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PHYSICS PROSPECTS, EXPERIMENTAL CHALLENGES — LHCb UPGRADE II[*]

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The second upgrade of the LHCb detector is planned for the long shutdown 4 of the LHC. In this upgrade, part of the existing spectrometer will be replaced and new tracking detectors allowing for time measurements will be installed. This upgrade will enable the exploitation of the physics potential of the high-luminosity LHC runs. The corresponding data sets will provide heavy-flavour results with unprecedented precision as well as significantly increase the sensitivity of BSM searches with displaced vertices. In this paper, the physics goals of Upgrade II will be reviewed, as well as the detector design and technology options which will allow for meeting the desired specifications.

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1. Introduction

The LHCb detector is a forward spectrometer installed at the Large Hadron Collider (LHC). The LHCb experiment took data during Run 1 (2010–2013) and Run 2 (2015–2018) and collected more than 9 fb^{-1} of integrated luminosity. The next period, Run 3, has just started, proceeded by the first major upgrade of the LHCb spectrometer. The main aim of this modernisation was to allow operation at the instantaneous luminosity up to 2×10^{33} $\text{cm}^{-2}\,\text{s}^{-1}$, what required upgrades in the readout system and almost the whole tracking system. This apparatus will operate up to the end of Run 4, which is currently planed for the year 2033 [1].

Over the last few decades, particle physics has witnessed the extraordinary success of the Standard Model (SM). Lacking any significant sign of discrepancies with experiments, SM itself is still not able to find the origin of huge matter–antimatter asymmetry in the Universe, explain puzzles

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of neutrinos, propose a solution of non-existence of supersymmetry or add a dark sector. Therefore, an extension of SM to new theories is proposed and it should be confirmed experimentally. Thus, the physics program of high-intensity experiments goes beyond the current LHC achievements and requires the jump into high luminosity scenarios. During the next LHC data-taking period, the peak luminosity in ATLAS and CMS experiments is planned to reach 5×10^{34} cm^{-2} s^{-1}. The High-Luminosity LHC (HL-LHC) will start operating (according to the plan from January 2022) in 2028, after Long Shutdown 3 (LS3) when Run 4 data collecting period is planned to begin.

The LHCb experiment is also eager to benefit from the expected huge statistics but the spectrometer has to be modernised once more. The LHCb aims to collect more than 300 fb^{-1} of data by the end of HL-LHC operation during Runs 5 and 6 [2, 3]. The experiment is planned to operate at the peak luminosity (1–2)$\times 10^{34}$cm^{-2} s^{-1} and face up to around 40 visible interactions per bunch-crossing.

2. Physics motivation for Upgrade II

The LHCb experiment was designed to study CP symmetry violation in heavy-flavour hadron decays, and for the searches of physics beyond the Standard Model. Thanks to the excellent performance, the LHCb physics program also covered QCD, observation of exotic hadrons and dark matter searches. Since LHCb experiment plays currently the leading role in flavour physics, the general aim of the Upgrade II is to consolidate and strengthen the discoveries of Run 3 together with planned Run 4 and fully exploit the current experimental potential.

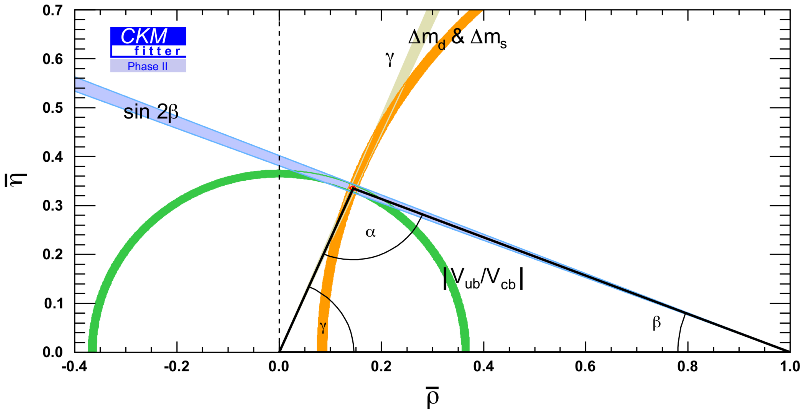

Fig. 1. Unitary Triangle in the $(\bar{\rho}, \bar{\eta})$ plane from LHCb measurements as anticipated from the data accumulated by 2035 with 300 fb^{-1} of data [5].

The anticipated impact of the improved knowledge of Unitary Triangle parameters can be seen in Fig. 1, which shows the constraints in the $(\bar{\rho}, \bar{\eta})$ plane expected from LHCb results. The comparison with the current results shows that the increased sensitivity will allow for extremely precise tests of the CKM paradigm [5].

