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Goals and performance of LHCb Upgrade II

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The proposed major upgrade of the LHCb detector for LHC Runs 5 and 6 aims to enhance the precision of flavour-physics observables significantly. Known as Upgrade II, this initiative is scheduled for implementation during the long shutdown 4 of the LHC. The upgraded detector is designed to operate at a maximum luminosity of $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, targeting an integrated luminosity of approximately $300\,\mathrm{fb}^{-1}$ over the lifespan of the high-luminosity LHC (HL-LHC). The ambitious goals of this upgrade demand the maintenance of the current detector performance, even in the face of an expected average number of simultaneous proton-proton collisions per bunch crossing (pileup) of around 42 which will be 7 times that of Run 4. To meet this challenge, the plan includes the replacement of all existing subdetector components to enhance granularity, reduce detector material, and incorporate new technologies, such as precision timing at the scale of a few tens of picoseconds. Here we discuss design considerations for each sub-detector, ongoing efforts to address technology challenges, goals and performances of LHCb Upgrade II.

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1. Introduction

The LHCb experiment, based at the Large Hadron Collider (LHC) at CERN, is uniquely designed for the precision study of heavy flavour decays, particularly those involving the bottom quark. The production of $b\bar{b}$ pairs predominantly occurs in the forward and backward directions. Hence, LHCb is configured as a single-arm forward spectrometer within the pseudorapidity range of 2 to 5. This setup enables the experiment to detect about 30% of the b hadrons produced in proton-proton (pp) collisions.

During the first major upgrade [2], the detector underwent significant modifications, with over 90% of its active electronics, detector channels, and the data acquisition system replaced. Figure 1 shows the timeline of the LHC overlaid with the LHCb instantaneous and integrated luminosities. In Run 3, the operational luminosity is set at $\mathcal{L}_{\text{inst}} = 2 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$, which is five times the luminosity achieved in Run 2.

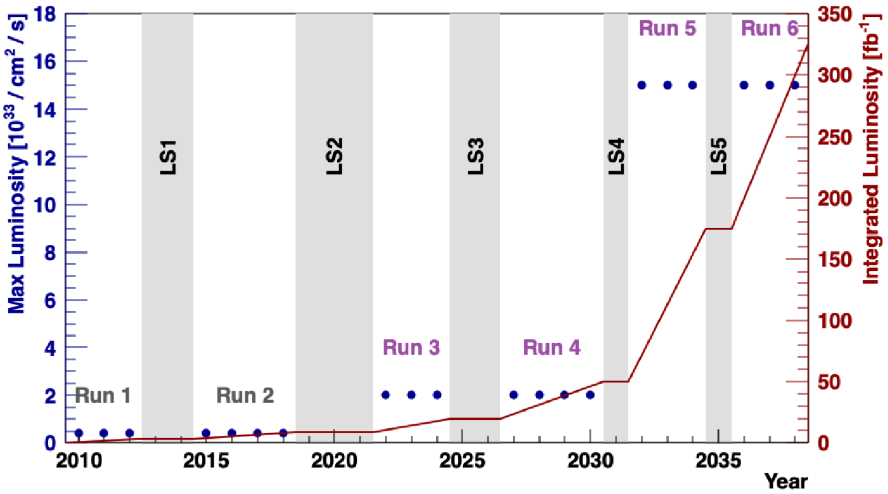

Figure 1: Cumulative luminosity progression for LHCb's initial deployment, subsequent Upgrade I (during Runs 3 and 4), and the forthcoming Upgrade II (encompassing Runs 5 and 6), aligned with the 2021 ratified LHC timetable. In this depiction, blue markers alongside the left vertical axis signify projected peak instantaneous luminosities, whereas the red trajectory aligned with the right axis showcases the total integrated luminosity over time. Figure from Ref. [1].

2. LHCb Upgrade II

The LHCb Upgrade II, entailing preparatory work during Long Shutdown 3 (LS3) and major construction and installation during Long Shutdown 4 (LS4), is set to span Runs 5 and 6 of the LHC, currently anticipated to commence in 2032. This upgrade will require the detector to operate at peak luminosity of $1.5 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$, which will represent an increase of approximately 7.5 times the instantaneous luminosity of Run 4.

