement of French physicists in the LHCb RTA project for Run 3.

For Upgrade II, the outline of real-time processing has been sketched in the Framework TDR [3], and the RTA project organization will be defined by 2026 in a *Framework Data Processing TDR* accompanying the sub-detector TDRs. Discussions on the design of the RTA system and the software framework are ongoing within LHCb, with a strong contribution from French LHCb physicists. The TDR for the RTA system is planned for 2030.

Discussions on the future evolution of the software framework for Upgrade II have started within LHCb during a workshop held in Marseille in 2023 and will continue at the next workshop in A Coruña in January 2025. In preparation of the

Table 2: Permanent physicists of French LHCb teams involved in Run 3 RTA activities.

Institution	People
CPPM	A. Poluektov, D. vom Bruch
IJCLab	C. Agapopoulou, Y. Amhis, P. Robbe
Irfu	B. Audurier
LAPP	J.-F. Marchand
LPCA	S. Akar
LLR	F. Fleuret
LPNHE	V. V. Gligorov

Framework Data Processing TDR, a first project structure will be defined during 2025, with a clear idea of the project and tasks foreseen by early 2026.

The timeline and milestones for the RTA France project are shown in Figure 13. The developments of the ALLEN framework will be carried out over the next years until LS3, so that the functionality can be tested during Run 4 already. Similarly, R&D for Artifical Intelligence (AI) methods in reconstruction and classification, as well as AI infrastructure will be developed over the next years, such that the tools are available for Upgrade II reconstruction tasks before Run 5. The system will be tested with Run 4 algorithms until LS4, while Upgrade II detector reconstruction algorithms can be deployed before Run 5.

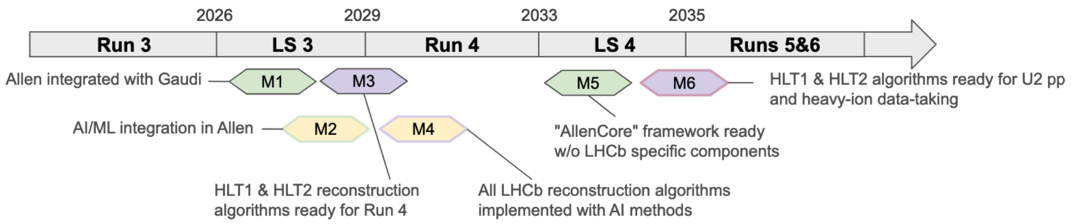

Figure 13: Overview of the timeline and milestones for the RTA project.

3.3 Technical achievements

Below we outline the technical achievements foreseen for the French RTA project, linked to the milestones shown in Figure 13.

3.3.1 Allen software framework

To meet the core requirements of LHCb Upgrade II, the functionalities of the ALLEN framework need to be extended and separated from LHCb-specific code for better maintainability and re-usability outside of LHCb, thus achieving milestones *M1* and *M5*. This requires a significant amount of modernisation for better maintainability and scalability, as well as to improve the interoperability of ALLEN with GAUDI: functionality optimised for high-throughput processing in ALLEN should be better available for GAUDI workflows, while GAUDI services and supporting infrastructure should be more accessible in ALLEN.

The range of supported computing architectures should be extended over time, in particular to better support ARM, RISC-V, and other low-power architectures. ALLEN's support for Machine learning (ML)/AI inference should be improved, with particular focus on ALLEN's unique use case of running multiple copies of the same ML model in parallel, reaching milestone *M2*. This is in contrast to most ML pipelines, which execute one model at a time and rely on parallelizing work within the model for speed gains.

A unique event model for reconstructed objects should be developed that can be used across a range of computing architectures. Finally, the monitoring functionality of ALLEN should be improved, in particular by allowing more flexibility in the distribution of work between the co-processors and the host server.

3.3.2 Machine Learning /Artificial Intelligence

To meet the real-time data processing challenges of LHCb, the use of Machine Learning (ML) techniques needs to be explored for all RTA algorithms, thus realizing milestones *M2* and *M4*. Quantisable models are essential, as memory and computational constraints require compact representations of large ML models. While LHCb has being using ad-hoc quantisation since 2011, a standardised, maintainable approach is now critical, given that most future algorithms will rely on ML.

Graph Neural Networks (GNNs), which show promise for tasks such as track-finding and jet building, have been extensively studied but pose significant memory challenges in LHCb's online environment. Further R&D will investigate whether these models can be adapted for real-time use. Transformer networks, which gained prominence through Large Language Models (LLMs), could bridge low-level particle reconstruction and high-level physics analysis, reducing computational and maintenance costs across LHCb's approximately 3 000 trigger selections.

Particle Identification (PID) is already NN-based in LHCb, but will need to be updated to take advantage of new timing information from Upgrade II sub-detectors. Embedding ML models directly in the FPGAs on the readout cards should be investigated for calorimeter clustering tasks. LHCb's calorimeter, hadronic PID, and the VELO will have timing information in Upgrade II, it is natural to explore how best to exploit this information in particle flow algorithms, including ones based on Deep Neural Networks (DNNs).

3.3.3 Reconstruction & Calibration

The LHCb France community has led the development of LHCb pattern recognition algorithms since the experiment's genesis. A common denominator of the algorithms developed are seeding techniques, *i.e.* finding hits consisting of a single particle traversing the detector and finding tracks belonging to the same primary vertex. Consequently, a natural extension for Upgrade II reconstruction is to focus on seeding algorithms for parallel architectures, in particular for the sub-detectors co-developed in France, delivering on milestones *M3* and *M6*. All seeding algorithms rely on a good understanding of the magnetic field map and material distribution, and they have to cope with varying multiplicities and the influence of detector (mis)alignment and inefficiencies. Common tools and methods to address these requirements will be developed.

Links to the AI/ML methods are in the combination of seed tracks from different sub-detectors using classifiers and in the reduction of fake tracks using classifiers. The track seeding algorithms in Upgrade II will be similar to Upgrade I, except for change in granularity and resolution. Primary Vertex reconstruction needs to be rewritten in 4D, to incorporate timing information.

Pattern recognition is crucial for both the L1 and L2 reconstructions. The goal of LHCb Upgrade II is to have an L1 reconstruction that is as close as possible to L2. Ideally, the L1 track reconstruction could achieve a track-finding efficiency compatible with the best possible efficiency achievable offline. If this is however not possible, a tuning of the pattern recognition algorithms will be developed for L2 reconstruction to achieve the best possible efficiencies and resolution.

Calibration of the calorimeter response and electron reconstruction efficiency are historically contributions from the French teams and will follow similar procedures for Upgrade II as for Run 3.

