RESULTS FROM LHCb*

Rudolf G.C. Oldeman

on behalf of the LHCb Collaboration

Università degli studi di Cagliari and INFN, Sezione di Cagliari, Italy

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The LHCb Collaboration has successfully recorded heavy-flavour decays during the first two runs of the LHC high-energy proton–proton collider between 2011 and 2018. A selection of recent precision measurements in beauty decays is presented. The detector has now been largely rebuilt for the first upgrade, to handle a higher collision rate and for a more efficient selection of collisions containing beauty and charm decays. Ideas for a second upgrade are under development.

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1. Introduction

The Standard Model (SM) of elementary particles and their interactions is incredibly successful in describing a rich spectrum of phenomena but, at the same time, incomplete by not accounting for gravity and not providing answers to basic questions about the content of our universe. Analysis of high-energy collisions has already led to many discoveries and finding evidence for new physics (NP) is the main motivation for the construction, operation, and research on high-energy colliders and their detectors.

Direct searches for new physics aim to produce new particles on-shell. If successful, this may result in very detailed knowledge about the new phenomenon, since mass and couplings can be studied in detail. A good example is the discovery of the Higgs boson [1, 2] that subsequently led to a detailed understanding of its interaction with the other SM fermions and bosons. However, this ideal scenario only works if the collision energy is high enough to produce the new particle.

Indirect searches provide a way to probe energy scales beyond the collision energy: new particles result in new couplings that may result in subtle

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deviations from the SM predictions. It is unlikely that a particular NP phenomenon will be uniquely identified by a single deviation, but a program of follow-up measurements in different channels could be expected to expose the nature of the new phenomenon.

The power of this method lies in the fact that the mass scales probed may far exceed the collision energy, if enough precision is achieved. With the LHC having almost reached the peak of its energy, it is expected that indirect searches will become more and more important in the near future, as high-luminosity running will improve the precision, and thus the energy scale, that can be achieved in indirect searches.

Decays of heavy quarks such as beauty (b) and charm (c) are particularly suited to precision measurements since they present a rich spectrum of decays, with probabilities that are well described by the Cabibbo–Kobayashi–Maskawa (CKM) matrix. Of particular interest are transitions between quarks of the first and third generation, described by the off-diagonal CKM elements V_{ub} and V_{td}. These transitions have a small amplitude and a large, $\mathcal{O}(1)$, value of the complex phase. In certain b decays, this leads to a large asymmetry between matter and its (antimatter) CP conjugate.

According to the Standard Model, the CKM matrix is unitary, which implies that V_{ub} and V_{td} are tightly related. This relationship allows for a strong test: the parameters of the off-diagonal CKM elements can be determined both by tree-dominated processes and by loop-dominated processes. New physics contributions may have a large effect on the weaker loop-induced SM processes, while they can be expected to have a negligible impact on the stronger tree-induced processes.

2. Experimental aspects

To perform precision measurements in heavy-flavour decays, large samples of b or c quarks need to be produced under well-controlled circumstances. Presently, there are two dominant techniques for the production of heavy-flavour quarks: e^+e^- collisions with a centre-of-mass energy corresponding to the $\Upsilon(4S)$ resonance, and high-energy hadron–hadron collisions. The former profits from small backgrounds, coherent production and a fixed Lorentz boost, and is presently used at SuperKEKB with the Belle II detector. The latter has larger yields and a larger spectrum of b-hadrons produced, as well as a stronger boost, resulting in better resolution of the lifetime. The LHCb experiment uses this technique, based on pp collisions at the LHC.

The LHCb detector, in contrast to the general-purpose detectors of ATLAS and CMS, is specialised for the detection of heavy-flavour produced in pp collisions [3, 4]. It is instrumented only in the forward direction ($10 < \theta < 300$ mrad) where the production per unit of solid angle is the highest, and where the heavy flavour hadrons are strongly boosted. The description that follows corresponds to the detector that was operational from 2010 to 2018, where 3 fb^{-1} of collision data were collected at centre-of-mass energies of 7 and 8 TeV, during Run 1, and 6 fb^{-1} of collision data were collected at a centre-of-mass energy of 13 TeV, during Run 2. Modifications made for the upgraded detector, used for Run 3, will be discussed later.

The vertex detector uses silicon strips and can measure the impact parameter of tracks with an accuracy of $(15 + 29/p_{\mathrm{T}})$ μm. The momentum of charged particle tracks is measured with a precision of 0.5–1.0% by recording the bending of tracks through the field of a 4 Tm warm dipole magnet. A system of two Ring Imaging Cherenkov detectors provides identification of pions, kaons, and protons in the momentum range of $2 < p < 100$ GeV. The electromagnetic calorimeter identifies photons and electrons, and measures their energy with a resolution of $\approx$ 6% for energies $E > 20$ GeV. The hadron calorimeter is predominantly used for the trigger, and the muon system identifies high-momentum muons with an efficiency of $\approx$ 98%.

3. The LHCb physics program

Apart from the core program of heavy-flavour physics, LHCb has also provided unique measurements in the area of electroweak measurements and high-E_{T} jet physics. Thanks to its forward geometry, LHCb plays a crucial complementary role here to ATLAS and CMS that cannot perform as well at very small angles to the beam. Heavy-ion collisions have also been studied, and a very innovative fixed-target physics program has been developed with the SMOG system, where gas is introduced in the area of the vertex detector, allowing for the study of collisions of high-energy protons or lead on helium, neon, and argon nuclei at rest.