Different operational strategies at high luminosity have been studied for Upgrade II, transitioning from the constant luminosity conditions experienced during Run 2 and Run 3 to a regime characterized by a brief leveling period followed by an extended exponential decay. Due consideration of optimal LHC beam configuration parameters are crucial for supporting the precision measurements that are central to LHCb's physics objectives.

2.1 Physics case

The Upgrade II physics program builds on previous successes, further expanding the physics program of flavour physics, spectroscopy, QCD, electroweak physics, heavy ion opportunities, and long-lived particles. The upgrade is planned with a goal to accumulate a minimum of 300 fb^{-1} of data, significantly enhancing the precision of various observables.

The achievements of LHCb in Runs 1 and 2 have validated its design and underscored its importance in heavy flavour physics. Notable achievements include the discovery of CP violation in the charm sector and the B_s^0 system, contributions to the study of lepton flavour universality, and the observation of exotic hadronic states such as tetraquarks and pentaquarks.

LHCb's approach to testing the Standard Model (SM) through precision measurements in flavour physics complements the search for new particles at high energies. Decays of beauty and charm hadrons, mediated by heavy gauge bosons or potentially new particles, can lead to deviations from SM predictions. Rare processes, particularly those occurring through loop diagrams such as flavour changing neutral currents (FCNCs), are considered prime channels for uncovering physics beyond the SM. The LHCb Upgrade II is set to provide unparalleled precision in flavour physics, leveraging the vast dataset and advanced detector technologies going beyond luminosity scaling. Detailed studies of possible physics gains are available at [1]. Some key objectives include:

- **Standard Model Benchmarks:** High-precision measurements of CP violation, exploiting processes such as $B \to DK$ decays, to test the CKM paradigm. The sensitivity of LHCb Upgrade II will notably improve the precision of the CKM angle γ and enable deep probes of new physics (NP) at tree level. The upgrade will enhance the sensitivity to NP in CP violation, particularly through the weak phase ϕ_s, which is highly sensitive to NP contributions due to its precise SM prediction.

- **New Physics in Rare Decays:** The LHCb Upgrade II will enable precision measurements of FCNC decays like $B_s^0 \to \mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$, which are highly sensitive to new physics due to the absence of tree-level FCNCs in the Standard Model. The large data set from Upgrade II will enhance the study of these rare process involving $b \to s\ell^+\ell^-$ and $b \to d\ell^+\ell^-$ transitions, enhancing our understanding of these rare processes and reducing the uncertainties.

- **Measurements of $|V_{ub}|$ and $|V_{cb}|$:** LHCb Upgrade II will provide appealing prospects for these measurements, with competitive sensitivity achievable through exclusive decays of B_s^0 and Λ_b^0 hadrons.

- **CP Violation in Charm Mixing:** The LHCb Upgrade II aims to delve deeper into time-dependent CP asymmetries within charm decays, an area relatively unexplored compared to beauty quark systems. This will enhance our understanding of up-type quark mixing and potential new CP-violating phases that are not accounted for in the Standard Model. The precise measurement of these asymmetries could reveal subtle effects of new physics.

- **Rare Radiative Decays:** The study of rare radiative decays such as $B \to K^*\gamma$ and $B_s \to \phi\gamma$ plays a crucial role in testing the flavour structure of the Standard Model and probing potential new physics. These decays, mediated by flavour-changing neutral currents, are highly suppressed in the Standard Model and thus are sensitive probes for new physics contributions. The LHCb Upgrade II will focus on measuring the branching fractions and photon polarization of these decays with unprecedented precision.

- **Hadron spectroscopy:** The exploration of exotic hadronic states, particularly tetraquarks and pentaquarks, is important in understanding the strong interaction and the nature of hadronic matter. The LHCb Upgrade II is set to significantly contribute to this field, by allowing for the detailed study of the properties, production mechanisms, and decay patterns of these exotic states. This not only aims to shed light on the internal structure and dynamics of such particles but also to test the predictions of QCD in the non-perturbative regime. A significant discovery has been the double charm Ξ_{cc}^{++} baryon, signaling the onset of a new spectroscopy era for doubly heavy hadrons. The LHCb Upgrade II aims to extend these studies to include the Ξ_{cc}^{+}, Ω_{cc}^{+}, and Ξ_{bc} baryons, contingent on effective background rejection. Additionally, the search for double beauty states, encompassing both baryons and tetraquarks, will be a focal point. These investigations are critical for understanding hadronic binding mechanisms and are uniquely suited to LHCb's capabilities.