3.3.4 Heavy Ions

Compared to regular proton-proton conditions, heavy-ion operations differ in two key aspects: 1) single colliding bunch crossings have about 30 times higher occupancy; and 2) the interaction rate is much lower (50 kHz). Since heavy-ion physics is highly dependent on collision properties, full event reconstruction and storage are required. These factors require minimal but highly efficient L1 and L2 reconstructions to avoid excessive computation time and storage requirements.

Due to bandwidth constraints and lower tracking efficiency for high occupancy events, the most 30% central events are not recorded in Run 3. The conditions for Run 5 will be similar, but LHCb's upgraded detector performance, such as the improved granularity in the tracking detectors, should allow analysis of the most central PbPb collisions, delivering on milestone *M6*. A typical challenge is the high rate of ghost tracks, which degrade performance and waste disk space. The development of ML-based algorithms (e.g., GNN) and new standalone seeding algorithms for subsystems such as the pixel tracker are particularly promising.

Calibration for ions is similar to proton-proton operations, but a key difference is the need to assess the relationship between detector quantities and the value of the centrality for each new sample. The selection strategy will evolve from the Run 3 model, adapting to the improved reconstruction performance. Ion collision data samples in both fixed target and collider modes require specific luminosity measurements for each configuration recorded. While using similar analysis tools as proton-proton operations, these samples require a comprehensive understanding of the detector due to different behaviour of the counters used to compute the integrated luminosity.

3.4 Project organization

The RTA France project is divided into four work packages: *WP1* ALLEN and *WP2 ML/AI* focus on infrastructure development, while *WP3 Reconstruction & Calibration* and *WP4 Heavy Ion* focus on algorithm and method development. Their planned technical achievements are outlined in the Section 3.3. Figure 14 shows the project organization, while Table 3 gives the interests expressed by French institutes in the work packages.

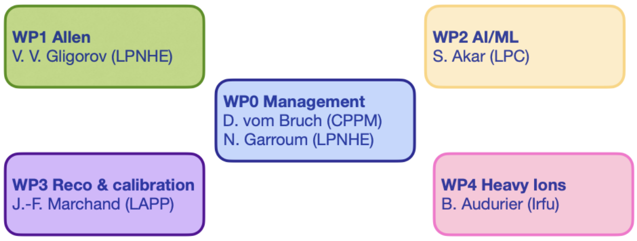

Figure 14: Proposed RTA France proto-project organization for Upgrade II.

Table 3: Distribution of RTA areas of interest across French LHCb teams.

Institution	Area of interest
WP1 Allen	CPPM, LPNHE, Subatech
WP2 ML/AI	LPCA, LPNHE, Subatech
WP3 Reconstruction & Calibration	CPPM, IJCLab, LAPP, LPNHE, LLR
WP4 Heavy Ions	Irfu, LLR

3.5 Schedule and costs

The milestones and their delivery dates are shown in Figure 13, while the FTEs required to achieve the described technical developments are summarized in Figure 15. The required FTEs for both physicists and engineers are covered by employed personnel or open positions until 2027. From 2028, however, only 50-70% of physicists and 0% of engineers are available according to the current planning.

While the RTA community in France has played a key role in delivering the successful software-only trigger system for LHCb in Run 3, a large proportion of the physicists involved have been financed by external funding (ERC, European Union), which is limited in time. As the project enters its second phase of consolidation as a software tool, long-term technical support from a coherent team of engineers and physicists is crucial.

The French teams can share a common computing infrastructure for R&D, hosted in one or two of the institutes. The costs for the infrastructure are detailed in the Table 4.

	Run 3	LS3				Run 4				LS4		Total
Physicists	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	
WP1	0	0.5	0.5	0	0	0	0	0	0	0	0	1
WP2	0	0	1	1	1	2	2	2	0.2	0.2	0.2	9.6
WP3	0.3	0.55	0.75	1.25	1.75	2.05	2.05	1.3	0.3	0	0	10.3
WP4	0	0	0	0.5	0.7	0.5	0.3	0.6	0.6	0.9	0.4	4.5
Management	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	2.75
Total	0.55	1.3	2.5	3	3.7	4.8	4.6	4.15	1.35	1.35	0.85	28.15

	Run 3	LS3				Run 4				LS4		Total
Engineers	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	
WP1	0.25	2.25	2	2	1.05	1	1	1.8	0.8	0.3	0.3	12.75
WP2	0	0	0	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	1.8
WP3	0	0	1	0.5	1.5	1.25	0.95	0.45	0.95	1.1	0.7	8.4
WP4	0	0	0	0	0	0	0	0	0	0	0	0
Management	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.1
Total	0.35	2.35	3.1	2.9	2.95	2.55	2.25	2.55	2.05	1.7	1.3	24.05

Figure 15: Estimated number of FTEs needed in IN3P3 institutes to accomplish the goals of the RTA France project

Table 4: Requested hardware support for the LHCb France RTA project.

Timescale	Request (k€)	Purpose
2026–2028	50	Two high-end CPU servers Six co-processors (2 GPUs, 2 FPGAs, 2 cards with emerging architectures (such as RISC-V)
2032–2034	50	

3.6 Risks

The RTA France project is very ambitious but offers the opportunity to build a coherent team with a mix of skills in key areas of interest for IN2P3: heterogeneous computing, high-performance and high-throughput computing, energy-efficient computing, as well as AI/ML methodologies. The development of ALLEN over the last six years shows that such a team can punch well above its weight in the global context. It can also develop a wide range of international partnerships with consequent benefits for the LHCb France community and with cross-experiment potential within IN2P3. An assessment of the potential risks is given below.

Slow-down of development cycle due to large legacy codebase: to counteract this slowdown, code modernisation and regular code clean-up are crucial. The relevant infrastructure for the GAUDI-ALLEN convergence must be carefully selected to avoid large overheads due to more than ten years of GAUDI development and backward compatibility requirements. Preserving the ALLEN standalone framework is particularly important for rapid prototyping of new emerging architectures.

Development of commercial technologies: technological trends may evolve in directions that are not conducive to HEP real-time processing, such as decreasing support for floating-point operations in favour of mixed-precision computations. Testing of architectures as they emerge within the ALLEN standalone framework is critical to ensure compatibility at an early stage, while code will be designed in a modular fashion with abstraction layers to decouple as much as possible from the underlying computing paradigm.

No knowledge transfer due to non-appointment of permanent staff: long-term development is threatened if knowledge transfer is not ensured and a critical mass of permanent project members is not available to pass on past experience to newcomers and PhD students who contribute for short periods.

