PROCEEDINGS OF SCIENCE

# Prospects of the Upgrade II of LHCb

**Alessandro Minotti**[a,*]

[a] *Università degli studi di Milano Bicocca, Piazza dell'Ateneo Nuovo, 1, 20126 Milano MI*

*E-mail:* alessandro.minotti@unimib.it, alessandro.minotti@cern.ch

The Large Hadron Collider beauty (LHCb) experiment has achieved remarkable milestones in the quest for Beyond the Standard Model (BSM) physics through its extensive exploration of rare decays, precise measurements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, and investigations into exotic hadrons. Additionally, it has made significant contributions to tests of lepton universality, charm physics, and electroweak physics. The upcoming LHCb Upgrade II, building on the successes of Runs 1 and 2, aims to further our understanding of fundamental particles and interactions by probing new physics phenomena. This article discusses the rationale for Upgrade II, and the key elements of the upgraded detector.

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## 1. Introduction

The LHCb experiment, situated at the Large Hadron Collider (LHC), has been at the forefront of particle physics research, making significant contributions to several key areas in flavour physics such as rare decay physics, constraints on the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, exotic hadron searches, tests of lepton universality, charm and electroweak physics, and also fixed target physics [1].

The absence of direct evidence for new physics (NP) at lower energy scales suggests that NP may either be very heavy or highly complex. Exploration of processes involving the decays of $B$ or $D$ mesons provides a unique opportunity to probe NP indirectly. Precision tests of lepton universality and accurate measurements of CKM amplitudes and phases (figure 1) will put LHCb in the best position to unveil NP effects [2]. To achieve the above goals, LHCb already underwent a major detector upgrade, named Upgrade I, which will allow the experiment to integrate $\sim 50\,\mathrm{fb}^{-1}$ within the Run 4 of High Luminosity LHC (HL-LHC). After that, a second upgrade, named Upgrade II, is proposed, with the purpose of integrating $\sim 50\,\mathrm{fb}^{-1}$/year during Run 5 and Run 6 of HL-LHC (table 1). This will allow to fully exploit the potential of the HL-LHC machine in the flavour physics domain, and LHCb will be the primary general purpose flavour physics experiment taking data in this period. Key challenges for Upgrade II include high radiation levels, extreme event complexity, and data rate. Finding the optimal detector design to address those challenges, and developing the appropriate technology solutions, form the foundation for the success of Upgrade II.

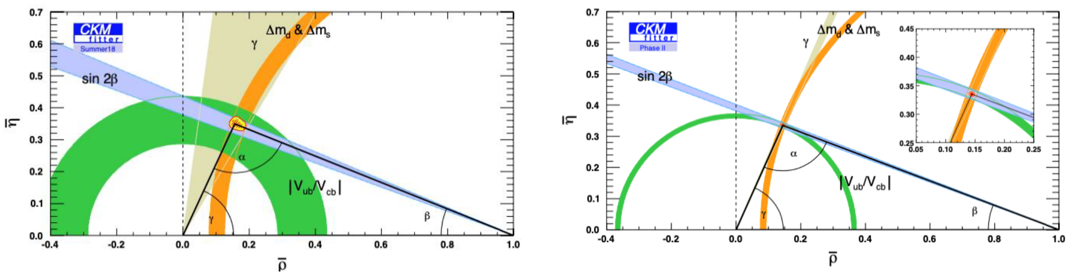


**Figure 1:** Unitary triangle obtained with measurements from LHCb at the end of Run 2 (left) and after Upgrade II (right) [3].

| | Upgrade I | Upgrade II |
|---|---|---|
| HL-LHC Runs | Run 3-4 | Run 5-6 |
| Peak Luminosity ($L_{peak}$) | $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ |
| Integrated Luminosity ($L_{int}$) | $50\,\mathrm{fb}^{-1}$ | $300\,\mathrm{fb}^{-1}$ |

**Table 1:** Comparison of luminosity of LHC and HL-LHC and the impact on LHCb Upgrade I and II.

## 2. The LHCb Upgrade II

LHCb Upgrade II maintains the same basic structure while refurbishing all subdetectors (figure 2). The goal is to maintain or improve performance despite a sevenfold increase in pileup compared to Run 3. Key features for each subdetector include granularity, fast timing, and radiation hardness. Ongoing research and development efforts are critical to achieving these goals [4].