2.1. CP violation measurements

The CP symmetry violation in the SM is governed by the irreducible complex phase in the Cabbibo–Cobayashi–Maskawa (CKM) matrix. This results in the non-zero apex of the Unitary Triangle, which can be probed by numerous processes. If SM is correct, all such measurements should give a consistent value, the discrepancy would be an indication for the new physics (NP).

The theoretically clean measurement of the CP-violating phase γ is crucial for determination of the position of the UT apex. The combined LHCb measurement yields: $\gamma = (65.4^{+3.8}_{-4.2})^\circ$ [4], which is the most precise result from a single experiment. The precision is dominated by measurement using $B^\pm \to DK^\pm$ decays. The systematic uncertainties are small and arise predominantly from sources that will naturally decrease with increasing data.

The expected precision on the CKM γ-angle measurement as a function of luminosity is shown in Fig. 2. The prediction takes central values from the unique LHCb results of the $B^\pm \to DK^\pm$ $B^\pm \to D^*K^\pm$, $B^\pm \to DK^{*\pm}$, and $B^0 \to DK^{*0}$ decays. Figure 2 (right) shows on the r_B and γ plane how the increase of the integrated luminosity impacts the precision of the

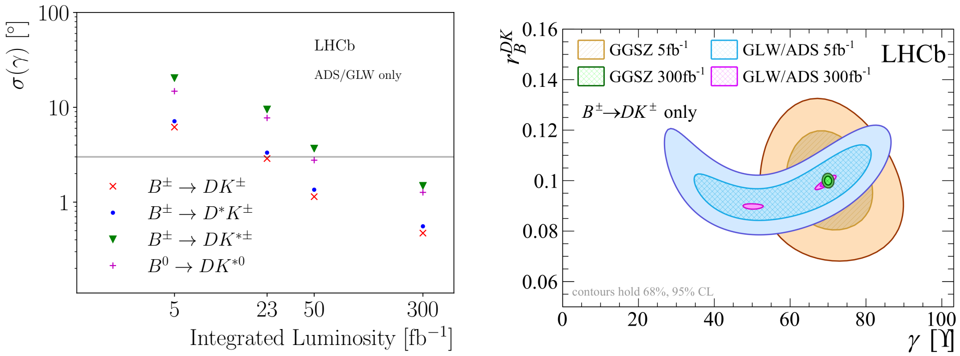

Fig. 2. Predicted sensitivity to the CKM γ-angle measurements extrapolated from the Run 2 results (left). The expected Belle II precision at an integrated luminosity of 50 ab^{-1} is shown by the horizontal grey line. Comparison between the current LHCb 3-body GGSZ and 2-body GLW/ADS measurements alongside their future projections with 300 fb^{-1} (right).

different method of the CKM γ-angle measurements. The LHCb Upgrade II predicts the measurement of γ with a precision of 0.35° [6].

Additional constraints on the UT enter through the measurement of B^0 and B_s^0 mixing, which are mediated by thr second-order diagram involving heavy virtual top and $W^{\pm}$ bosons. The phase of B^0 mixing is currently measured in time-dependent analysis with a systematic uncertainty much higher than the statistical one. The phase associated with B_s^0 mixing in the Standard Model is expected to be very small and the LHCb results claims: $\phi_s = -36.5^{+1.3}_{-1.2}$ mrad. With the full Upgrade II sample, the LHCb anticipates an uncertainty of the $\sin(2\beta)$ of about 0.003, whereas the precision of the ϕ_s measurement will fall to 4 mrad. The expected uncertainties for other key measurements with 300 fb^{-1} of data are presented in [6].

2.2. New measurements

Future plans of the LHCb are built on the success of the experiment during Runs 1 and 2, also in the area of unexpected discoveries like the test of lepton flavour universality (LFU), exotic hadrons or CPV observation in the charm sector. The large data samples expected after Upgrades I and II will allow the LHCb measurements of LFU observables to reach 1%-level uncertainties. This precision would be sufficient to establish or reject the level of LFU violation seen in the current measurements.

Within the SM, mixing and CP violation in the charm sector are predicted to be extremely small, the latter of the order $\mathcal{O}(10^{-4})$. The numerous charm mesons reconstructed in the experiment with a dedicated stream showed first results on CP violation parameters, but the expected sensitivity after Upgrade II is one order of magnitude better than theoretical predictions and Run 4 measurements [6].

Searches of the dark photon in di-muon decay performed by the LHCb were limited by the low luminosity and hardware trigger. The former is no longer present in Run 3, but HL Runs 5 and 6 should show limits or discoveries in ranges not accessible by other experiments, for example, low mass, with displaced well-reconstructed vertices, and also in decays to e^+e^-.

The unique forward acceptance and very good particle reconstruction and identification allow also for a program of precise electroweak and QCD measurements such as Z-boson production, effective weak mixing angle or W-boson mass. With the Upgrade II dataset, a statistical precision of a few MeV should be reached, and the systematic uncertainties further constrained, leading to a precise electroweak measurement from the LHCb, and significant improvement in the world average.