4 Data Acquisition

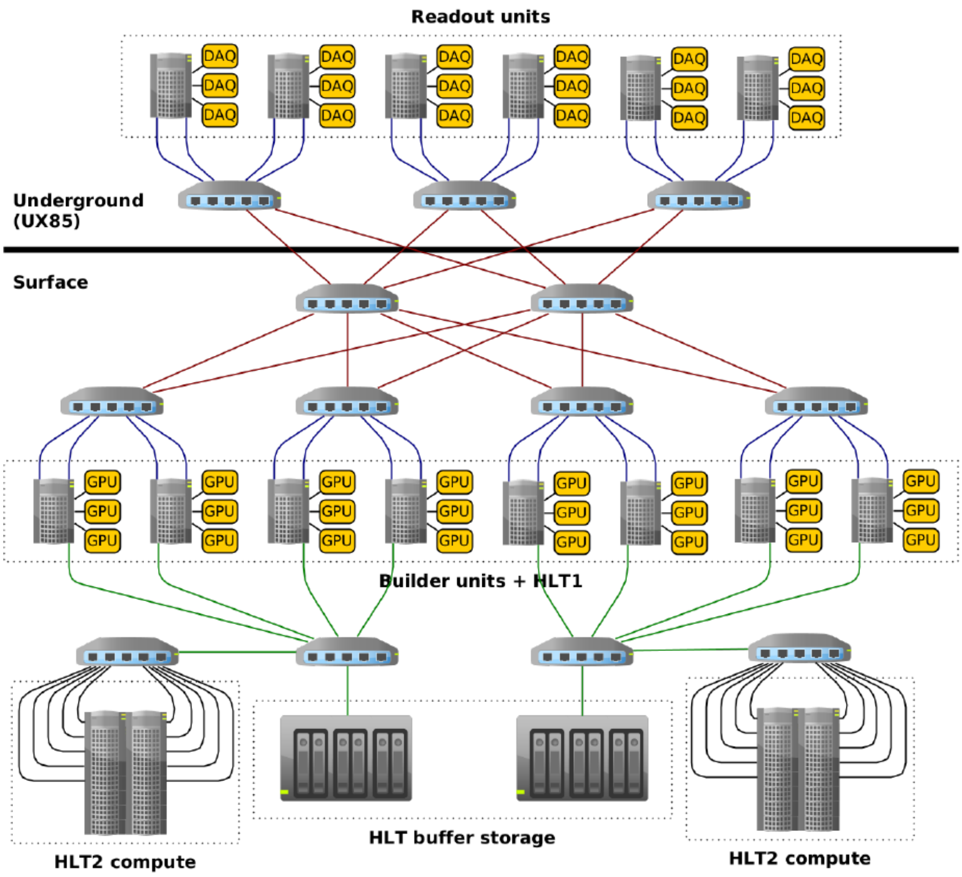

Figure 16: Schema data acquisition system for the LHCb Upgrade II.

The LHCb Upgrade I [5] is designed to operate at a bunch-crossing rate of up to 40 MHz with an average of six proton-proton interactions per bunch crossing. Under these operating conditions, the detector produces an input bandwidth to the data acquisition system of 5 TB/s. For LHCb Upgrade II, the mean number of proton-proton interactions per bunch crossing will increase to up to 40 while the input bandwidth of the data acquisition system can reach 200 TB/s or more.

The readout and data acquisition must be reliable, scalable and as cost-efficient as possible. It should also be flexible for the addition of heterogeneous compute elements for processing. Like in LHCb Upgrade I, we base ourselves on a single custom-made readout board as a building block together with COTS hardware available for data centers.

Since advanced computing technologies are becoming more expensive, only devices produced at a massive scale, such as used by hyper-scale cloud providers, will continue to offer significant performance increase at equal or lower cost. The proposed global architecture, shown in Figure 16, looks therefore quite similar to the one of Upgrade I. This is a single stage readout followed by event-building on a local area network, followed by a two-stage event-filtering by various compute elements. The latter stage is helped by a suitable intermediate storage system if necessary.

It is not possible to consider the architecture independently of the technologies envisaged to be used. We assume the use of Ethernet, PCIe-based computers, the versatile lpGBT link [45] and a custom FPGA based readout module. The distribution of the LHC clock will rely on the White Rabbit system [57] providing a jitter and phase determinism at the level of $\mathcal{O}(10\,\text{ps})$ or even better.

The size of the data acquisition system is driven by the number of lpGBT links and their occupancy. The estimations quoted in the *Framework TDR for the LHCb Upgrade II* [3] are given in Table 5. It shows that link occupancies are suboptimal, when compared to the nominal bandwidth of 9.8 Gbit/s. Concatenating data either on detector or before the readout module in order to push them on very high bandwidth links is an interesting option to be pursued.

Table 5: Number of LpGBT links and their occupancies for LHCb Upgrade II [3]

Sub-detector	DAQ links	Total bandwidth in Tbit/s	Average bandwidth per lpGBT link in Gbit/s
VELO	3 400	34	10.0
UP	1 888	7	3.7
Magnet Station	1 400	5	3.6
Mighty Tracker	9 500	30	3.2
RICH	5 700	30	5.3
TORCH	4 312	27	6.3
PicoCal	2 360	21	8.9
MUON	1 576	16	10.2
Total	30 136	170	

The readout module is one of the key elements of the online system. It is a PCIe card installed in the PC-server of the event-builder. The board provides interfaces between custom protocols used by front-ends and industry-standard protocols used in data-centers, like in the event-builder.

4.1 Genesis and timeline

The PCIe40 readout board designed for LHCb Upgrade I was introduced as a common and multipurpose board in the system. The same hardware is used for the readout of all sub-detectors, and to distribute fast commands as well as the LHC clock to front-end electronics. The board is connected to front-end electronics via 48 GBT links and push data to the event-builder via PCIe buses at over 100 Gbit/s. For Upgrade II, the former protocol will be replaced by the lpGBT one, while the latter will be either PCIe or Ethernet at over 400 Gbit/s. This will allow relying on COTS technologies upstream of the data acquisition chain.

The versatility of the board is obtained by programming different gatewares[2] in the FPGA. For Upgrade II, we will take advantage of the latest technology to cope with the larger volume of data acquired and more stringent requirements on clock distribution. The gateware mostly reorder and time align bunch-crossings, compute primitives like clusters, and concatenate event fragments before transmitting them to the High Level Trigger (HLT). It also formats the raw data in order to speed up the decoding in HLT.

Today, the increasing processing capabilities of new FPGAs encourage more processing in the FPGAs of the readout boards. One pioneering work in this field is the VELO gateware, implementing the Retina-based clustering architecture already in the PCIe40 [58].

The development of the readout board for the Upgrade II will be performed in two steps. A first version, named PCIe400, will be deployed during LS3 while the Upgrade II version should be produced at the horizon of 2030. The PCIe400 accommodates the RICH extension of number of channels as well as the DWT custom processor [8].