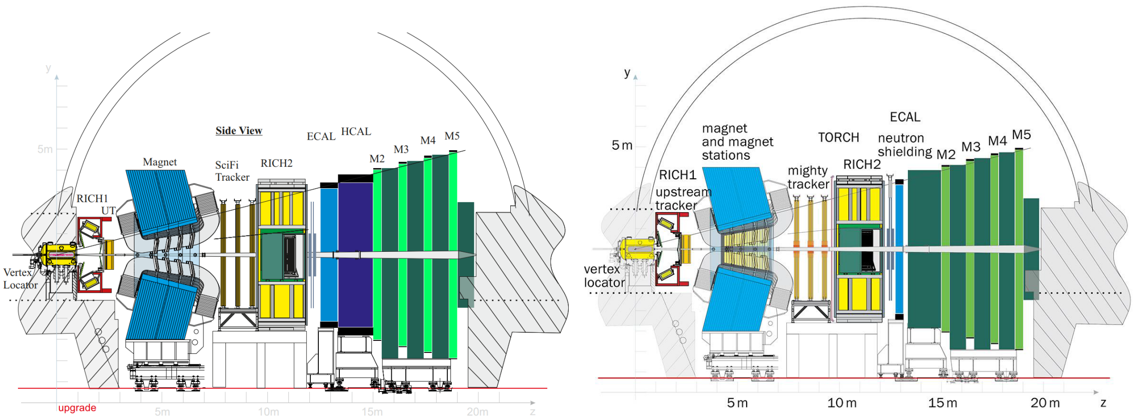


**Figure 2:** Side view of LHCb and its subdetectors as it is now (left), and as it will be after Upgrade II (right).

## 2.1 Vertex Locator (VELO)

The peak luminosity of $1.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ leads to $\sim$ 42 interactions per crossing or approximately 2,000 charged particles in the VELO acceptance. Performances comparable to the Upgrade I are achieved through timestamping, enabling 20 ps track resolution [5]. Ongoing research explores various technologies, including LGADs, 3D trench silicon sensors, and ultra-fast planar silicon sensors. For the front-end (FE) electronics, the TIMESPOT demostrator chip (28 nm CMOS) [6] shows excellent time resolution (figure 3), while the PicoPix design is also under study.

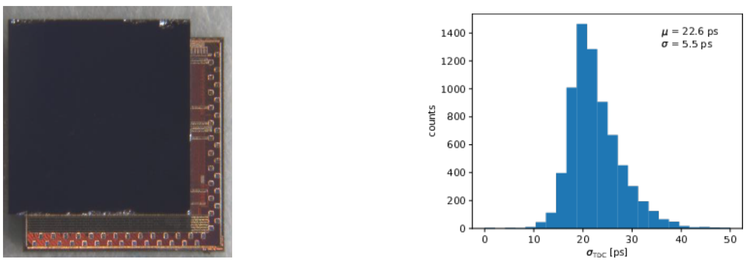


**Figure 3:** The 55 $\mu$m pitch 32x32 pixels hybridized Timespot1 ASIC (left) and the time resolution in different pixel, averaging an RMS of 22.6 ps (right) [6].

## 2.2 Upstream (UT) and Mighty Tracker (MT)

The high track density in Upgrade II necessitates active pixel detectors upstream (UT) and downstream (MT) of the magnet. Requirements include a few ns resolution, minimal material budget, and high radiation tolerance. To meet these specifications, detector options include DMAPS (Depleted Monolithic Active Pixel Sensors) coupled with CMOS electrodes for the inner part of the MT and the whole UT, and scintillating fibers coupled with SiPMs (SciFi) for the outer MT, to meet these specifications (figure 4). Research and development focus on improving timing resolution and radiation hardness of DMAPS [7]. Prototypes and testing are ongoing, including thermal testing and studies of cooling methods. SciFi R&D aims to reduce SiPM dark noise and improve radiation hardness.