- **QCD and Electroweak Physics:** LHCb's unique setup allows for studies in regions inaccessible to other LHC experiments, particularly in W and Z boson production, improving the understanding of parton distribution functions (PDFs) crucial for Higgs and new physics searches. The geometry of LHCb also aids in precise electroweak measurements, such as the W mass, where improvements are expected with Upgrade II. Additionally, the effective weak mixing angle can be accurately measured through leptonic decays from Z bosons due to LHCb's forward coverage.

- **Long-lived particles and exotic new physics searches:** Some new physics scenarios predict long-lived particles that decay into SM particles outside of the LHCb's VELO region. LHCb Upgrade II, with its expanded data set and enhanced acceptance due to additional magnet stations and new trigger strategies, is poised to improve sensitivity to decays involving these particles. LHCb's sensitivity to dark photons, from both inclusive production and charm meson decays, positions it to potentially confirm or refute dark photon existence across much of the parameter space

2.2 Sub-detectors and performance

The Upgrade II detector layout, as shown in Figure 2, will have a similar footprint to the current detector used in Run 3. However, LHCb Upgrade II must address significant challenges due to increased peak luminosity and pile-up, which enhance particle multiplicities and necessitate advancements in detector technologies. Key improvements include enhanced radiation hardness and the incorporation of fast-timing capabilities to reduce background, requiring advancements in sensor technology. Augmented performance across tracking, particle identification, and data acquisition and online systems is essential for exploiting the anticipated physics program.

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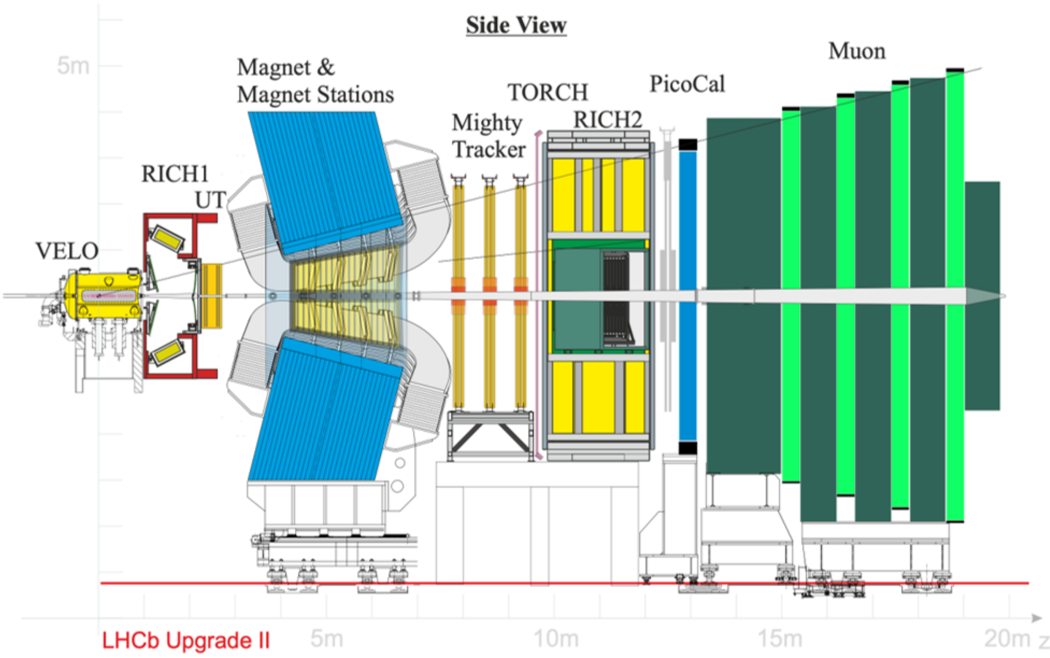

Figure 2: Schematic side-view of the Upgrade II detector Ref. [1].

Different sub-detectors and some key technology considerations are outlined here:

- **Tracking system**:

  The tracking system for LHCb Upgrade II will need to meet stringent physics performance criteria. Key specifications include a momentum resolution of $\sigma(p)/p \approx 0.5\% - 1\%$, and an impact parameter resolution of $\sigma(\text{IP}) \approx 25\mu\text{m}$ for tracks with momentum exceeding 1GeV/c, while maintaining the current detector acceptance. Enhanced granularity and precision timing will be critical for managing the high track densities expected. The schematic of the tracking system is shown in Figure 3.