During LS3, the LHCb detector will be modified with new front-end electronics for the RICH [7]. It will use Versatile Link+ (VTRx+) with lpGBT protocol and a new ASIC providing time information at the level of $\mathcal{O}(10)$ ps precision. However, the jitter and phase determinism requirements are limited to $\mathcal{O}(50)$ ps by the MaPMTs used in the RICH as they will only be upgraded during LS4. In addition, the TTC system that distributes the LHC clock to the experiments will be modified to use the White Rabbit protocol. This gives an opportunity to test a refined clock distribution architecture after LS3 [59].

The development of the PCIe400, with current technology, is a stepping stone to keep pace with the latest generation of FPGAs being developed for data-centres, and to take advantage of them to build in the future a very large readout system running at over 200 Tbit/s. In addition, the data taking during the Run 4 will be the learning path toward mastering lpGBT links as well as clock distribution at the ultimate precision.

Defining the specification for the Upgrade II version of the readout board is a difficult task as there are many unknowns, namely the roadmap for the future generation of FPGA, the evolution of the computing market, and the processing power required to prepare the sub-detector's raw data for HLT. To prepare these specifications, the collaboration organized its activities around a number of milestones:

- By Q1/2026, the LHCb online team will provide a mini data acquisition system based on the PCIe40 card with lpGBT transceivers and will qualify

[2] Gateware refers to the electronic design and configuration of digital circuits within programmable logic devices, such as field-programmable gate arrays (FPGA) or complex programmable logic devices (CPLDs). It is a term that combines "gate" from digital logic gates and "ware" from software, highlighting the software-like programmability of digital circuits at the gate level.

it for clock jitter and phase determinism to meet the requirement of LS3-enhancement, $\mathcal{O}(50)$ ps precision;

- By the end of 2026, the PCIe400 team will measure data quality on lpGBT links, clock jitter and phase determinism, and performance on high-speed links at 100 Gbit/s;
- By the end of 2026, the back-end Think Tank will have reached its conclusions. This is a small group of experts who are estimating the processing power required in the back-end and studying the optimum data acquisition system from the front-end electronics up to the HLT1 decoding.
- The Upgrade II version of the readout board will be specified in 2027.

Table 6: Envisaged dates for submission to the LHCC of the LHCb Upgrade II Technical Design Reports (TDRs) [6].

Subsystem(s)	Date of TDR
VELO	Q2/2026
Tracker (UP, MT, Magnet Stations)	Q3/2026
PID (RICH, TORCH, PicoCal, Muon)	Q2/2026

The schedule is also defined by the submission dates of the sub-detector TDRs described in the *Scoping document* 6. In addition, the LHCb Collaboration will also prepare a *Framework Data Processing TDR*, by the end of 2026. It will describe a framework for sub-detectors and define the main strategy for the data acquisition system. Finally, the Data Processing TDR should be ready by 2030.

Depending on the results of the ongoing R&D, the occupancy of the lpGBT links and the processing power required in the back-end, there are several options for the integration of the readout board in the data acquisition system for Upgrade II:

1. Only PCIe400 board;
2. PCIe400 with an upstream concentrator that aggregates many low-bandwidth lpGBTs into a medium-bandwidth 25 Gbit/s link. This serves as the input to the PCIe400 card.
3. A mix of PCIe400 and Upgrade II version, the latter with increased processing power;
4. Only Upgrade II version;
5. New idea which can appear in the future.

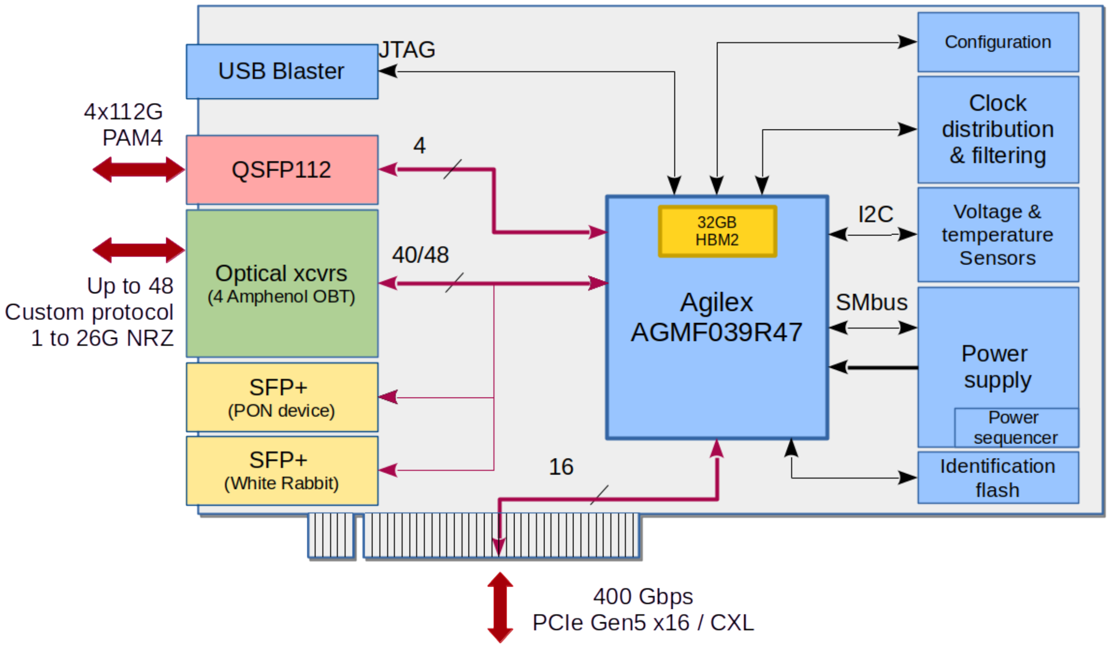

Figure 17: The synoptic of the PCIe400 board.

Figure 18: Photography of the PCIe400 prototype.

4.2 Technical achievements

The synoptic of the PCIe400 board is shown on Figure 17 and the first prototype on Figure 18. The board contains Intel's latest and most powerful FPGA from the Agilex series: AGMF039R47. The FPGA has 4 million logic elements running at up to 1 GHz. A conservative value of 600 MHz already provides a 12x increase in processing power over the PCIe40 board. The PCIe400 card has up to 48 bi-directional links for front-end interfacing between 1 and 26 Gbit/s each. It connects to a PCIe GEN5 x16 bus, giving it an effective bandwidth of 500 Gbit/s with the host server CPU.

The high-end FPGA opens the door to exploratory features: high-speed serial links at 100 Gbit/s; 32 GB integrated memory allowing a data transfer of up to 5.2 Tbit/s with the FPGA fabric; and an ARM Cortex four-core co-processor. They might allow integrating a network interface running the 400GBASE Ethernet protocol over a QSFP112 form factor.