In Run 2, the LHC experiment joined the ion physics program offering access to the lowest Bjorken x and Q^2 values. In addition, collisions with gas targets (noble gases and oxygen) took place. The future of this project depends on the possibilities of the gas injection in the Upgraded HL-LHC runs detector but the interest of the theory and astrophysics community is significant [7].

3. Experimental challenges for High-Lumi LHCb spectrometer

The LHCb experiment's ambitious physics program planned for Upgrade II assumes that the excellent performance achieved during Run 2 and continued after Upgrade I will be achievable during HL-LHC Runs 5 and 6. It especially considers tracking, resolution of vertices' reconstruction, and efficiency and purity of identification which should remain at the same level. Since the number of visible interactions per bunch crossing increases up to 40 and the number of charged particles produced in collision rockets to 2000, track reconstruction with the current system will be no longer possible. In addition, the expected particle fluence will be more severe for most detectors.

In the HL-LHC condition, the interactions within each beam-crossing are spread in time of about 180 ps. Adding time stamps can be a way to reduce overlapping interactions and eliminate hits and tracks which are incompatible in production time. Only a few tracks have to be reconstructed in slices of duration 20 ps time if novel tracking and timing devices were deployed. In the same way, a new dimension to the experiment would be added not only for tracking but for identification as well. VELO, RICH, electromagnetic calorimeter, and a new time-of-flight detector TORCH will then become fast timing detectors.

Innovative technology for fast, 4D tracking detectors is currently under development [8]. Devices must be radiation hard and withstand fluence of 6×10^{16} neq/cm^2. For the Upgrade II VELO detector, three technologies are considered: hybrid planar sensors, Low Gain Avalanche Diodes (LGADs), and 3D sensors [9]. Sensors will be either kept at their current distance of 5.1 mm from the beam line with the necessity of periodic replacement or will be moved to 12.5 mm. The second approach requires sensors with better hit resolution (9 μm) and reduction of material budget (redesigning or removing the RF foil). The detailed description of the proposed changes to the current VELO detector can be found in the Technical Report [2].

The Mighty Tracker will be split in a Silicon Tracker covering the inner region, and a Scintillating Fiber Tracker covering the outer region. As a new feature with respect to Upgrade I, additional tracking stations will cover the magnet side walls. The particle identification system will consist of a RICH system composed of RICH1 and RICH2 detectors placed upstream and downstream of the magnet, respectively, an electromagnetic calorimeter, and 4 muon stations. The baseline design will not include any more a hadron calorimeter in front of the muon detector, replaced by additional shielding, and will feature instead a time-of-flight detector (TORCH) in front of RICH2 [2].

4. Summary

The LHCb experiment justified its discovery potential in flavour physics during Runs 1 and 2 LHC data-taking period. Currently, the spectrometer, modernised for the first time, started taking data in Run 3. Upgrade II is under development to fully exploit the potential of the HL-LHC. The main challenges for the upgraded tracking system are high occupancy and harsh radiation environment. In order to maintain the current performance, the tracking system is redesigned with the innovative timing sensors, new tracking stations, and detectors for particle identification.

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REFERENCES

[1] LHCb Collaboration, «Framework TDR for the LHCb Upgrade: Technical Design Report», Technical Report CERN-LHCC-2012-007, LHCb-TDR-012.

[2] LHCb Collaboration, «Framework TDR for the LHCb Upgrade II — Opportunities in flavour physics, and 215 beyond, in the HL-LHC era», Technical Report CERN-LHCC-2021-012, LHCB-TDR-023.

[3] LHCb Collaboration, «Physics case for an LHCb Upgrade II — Opportunities in flavour physics, and beyond, in the HL-LHC era», Technical Report LHCB-PUB-2018-009, CERN-LHCC-2018-027,LHCC-G-171.

[4] LHCb Collaboration, «Update of the LHCb combination of the CKM angle γ», LHCb-CONF-2018-002; CERN-LHCb-CONF-2018-002

[5] A. Cerri *et al.*, «Opportunities in Flavour Physics at the HL-LHC and HE-LHC», CERN-LPCC-2018-06.

[6] LHCb Collaboration, «Future physics potential of LHCb», LHCb-PUB-2022-012, CERN-LHCb-PUB-2022-012.

[7] G. Graziani, *PoS* **EPS-HEP2019**, 039 (2020).

[8] M. Mandurrino (RD50 Collaboration), `arXiv:1910.06045 [physics.ins-det]`.

[9] LHCb Collaboration, «Considerations for the VELO detector at the LHCb Upgrade II», Technical Report LHCb-PUB-2022-001, CERN-LHCb-PUB-2022-001.