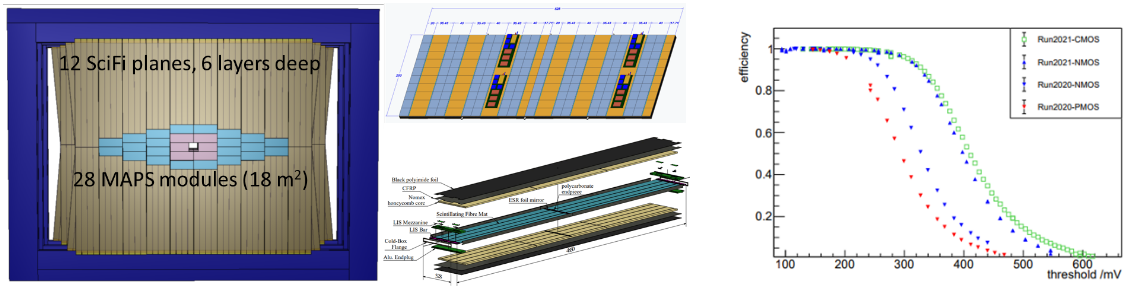


**Figure 4:** Design of the upgraded Mighty Tracker (left), and performance of DMAPS in terms of efficiency (right) [7].

### 2.3 Magnet Station (MS)

The MS is a new system proposed for Upgrade II, consisting of scintillating-based tracking chambers installed on the magnet inner walls, with the purpose of increasing acceptance for low-momentum particles and of enhancing momentum resolution fro upstream tracks. The chamber design is based on scintillating bars equipped with wavelength-shifting fibers and SiPMs for photon readout.

### 2.4 RICH Detectors

The redesign of the RICH systems with improved timing and Cherenkov angle resolution is essential to cope with the high luminosity. The tilt of RICH1 mirrors will be reduced to decrease chromatic aberration (figure 5). The foreseen resolution will be 0.22 (0.13) mrad for RICH1 (RICH2). Exploratory research includes the use of SiPMs and microchannel plate (MCP) sensors for high-occupancy regions. For the former, ongoing efforts aim to reduce dark count rates and improve radiation tolerance (cryogenic cooling, n-shielding). Other R&D include the testing of new gas mixtures to improve angular precision.

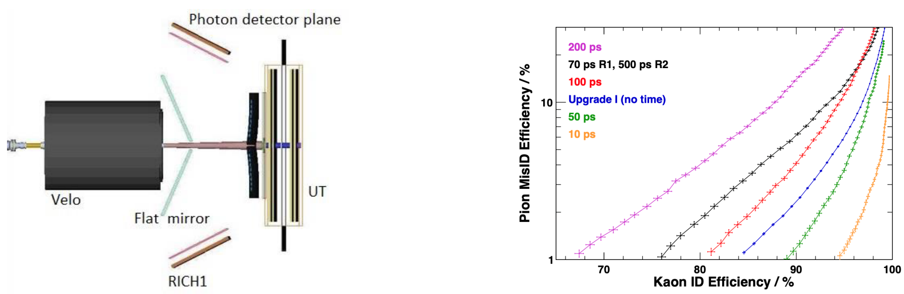


**Figure 5:** Top view of the RICH1 subdetector (left), and a plot showing the effect of timing on the PID performance (right) [4].

### 2.5 TORCH

The TORCH Time-of-Flight (ToF) detector uses quartz planes which generate photons and which are read out by micro channel plate PMTs [8]. The detector will be located in front of RICH2. It improves particle identification for low-momentum particles, offering benefits for multiple physics channels.

### 2.6 Electromagnetic Calorimeter (ECAL)

Upgrade II requirements for the ECAL include increased radiation tolerance (up to 1 MGy in the innermost region), while retaining present energy resolution ($\sigma(E)/E = 10\%/\sqrt{E} \oplus 1\%$), precise timing ($\sim 10\,\text{ps}$) to mitigate pileup, and higher granularity. A modular structure, including SpaCal (Spaghetti Calorimeter, for the inner region, figure 6) and Shashlik (for the outer region) modules, is employed to achieve these objectives. Ongoing research investigates radiation-hard materials and timing improvement for both SpaCal and Shashlik technologies, showing excellent resolution [9]. The upgrade strategy foresees a gradual implementation of SpaCal modules during LS3 and LS4.