Finally, the card should be able to distribute clocks with an accuracy of around 10 ps by using various time distribution protocols, such as *Passive Optical Network* and *White Rabbit*. More technical details can be found in Ref. [8].

Table 7: Number of readout boards, PCIe400, required for the evolution of the event-builder for Run 4 [8].

Sub-detector	lpGBT links	PCIe400s
RICH	2 500	55
DWT (axial)		64
DWT (stereo)		32
Total	2 940	151

The supply for LS3 is shown in Table 7 and amounts to 151 cards in total without spares. The number of boards to be produced for the Upgrade II system can be estimated from the number of lpGBT links, as they all need to be connected to a board. The total is $\mathcal{O}(750)$ modules without spares. This is comparable to the number of PCIe40 cards produced for LHCb Upgrade I.

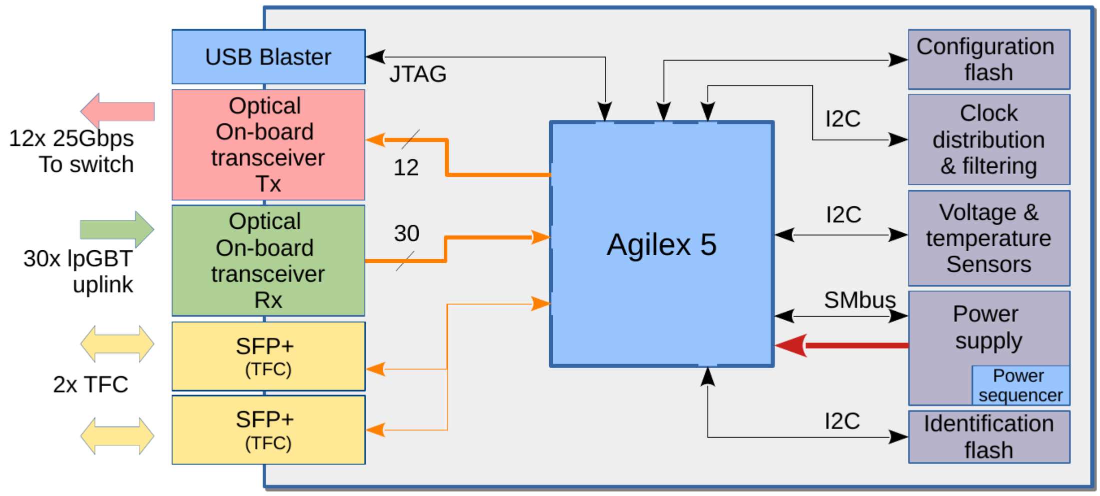

Figure 19: First sketch of a concentrator board upstream to the PCIe400 board.

Reflections are underway to specify a concentrator board upstream of the PCIe400 card. A possible sketch is shown in Figure 19. It is based on a low cost FPGA from the Agilex family. The first Agilex 5 development kits have been ordered and are scheduled for delivery late 2025.

The development of PCIe400 and of the Upgrade II readout system are opportunities to perfect our know-how in cutting-edge technologies that could find applications in future experiments.

4.3 Project organization

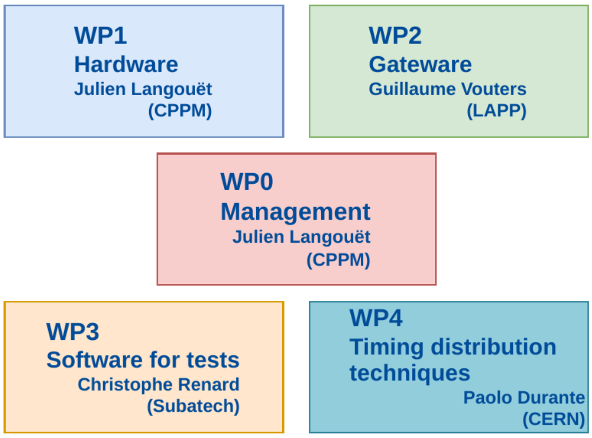

Figure 20: Work packages for the PCIe400 project.

The PCIe400 project organization is summarized in Figure 20. The Scientific Coordinator is *Renaud Le Gac* while the Technical Coordinator is *Julien Langouët*. The work is divided in four Work Packages with the following activities:

- *WP1 Hardware*: preparatory studies, design, qualification, production and maintenance of the PCIe400 cards and of the Upgrade II versions.

- *WP2 Gateware*: the development of the gatewares is limited to the abstraction layer of the hardware board interfaces, known as the *Low Level Interface*. It includes elementary blocks to measure the quality of data transmission and to ensure phase determinism after a power cycle or reset. It also provides the framework for versioning and for the continuous integration of gatewares specific to the sub-detectors.

- *WP3 Software*: the aim of the software development is to implement a battery of tests for qualification and then production testing. The latter is carried out by the company manufacturing the boards. The work package also provides tools to configure and monitor the board.

- *WP4 Timing distribution techniques*: the readout module has to be integrated into a large system, the LHCb detector. The aim of this work package is to validate the board against the LHCb requirements. One of the most critical aspects is the clock distribution with phase determinism in the LHCb configuration, with multiple boards, multiple front-end links and realistic clock interfaces between them and with the LHC.

Table 8: Fields of interest per institutes for the readout board.

Work Packages	Institutes
WP1 Hardware	CPPM, LHCb/Online
WP2 Gateware	CPPM, LAPP
WP3 Software	CPPM, SUBATECH, LHCb/Online
WP4 Timing distribution techniques	CPPM, IJCLab, LPNHE, LHCb/Online

The project is supported by five participating institutes: CPPM, IJCLab, LAPP, LPNHE, SUBATECH and the CERN LHCb/Online team. The fields of interest are given in Table 8.

In September 2024, we assessed the staffing requirements for the PCIe400 project in detail, specifically for the IN2P3 KDP2 review of the LS3 enhancements. For the Upgrade II version, the person-power will depend on the option chosen. It will require the same commitment, $\mathcal{O}(6)$ FTE per year, if the Upgrade II version is similar in complexity to the PCIe400.

		Long shutdown 3			
Work Package	**2025**	**2026**	**2027**	**2028**	**Total (FTE)**
Management	0.7	0.4	0.3	0.3	1.7
Hardware	1.0	1.2	2.1	2.0	6.3
Gateware	2.4	1.7	1.9	0.6	6.6
Software for tests	1.2	1.1	0.4	0.2	2.9
Timing distribution techniques	2.5	2.5	1.0	1.0	7.0
Total (FTE)	**7.9**	**6.8**	**5.6**	**4.1**	**24.5**

Figure 21: Required person-power for the PCIe400 project, estimated in September 2024. For the Upgrade II version, the person-power will depend on the option chosen. It will require the same commitment, if the Upgrade II version is similar in complexity to the PCIe400.