  – **Vertex Locator (VELO):**

    The VELO Upgrade II is confronted with a series of challenges due to increased charged-particle multiplicity and the resultant data rates, pattern-recognition issues, and non-uniform radiation exposure. With an instantaneous luminosity of $1.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and an average of 42 pile-up collisions, the detector is expected to experience a charged-particle density of $39 \times (R/\text{cm})^{-1.9}$ tracks per cm^2 per event, leading to 1.2×10^{12} tracks/cm^2/s at a 1 cm radius from the beamline. It is a significant challenge to precisely reconstruct and assign trajectories of charged particles to their respective vertices in this environment. The introduction of time stamps to space-point measurements is crucial for overcoming reconstruction inefficiencies due to high pile-up. A reduction in pixel pitch might be necessary to maintain performance while enduring radiation damage. Additionally, a redesign of the detector's mechanics, vacuum, and cooling systems is required to optimize the material budget.

A 4D tracking system with per-hit time resolution of 50 ps or better has been proposed to enhance vertex reconstruction efficiency at higher luminosities. Ongoing R&D is focusing on fast timing sensors, particularly 3D devices, to meet the spatial and temporal resolution demands.

– **Upstream Tracker (UT):**

The UT detector, essential for track matching and momentum resolution, is engineered to handle the expected high data rates and occupancy in Upgrade II. Positioned upstream of the magnet, it enhances track reconstruction capabilities, particularly for long-lived particle decays. The initial UT design featured four planes of silicon strip sensors with a strip pitch of approximately 100 μm, tailored for a luminosity of $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This setup, however, is not equipped to manage the 7.5-fold increase in peak luminosity or the radiation dose of $3 \times 10^{15}\mathrm{n_{eq}}/\mathrm{cm}^2$ expected in Upgrade II.

To address the demands of HL-LHC operations for Run 5 and subsequent runs, a novel UT detector employing CMOS Monolithic Active Pixel Sensors (MAPS) technology is proposed to supersede the existing silicon strip sensors. Development and prototyping of MAPS are underway for the UT and the innermost region of the Mighty Tracker. The UT's two stations have to be designed to withstand a baseline radiation level of $3 \times 10^{15}\, n_{\mathrm{eq}}/\mathrm{cm}^2$. New detector layout will consist of staves formed from MAPS chip modules linked together, with a configuration optimized efficient data transfer.

– **Mighty Tracker:** The Run 3 scintillating fibre (SciFi) based tracker will not be able to cope with the increased instantaneous luminosity and radiation damage expected in Upgrade II.

Simulations indicate that tracking efficiency would drop to 50% and the ghost rate would approach nearly 100% with the current system under Upgrade II conditions. A mixed technology solution is being proposed to enhance granularity and improve radiation hardness, especially near the beampipe. This solution will incorporate silicon technologies in the central regions and SciFi in the peripheral areas, comprising three stations (T1–T3) positioned downstream of the magnet.

For the SciFi system, the main challenges are radiation damage and high track density. To address these, upgraded Silicon Photomultipliers (SiPMs) with micro-lenses and cryogenic cooling are being considered to mitigate noise and manage the effects of radiation. The central region of the tracker will employ HV-MAPS technology with a baseline pixel size of $50\,\mu\mathrm{m} \times 150\,\mu\mathrm{m}$, which is expected to improve pattern recognition and facilitate real-time track reconstruction.

The planned layout for each station of the Mighty Tracker will consist of four layers of SciFi detection, including X-layers and layers tilted by $\pm 5^\circ$ (U- and V-layers). The area around the beampipe will be covered by two layers of HV-CMOS pixel detectors. The SciFi layers will be organized into up to six modules, each module containing eight 2.4 m long fibre arrays. Meanwhile, the MT MAPS will feature 28 modules per layer, each layer covering an area of 3.0 m^2 excluding the space for the beam-pipe. In total, six silicon panels, each with an area of 3.0 m^2, will be strategically positioned across the X-layers to optimize tracking performance.