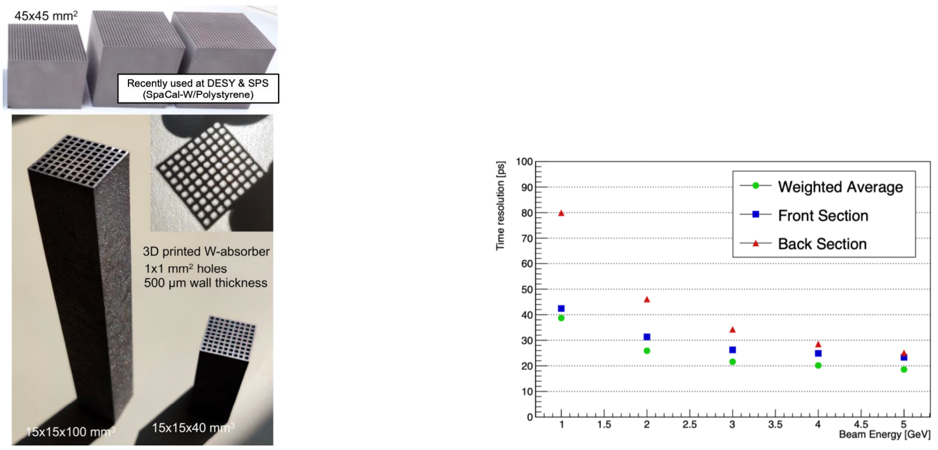


**Figure 6:** 3D printed tungsten absorber prototypes for the ECAL (left) and their measured time resolution (right) [9].

### 2.7 Muon Station

Novel micro pattern gas detectors (muRWELL) [10] are introduced for the inner region, while existing multi-wire proportional chambers are retained for the outer region. Additional shielding (from 6 to 10 absorption lengths) reduces particle rate while maintaining trigger and hadron reconstruction capabilities.

### 2.8 Trigger and Data Acquisition

Upgrade II demands reliable, scalable, cost-effective, and flexible readout and DAQ systems. A single-stage readout, local network event building, and two-stage high-level trigger (HLT1 & HLT2) architecture are utilized, similarly to Run 3. The system will have to process about 200 Tb/s of data flowing from the detector, a factor of $\sim 5$ above Run 3. The full throughput of events


**Figure 7:** Data taking and shutdown plans for LHC.

will be reconstructed and analysed by a software trigger, building on the experience accumulated during Run 3, where an HLT1 processing stage entirely based on GPUs has been successfully deployed [11].

## 3. Status and Timeline of Upgrade II

The LHCb Upgrade II project has made significant progress, with the Framework Technical Design Report (FTDR) approved in March 2022 [4]. Detailed plans, scoping scenarios, and adequate resources are being developed to complement this achievement. The collaboration aims to produce a Scoping Document by 2024. In the coming years, the priority for the LHCb collaboration is to fully exploit the physics potential of the Upgrade I detector. Simultaneously, plans for Upgrade II are being formulated, mindful of time constraints and the need for careful preparation (figure 7). R&D efforts will persist throughout Run 3, preceding the development of sub-detector Technical Design Reports (TDRs). This proactive approach is essential for ensuring that the upgraded detector can meet its ambitious scientific goals. Infrastructure preparation and the construction of the upgraded detector should commence during Long Shutdown 3 (LS3). This critical phase will lay the groundwork for the installation and operation of Upgrade II, which is anticipated to be ready for installation during Long Shutdown 4 (LS4).

LHCb has witnessed strong interest and support from the scientific community, exemplified by the twofold increase in the collaboration's size over the last decade. This growing interest will propel the ambitious goals outlined in the Framework TDR of Upgrade II [4].

## 4. Conclusion

LHCb's pursuit of new physics and precision measurements underscores its commitment to advancing our understanding of the universe's fundamental building blocks. The LHCb Upgrade II project, with its ambitious objectives, rigorous timeline, and the indispensable support of a growing collaboration, promises to usher in a new era of discovery in the field of particle physics.

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