The staff required and available for the PCIe400 is shown in Figure 21 and 22. The comparison between the two tables shows that the PCIe400 project is understaffed by about 20%. The deficit is mainly in the *timing distribution techniques* and *exploratory features*. Efforts are being made to encourage the IN2P3 institutes to increase their contributions to this flagship project.

The project is also part of the LHCb collaboration. In December 2024, the PCIe400 became a subproject of the LHCb Online project. In agreement with the LHCb management, the Online Project Leader appointed Renaud Le Gac as a deputy project leader in charge of the development of future back-end boards. The aim is to strengthen the collaboration between the online project and the teams responsible for the development of new readout boards for the LS3 enhancement

Physicists	Run 3	LS3			Total
	2025	2026	2027	2028	
CPPM	0.5	0.5			**1.00**

Engineers	Run 3	LS3			Total
	2025	2026	2027	2028	
CPPM	2.45	2.30	2.20	1.70	**8.65**
IJCLab	0.50	0.50			**1.00**
LAPP	0.15	0.15	0.15	0.15	**0.60**
LPNHE	0.80	1.00	1.00	1.00	**3.80**
SUBATECH	0.75	0.75	0.75	0.75	**3.00**
LHCb/Online	0.50	0.80	0.80	0.80	**2.90**
TOTAL (FTE)	**5.65**	**6.00**	**4.90**	**4.40**	**20.95**

Figure 22: Available person-power for the PCIe400 project, estimated in September 2024.

and Upgrade II, which is essential to achieve the required data rates and timing accuracies. It also gives visibility to the back-end development project and will attract new contributors.

4.4 Schedule and costs

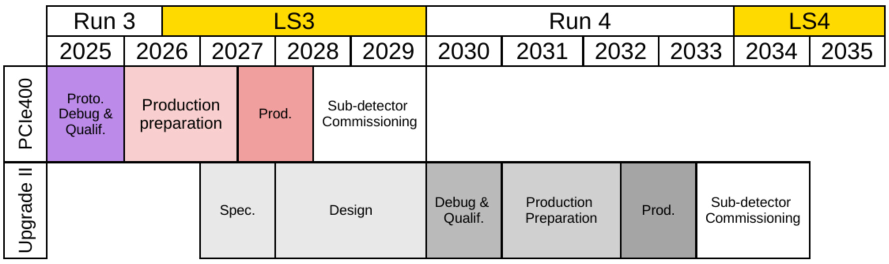

Figure 23: Master schedule for PCI400 and Upgrade II readout boards. It is based on the latest LHC schedule release in September 2024.

The master schedule for the PCIe400 board and the Upgrade II version is shown in Figure 23. The year 2025 will be dedicated to debugging and qualifying the PCIe400 prototype. If there are no showstoppers after the debug phase, the prototype can be duplicated in the second half of 2025. A handful of boards may be useful for the online, RICH and DWT projects to gain experience for their use in LS3. Once the PCIe400 is qualified, it will take 18 months to prepare for production and about a year to manufacture. By mid-2028, all boards will be delivered to the collaboration, ready for installation in the pit, leaving 18 months for detector commissioning.

For the schedule of the Upgrade II version, we assume that: a) the final version will be similar in complexity to the PCIe400; b) the Intel company will provide a new family of FPGA increasing the processing power; and c) the processing power required in the back-end will exceed the capacity of the PCIe400. In this scenario, based on the experience of the PCIe400, installation and commissioning can begin as early as the second half of 2032, when the first batch arrives.

The total cost of the PCIe400 and Upgrade II developments is given in Figure 24. The production of the boards is funded by the sub-detector projects. Only pre-series boards and tooling required for the Electronic Manufacturing Services production line should be financed by IN2P3.

Item	Run 3		LS3			Run 4				LS4		Total
	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	
Test bench	10											10
Study liquid cooling		16										16
Production tools at EMS	20	35										55
PCIe400 production pre-series		150										150
Development kits	16	8	2									26
Prototypes Upgrade II version				10	300							310
Production tools at EMS						60						60
Upgrade II production pre-series							240					240
Total per year	46	209	2	10	300	60	240					867

Figure 24: IN2P3 funding for the PCIe400 and Upgrade II readout boards.

The unit cost estimate for the PCIe400 is based on prototype procurement and subcontractor costs. The board production's cost estimate includes 10 year warranty overheads and takes into account economies of scale for a quantity above 100 boards. Reference prices are in Euros, except for the FPGA which is in USD and represent 50% of the unit cost estimate. We should keep in mind that architectural choice of the Upgrade II board may evolve as well as the cost in the coming years.

4.5 Risks

Retirement of the Scientific Coordinator. Additional resources made available by CPPM or project taken on by someone from another participating institutes.

Departure of a project member with a key skill. Follow up on the recruitment strategies in the light of the identified competences with the participating institutes and IN2P3 management.

Reduction in workforce due to non-extension of fixed-term contracts or non-appointment of permanent staff. Reallocation of tasks to other members of the project team or identification of a new member of staff through networks.

No phase determinism for Agilex transceivers. The PCIe40 might be a backup solution for Run 4. Another approach is to use competitor board for the time distribution.

Non-functional PCIe400 prototype. Reorganizing the schedule to bring forward the revision phase.

Delays in development and qualification due to technical difficulties. No more duplication of prototype boards. PCIe Gen5 servers will be qualified using the four prototype boards, while RICH sub-detector developers will use the PCIe40 board.

5 Conclusions

The Standard Model of particle physics has been remarkably successful in describing the fundamental constituents of nature and their interactions. However, it remains unable to explain features such as dark matter or the baryon density of the universe. Searching beyond the Standard Model requires the exploration of higher energy scales. A particularly powerful way to do this is to precisely measure known Standard Model processes where new particles or mediators can participate virtually. This probes energy scales from tens to tens of thousands of TeV, and particle masses beyond the reach of direct searches.

The LHCb experiment is one of the most sensitive instruments for indirect searches in operation. Over the past decade, LHCb measurements have improved our knowledge of the CKM mechanism, discovered CP violation in charm meson decays, and placed strong constraints on particles beyond the Standard Model by studying rare and forbidden Standard Model processes. The robustness of the detector and the adaptability of its data processing model have also led to the discoveries of tetra- and penta-quark exotic states. A unique programme of heavy-ion physics at forward pseudorapidities was initiated. The vast majority of interesting observables measured by LHCb will be statistically limited at the end of the detector's operation and second upgrade of the detector is proposed to fully exploit the HL-LHC, including for flavour physics.