– **Magnet Stations:** The Magnet Station (MS) is a new tracking sub-detector, designed to enhance the tracking coverage of the LHCb detector for low-momentum particles, which currently lack full tracking information due to deflection by the magnet. With a $\frac{\delta p}{p}$ resolution of 12.3% for tracks reconstructed with only the VELO and UT, the MS aims to improve this to sub-percent levels.

  Composed of four panels, each with dimensions $350 \times 100\text{cm}^2$ and positioned to maximize acceptance for particles with momenta greater than 500 MeV/c, the MS will be equipped with four layers of scintillating bars. These bars are triangular, with 5 mm sides and utilize 1 mm wavelength-shifting fibres to guide scintillation light to Silicon Photo-multipliers (SiPM) located outside the magnet's high radiation zone.

  The system is expected to significantly improve the mass resolution of upstream tracks and contribute to the rejection of ghost tracks. The MS will also support track reconstruction at the edges of the SciFi detector. The SiPM arrays are expected to receive a radiation dose of only 1 Gy, which is considerably lower than that in the SciFi readout region. The MS will facilitate high precision momentum and position measurements for both long and upstream tracks without affecting the material budget seen by long tracks.

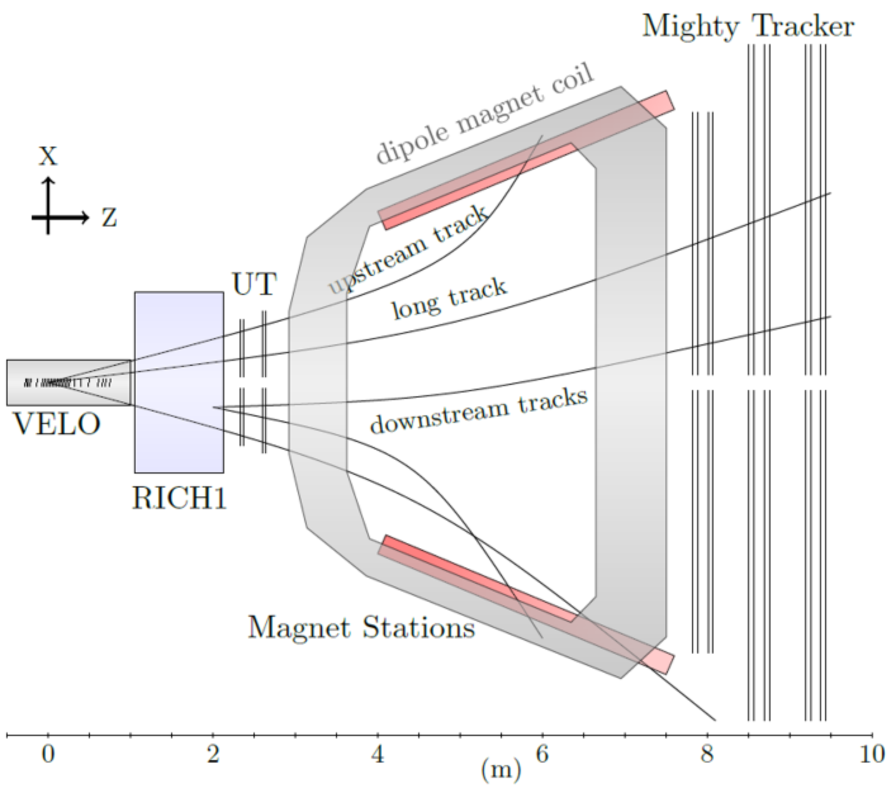

Figure 3: Illustration of track types in LHCb: Long tracks span the full spectrometer, registering in the VELO, UT, and Mighty Tracker. Downstream tracks, often from long-lived particle decays like K^0_S mesons and Λ baryons or secondary interactions, mark the UT and Mighty Tracker. Upstream tracks, low momentum and diverted by the magnet's coils, are detected in the VELO, UT, and magnet stations [1].

- **Particle Identification (PID) system**: The LHCb particle identification (PID) system is essential for flavour-physics experiments. The Upgrade II PID system aims to sustain the performance from previous runs under high luminosity and expand the kinematic range. Designed for particle identification, differentiation, and energy measurement. This system will incorporate Ring Imaging Cherenkov detectors (RICH1 and RICH2), a new Time of Flight detector called TORCH , muon chambers, and electromagnetic and hadronic calorimeters.