LHCb Upgrade II will be installed after the completion of Run 4. It will be possible to operate at instantaneous luminosity of up to $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, by increasing granularity and by using radiation-hard technologies, while maintaining or even exceeding the detector performance in the current experiment. A total of more than $300\,\mathrm{fb}^{-1}$ will be integrated by the end of HL-LHC operation, and will provide unprecedented sensitivity to physics beyond the Standard Model and provide several other unique opportunities in hadron spectroscopy, precision electroweak measurements, dark sector searches and studies of heavy ion collisions.

The baseline choices for the detector design have been consolidated and estimated to amount to 182 MCHF. Detector scoping options have been explored, with the aim of identifying scenarios that reduce cost and complexity of the overall project. Two descoped scenarios, Middle and Low, are identified with costs estimated at 156 MCHF and 125 MCHF. In both cases, the peak luminosity is reduced from 1.5 to $1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Due to the longer levelling time at the lower peak luminosity, the reduction in the total integrated luminosity is proportionally less than that of the peak luminosity, but is still significant.

The impact of the different scenarios on physics performance has been investigated. The Middle scenario has less redundancy than the Baseline, with the reduction in ability to operate at the highest pile-up reducing the flexibility to compensate for possible changes in the LHC operation. Nevertheless, this scenario is still expected to provide robust tracking and PID performance. In the Low scenario, the loss of redundancy in detector features puts at risk the success of some key measurements that require the full capabilities of the detector.

The IN2P3 flavour physics community has played a key role in LHCb since the design of the original detector. It has made pioneering contributions to the calorimeter, SciFi, the trigger system, detector readout and reconstruction, and the measurement of key flavour observables. In this document we propose major contributions for LHCb Upgrade II: the development of a highly granular calorimeter with particle timing measurement at the ps level; a 200 Tbit/s full detector readout using a generic and highly flexible data acquisition board; and a real-time physics-quality reconstruction in both proton and heavy-ion collisions driven by highly parallel heterogeneous computing architectures. The increase of the community with heavy-ion physicists gives the opportunity to participate in the silicon pixel tracking detectors.

The estimated cost envelopes for IN2P3 depend on the scoping scenarios. Assuming a fair share fraction of 6.85% to estimate common fund contributions, the IN2P3 funding is expected to be 10 M€ for the Baseline, 9 M€ for the Middle and 8 M€ for the Low scenarios. The estimated person-power requirements over a ten-year period (2025 – 2035) are 90 FTE for the calorimeter, 54 FTE for the generic readout card and 52 FTE for the real-time processing.

References

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

[2] 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.

[3] 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.

[4] LHCb collaboration, A. A. Alves, Jr. *et al.*, *The LHCb Detector at the LHC*, JINST **3** (2008) S08005.

[5] LHCb collaboration, R. Aaij *et al.*, *The LHCb Upgrade I*, JINST **19** (2024) P05065, arXiv:2305.10515.

[6] LHCb collaboration, *LHCb Upgrade II Scoping Document*, CERN-LHCC-2024-010, 2024.

[7] LHCb collaboration, *LHCb Particle Identification Enhancement Technical Design Report*, CERN-LHCC-2023-005, 2023.

[8] LHCb collaboration, *LHCb Data Acquisition Enhancement Technical Design Report*, CERN-LHCC-2024-001, 2024.

[9] LHCb collaboration, R. Aaij *et al.*, *Simultaneous determination of CKM angle γ and charm mixing parameters*, JHEP **12** (2021) 141, arXiv:2110.02350.

[10] LHCb collaboration, *Simultaneous determination of the CKM angle γ and parameters related to mixing and CP violation in the charm sector*, LHCb-CONF-2024-004, 2024.

[11] Belle-II collaboration, L. Aggarwal *et al.*, *Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond*, arXiv:2207.06307.

[12] LHCb collaboration, R. Aaij *et al.*, *Improved measurement of CP violation parameters in $B_s^0 \to J/\psi K^+K^-$ decays in the vicinity of the $\phi(1020)$ resonance*, Phys. Rev. Lett. **132** (2024) 051802, arXiv:2308.01468.

[13] LHCb collaboration, R. Aaij *et al.*, *Measurement of the semileptonic CP asymmetry in B^0–$\overline{B}^0$ mixing*, Phys. Rev. Lett. **114** (2015) 041601, arXiv:1409.8586.

[14] LHCb collaboration, R. Aaij *et al.*, *Measurement of the CP asymmetry in B_s^0–$\overline{B}_s^0$ mixing*, Phys. Rev. Lett. **117** (2016) 061803, arXiv:1605.09768.

[15] LHCb collaboration, R. Aaij *et al.*, *Observation of CP violation in charm decays*, Phys. Rev. Lett. **122** (2019) 211803, arXiv:1903.08726.

[16] A. L. Kagan and L. Silvestrini, *Dispersive and absorptive CP violation in $D^0 - \overline{D^0}$ mixing*, Phys. Rev. D **103** (2021) 053008, arXiv:2001.07207.

[17] LHCb collaboration, R. Aaij *et al.*, *Measurement of the time-integrated CP asymmetry in $D^0 \to K^-K^+$ decays*, Phys. Rev. Lett. **131** (2023) 091802, arXiv:2209.03179.

[18] LHCb collaboration, R. Aaij *et al.*, *Analysis of neutral B-meson decays into two muons*, Phys. Rev. Lett. **128** (2022) 041801, arXiv:2108.09284.

[19] LHCb collaboration, R. Aaij *et al.*, *Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ decays*, Phys. Rev. **D105** (2022) 012010, arXiv:2108.09283.

[20] LHCb collaboration, R. Aaij *et al.*, *Search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay*, JHEP **07** (2024) 101, arXiv:2404.03375.

[21] LHCb collaboration, R. Aaij *et al.*, *Measurement of lepton universality parameters in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays*, Phys. Rev. **D108** (2023) 032002, arXiv:2212.09153.

[22] LHCb collaboration, R. Aaij *et al.*, *Test of lepton universality in $b \to s\ell^+\ell^-$ decays*, Phys. Rev. Lett. **131** (2023) 051803, arXiv:2212.09152.

[23] G. Bozzi, L. Citelli, M. Vesterinen, and A. Vicini, *Prospects for improving the LHC W boson mass measurement with forward muons*, Eur. Phys. J. **C75** (2015) 601, arXiv:1508.06954.

[24] LHCb collaboration, R. Aaij *et al.*, *Measurement of the W boson mass*, JHEP **01** (2022) 036, arXiv:2109.01113.

[25] A. Bodek, *A simple event weighting technique for optimizing the measurement of the forward-backward asymmetry of Drell-Yan dilepton pairs at hadron colliders*, Eur. Phys. J. **C67** (2010) 321, arXiv:0911.2850.

[26] LHCb collaboration, R. Aaij *et al.*, *Measurement of the effective leptonic weak mixing angle*, JHEP **12** (2024) 026, arXiv:2410.02502.

[27] W. J. Barter, *Prospects for measurement of the weak mixing angle at LHCb*, LHCb-PUB-2018-013, 2018.

[28] J. F. Grosse-Oetringhaus and U. A. Wiedemann, *A Decade of Collectivity in Small Systems*, arXiv:2407.07484.

[29] ALICE collaboration, J. Adam *et al.*, *Centrality dependence of the pseudorapidity density distribution for charged particles in Pb–Pb collisions at* $\sqrt{s_{NN}} = 5.02$ *TeV*, Physics Letters B **772** (2017) 567.

[30] LHCb collaboration, *Physics opportunities for heavy-ion and fixed-target physics with LHCb Upgrade II*, LHCb-PUB-2024-007, 2024.

[31] M. Coquet *et al.*, *Intermediate mass dileptons as pre-equilibrium probes in heavy ion collisions*, Phys. Lett. B **821** (2021) 136626.

[32] M. Coquet *et al.*, *Dilepton polarization as a signature of plasma anisotropy*, Phys. Rev. Lett. **132** (2024) 232301.

[33] X. Dong, Y.-J. Lee, and R. Rapp, *Open Heavy-Flavor Production in Heavy-Ion Collisions*, Ann. Rev. Nucl. Part. Sci. **69** (2019) 417, arXiv:1903.07709.

[34] M. He and R. Rapp, *Charm-Baryon Production in Proton-Proton Collisions*, Phys. Lett. B **795** (2019) 117, arXiv:1902.08889.

[35] LHCb collaboration, R. Aaij *et al.*, *Observation of Enhanced Double Parton Scattering in Proton-Lead Collisions at* $\sqrt{s_{NN}}$ *=8.16 TeV*, Phys. Rev. Lett. **125** (2020) 212001, arXiv:2007.06945.

[36] LHCb collaboration, R. Aaij *et al.*, *Observation of Multiplicity Dependent Prompt* $\chi_{c1}(3872)$ *and* $\psi(2S)$ *Production in pp Collisions*, Phys. Rev. Lett. **126** (2021) 092001, arXiv:2009.06619.

[37] L. Apolinario, Y.-J. Lee, and M. Winn, *Heavy quarks and jets as probes of the QGP*, Prog. Part. Nucl. Phys. **127** (2022) 103990.

[38] T. Matsui and H. Satz, *J/ψ suppression by quark-gluon plasma formation*, Phys. Lett. B **178** (1986) 416.

[39] CMS collaboration, A. Tumasyan *et al.*, *Observation of the* $\Upsilon(3S)$ *Meson and Suppression of* Υ *States in Pb-Pb Collisions at sNN=5.02 TeV*, Phys. Rev. Lett. **133** (2024) 022302, `arXiv:2303.17026`.

[40] ALICE collaboration, S. Acharya *et al.*, Υ *production and nuclear modification at forward rapidity in Pb-Pb collisions at* $\sqrt{s_{\rm NN}} = 5$ *TeV*, Phys. Lett. B **822** (2021) 136579, `arXiv:2011.05758`.

[41] ATLAS collaboration, G. Aad *et al.*, *Production of* $\varUpsilon(nS)$ *mesons in Pb+Pb and pp collisions at 5.02 TeV*, Phys. Rev. C **107** (2023) 054912, `arXiv:2205.03042`.

[42] LHCb collaboration, R. Aaij *et al.*, *Measurement of the* $\psi(2S)$ *to* J/ψ *cross-section ratio as a function of centrality in PbPb collisions at* $\sqrt{s_{NN}} = 5.02$ *TeV*, `arXiv:2411.05669`.

[43] O. B. Garcia *et al.*, *High-density gas target at the LHCb experiment*, Phys. Rev. Accel. Beams **27** (2024) 111001.

[44] C. Abellán Beteta *et al.*, *Calibration and performance of the LHCb calorimeters in Run 1 and 2 at the LHC*, `arXiv:2008.11556`.

[45] lpGBT project collaboration, *Low Power GigaBit Transceiver (web page)*, `http://lpgbt-fpga.web.cern.ch/doc/html/`.

[46] D. Breton, E. Delagnes, J. Maalmi, and P. Rusquart, *The WaveCatcher family of SCA-based 12-bit 3.2-GS/s fast digitizers*, in *2014 19th IEEE-NPSS Real Time Conference*, 1–8, 2014.

[47] D. Breton *et al.*, *Measurements of timing resolution of ultra-fast silicon detectors with the SAMPIC waveform digitizer*, Nucl. Instrum. Meth. A **835** (2016) 51, `arXiv:1604.02385`.

[48] P. Robbe, *Projet LHCb-ECAL2*, Journées R&T IN2P3 Strasbourg, Nov 2023.

[49] B. Joly, *Status of SPIDER development*, Presentation 14 Nov 2024.

[50] R. Aaij *et al.*, *Allen: A High-Level Trigger on GPUs for LHCb*, Computing and Software for Big Science **4** (2020) , `arXiv:1912.09161`.

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

[52] R. Aaij *et al.*, *A Comparison of CPU and GPU implementations for the LHCb experiment Run 3 trigger*, Comput Softw Big Sci **6** (2022) , `arXiv:2105.04031`.

[53] R. Aaij *et al.*, *Evolution of the energy efficiency of LHCb's real-time processing*, EPJ Web Conf. **251** (2021) , arXiv:2106.07701.

[54] G. Eulisse and D. Rohr, *The O2 software framework and GPU usage in ALICE online and offline reconstruction in Run 3*, Arxiv (2024) , arXiv:2402.01205.

[55] A. Bocci *et al.*, *Bringing heterogeneity to the CMS software framework*, EPJ Web of Conferences **245** (2020) , arXiv:2004.04334.

[56] M. Kiehn *et al.*, *The TrackML high-energy physics tracking challenge on Kaggle*, EPJ Web Conf **214** (2019) 06037.

[57] T. Włostowski *et al.*, *White Rabbit and MTCA.4 use in the LLRF upgrade for CERN's SPS*, https://ohwr.org/project/white-rabbit/wikis/uploads/76d4587a2943d1ed0a1d605242d1979c/THBR02.pdf, 2021.

[58] G. Bassi *et al.*, *A FPGA-Based Architecture for Real-Time Cluster Finding in the LHCb Silicon Pixel Detector*, IEEE Transactions on Nuclear Science **70** (2023) 1189.

[59] F. Alessio and P. Durante, *Timing and Fast Control architecture for the Run4 LHCb readout system*, LHCb-INT-2024-016, 2024.