  - **RICH Detectors:** Hadron identification is crucial for CP-violation measurements, such as differentiating $B_s^0 \to D_s^{\pm} K^{\mp}$ and $B_s^0 \to D_s^{\pm} \pi^{\mp}$ decays, and for initial-state flavour tagging. The RICH system is to be redesigned with a footprint similar to the Run 3 RICH 1 & 2. An R&D program is underway to enhance the RICH detectors with sensors and readout electronics designed for time resolutions better than 100 ps. This upgrade, along with the introduction of front-end electronics providing timestamps for each photon, is essential for achieving the desired performance criteria. This will require development of a new ASIC and photon detectors, which may utilize SiPM or MCP technologies. Testing of new gas mixtures aims to enhance angular precision, complemented by research into radiator materials. The anticipated resolution stands at 0.22 (0.13) mrad for RICH1(2).
  - **TORCH Detector:** A new Time Of internally Reflected CHerenkov light based Time of Flight (ToF) detector abbreviated as TORCH with quartz planes read by MCP-PMTs, will be placed in front of RICH2, approximately 9.5 m away from the primary interaction. It will offer 10-15 ps time resolution per track and enable PID of pion/kaon (kaon/proton) up to 10 (20) GeV/c momentum. This will complement low-momentum heavy particle identification within its range.
  - **Calorimeters:** The ECAL's performance in Run 1 and 2 enabled significant studies involving neutrals and electrons, such as photon polarization in $b \to s\gamma$, and lepton universality via $b \to s e^+ e^-$ transitions. The goal is to match the energy resolution and reconstruction efficiency of Run1 & 2. The current ECAL, optimized for neutral pion and photon identification in the few-100 GeV range and radiation-hardened up to 40 kGrays, is not capable of withstanding a dose of 1MGrays while keeping the resolution at $\sigma(E)/E \approx 10\%\sqrt{E} + 1\%$. For the Upgrade II ECAL, different technologies will be employed in various detector regions to optimize performance. SpaCal technology will be used in both the innermost and the second inner regions, with varying absorber materials to meet specific detector requirements. The innermost SpaCal region will employ scintillating crystals combined with a tungsten absorber, each element sized at 1.5×1.5 cm^2. The second inner SpaCal region with dimensions of 3×3 cm^2 will utilize scintillating fibers (SciFi) embedded in a lead absorber. The SpaCal is designed for enhanced spatial resolution and distinct separation of particle interactions, leveraging the dense absorber material's properties to measure the energy of incident particles effectively. The outer region will include Shashlik design with wavelength-shifting fibers. The HCAL from previous runs will be discontinued.
  - **Muon System:** The muon system, instrumental in analyses like $B_s^0 \to \mu^+ \mu^-$ and a va-

riety of $b \to s\mu^+\mu^-$ decays, offered multiple working points, such as 95-98% efficiency with a 1% hadron misidentification rate. Upgrade II will preserve these capabilities. Novel micro-pattern gas detectors will be installed in the innermost region, consisting of 144 chambers. The existing multi-wire proportional chambers will be reused in the outer region, with 880 existing and 80 new chambers with higher granularity. Additional shielding will be implemented, increasing from 6 to 10 interaction lengths, in front of the Muon system in place of HCAL to control rates by approximately a factor of 2 without affecting trigger and hadron reconstruction.

- **Data Acquisition and online processing** Enhancements in data acquisition and online processing systems are critical to handle significantly increased data volumes in Upgrade II conditions.

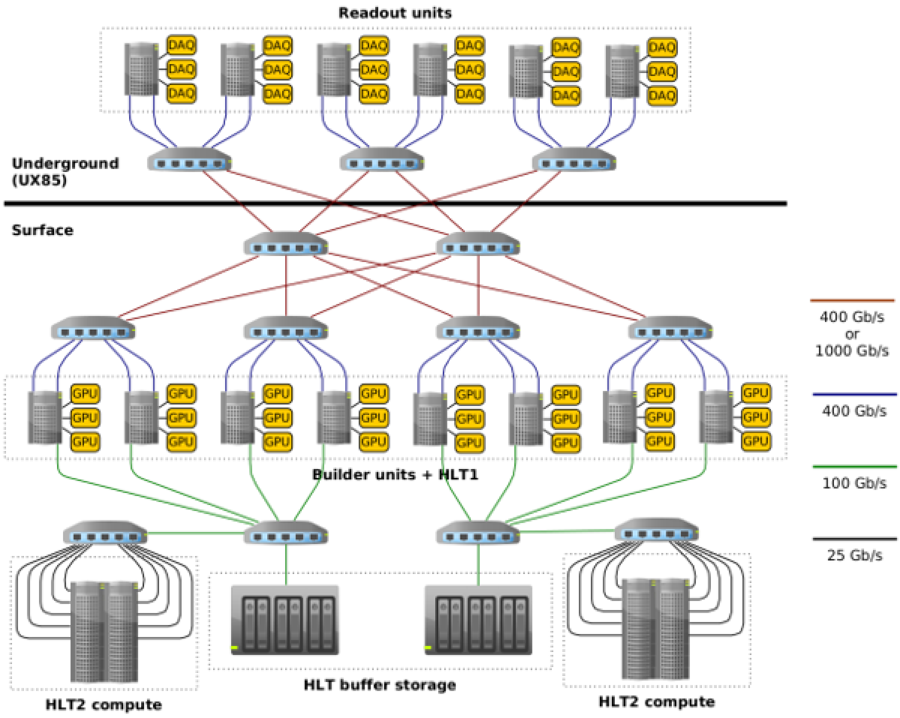

Figure 4: Event-builder architecture for Upgrade II of LHCb [1].

  – **Readout and Data Acquisition:** The LHCb Upgrade II Data Acquisition (DAQ) system is designed to manage substantial increases in data volumes. The number of data links will triple, expanding from 11,000 at 5 Gbps to 30,000 at 10 Gbps. Accordingly, readout throughput will rise fivefold, from 32 Tbps to 160 Tbps, and tape output capacity will grow from 80 Gbps to 400 Gbps. To facilitate these enhancements, Event Builder (EB) systems will undergo reconfiguration and will be relocated underground to overcome link capacity limitations. FPGA-based (PCIe400) read-out boards will be deployed to interface with the front-end electronics, enabling the DAQ system to process data rates of approximately 200 Tbit/s.

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– **Online Processing System:** The Online processing system encompassing the High-Level Trigger (HLT), is integral for real-time data analysis. The processing methodology will emulate the Run-3 HLT architecture, with a two-tier trigger system where HLT1 performs a swift reconstruction identifying inclusive beauty, charm signatures, and high p_T muons. HLT2 will execute a comprehensive reconstruction, utilizing extensive data from tracking sub-detectors and particle identification systems to filter signals of interest. LHCb's ongoing advancement in heterogeneous architectures, initiated in Run 3 with the full GPU-based HLT1 and the usage of DAQ FPGAs for VELO clustering, will continue into Run 5 with the processing of data volumes five times greater than current levels. The strategy includes pre-processing of track primitives at the DAQ stage, utilizing FPGAs to enhance the efficiency of data handling—activities encapsulated within the RETINA project, which is currently testing various approaches in this area. To accommodate these architectures, programs and algorithms would need to be designed with architecture-awareness, with memory optimizations playing a pivotal role in the development of future algorithms.

2.3 Outlook and Conclusion

LHCb Upgrade II is set for data-taking in 2032 during Run 5, targeting operations at luminosities up to $1.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$. It aims to harness the High Luminosity LHC (HL-LHC) for extensive flavour physics studies and research in the forward region. The upgrade plans to gather over 300 fb^{-1} of data, significantly expanding the scope of physics investigations. An intensive R&D program is in progress to meet this goal. The first steps toward approval have been achieved, adhering to a strategy outlined by the LHCC. A scoping document is projected for 2024, with Subdetector Technical Design Reports (TDRs) expected in the early phase of Long Shutdown 3 (LS3). Technological advancements will address the anticipated challenges of high-pileup environments, enhancing detector performance for precise reconstruction of decay processes. Key developments include improved radiation hardness, fast-timing capabilities, and advanced data processing technologies to cope with increased data rates. Installation during Long Shutdown 4 (LS4) will equip the detector for high-luminosity data-taking. Significant R&D will also be needed to meet the computing requirements of offline data processing and simulation.

The project aligns with strategic recommendations to exploit the LHC's full potential, particularly in flavour physics. By advancing detector technology and computational methods, LHCb Upgrade II aims to deepen our understanding of fundamental physics, navigating the complexities of high-luminosity conditions to contribute to the broader field of particle physics.

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