These proceedings focus on recent measurements of CP violation and rare B decays. Charm physics results are covered by other contributions in these proceedings.

4. Measurement of $\sin 2\beta$

If both a B^0 and a $\bar{B}^0$ meson can decay to the same final state f, the interference between mixed and non-mixed decays results in a time-dependent asymmetry

$$\mathcal{A}^{\mathrm{CP}} \equiv \frac{\mathit{\Gamma}\left(\bar{B}^0 \to f\right) - \mathit{\Gamma}\left(B^0 \to f\right)}{\mathit{\Gamma}\left(\bar{B}^0 \to f\right) + \mathit{\Gamma}\left(B^0 \to f\right)} = \frac{S \sin\left(\Delta m_d t\right) - C \cos\left(\Delta m_d t\right)}{\cosh\left(\frac{1}{2}\Delta \mathit{\Gamma}_d t\right) - A_{\Delta \mathit{\Gamma}} \sinh\left(\frac{1}{2}\Delta \mathit{\Gamma}_d t\right)} \,. \tag{1}$$

In $B^0 \to J/\psi K^0_{\mathrm{S}}$ decays, the measurement of S, often referred to as $\sin 2\beta$ or $\sin 2\phi_1$, is closely related to the phase of the CKM element V_{td}. The observation of the non-zero value of $\sin 2\beta$ represented the first observation of CP violation in B decays [5, 6]. Improving upon the already impressive precision remains relevant due to the very clean relationship between the experimental observation and the corresponding SM parameter: contrary to many other decay channels, $B^0 \to J/\psi K^0_{\mathrm{S}}$ is strongly dominated by a single tree diagram, and higher-order loop diagrams have a negligible influence at the current level of experimental precision.

Experimentally, the measurement of $\sin 2\beta$ is challenging at hadron colliders, because of the need for determining whether the observed decay originated from a B^0 or a $\bar{B}^0$ decay. Flavour tagging techniques at hadron colliders combine information from fragmentation tracks produced together with the B meson, as well as information collected from the decay of the 'other' b hadron that was produced simultaneously in a $b\bar{b}$ pair. The finite efficiency ε and the dilution D from wrong tags, results in a statistical efficiency of $\varepsilon D^2 \approx 4\%$ at the LHCb.

LHCb has recently completed a new measurement of $\sin 2\beta$, based on $6\,\mathrm{fb}^{-1}$ of Run 2 collision data [7]. The data sample is dominated by 306×10^3 $B^0 \to J/\psi K^0_{\mathrm{S}}$ decays, where the J/ψ is reconstructed through its decay to two muons. The J/ψ meson is also reconstructed in its decay to electrons, adding 43×10^3 signal decays. The decay $B^0 \to \psi(2S) K^0_{\mathrm{S}}$ contributes to the other 24×10^3 signal decays. The observed time-dependent asymmetry is shown in Fig. 1. The measurement gives $S_{\psi K^0_{\mathrm{S}}} = 0.717 \pm 0.013(\text{stat.}) \pm 0.008(\text{syst.})$ and $C_{\psi K^0_{\mathrm{S}}} = 0.008 \pm 0.012(\text{stat.}) \pm 0.003(\text{syst.})$. This is the world's single most precise measurement of $\sin 2\beta$, and the result is consistent with expectations from a global fit.

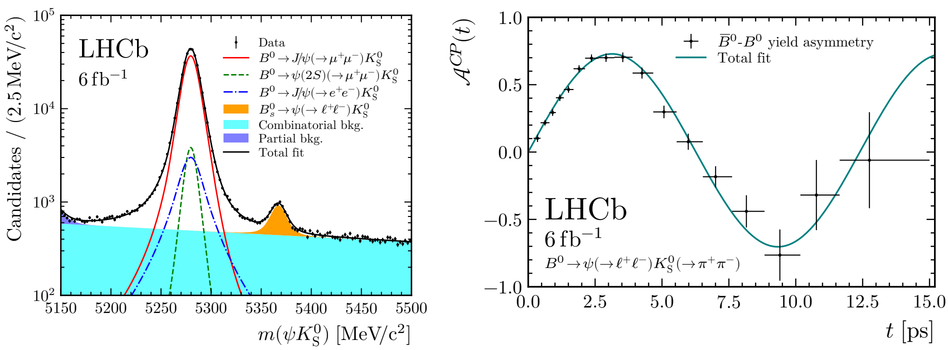

Fig. 1. Reconstructed mass spectrum (left) and measured time-dependent CP asymmetry, with fit overlayed (right).

5. Measurement of ϕ_s and $\Delta\Gamma_s$

The equivalent of $B^0 \to J/\psi K^0_\mathrm{S}$ for B^0_s decays is $B^0_s \to J/\psi\phi$. However, the CP asymmetry is now related to the phase of V_{ts}, with a predicted value of $\phi_s = 36.8^{+0.9}_{-0.6}$ mrad. Experimentally, the time-dependent asymmetry is modulated by the much faster B^0_s oscillations, and the two vector particles in the final state require an angular analysis to disentangle the CP-even and CP-odd components. The latest Run 2 analysis of LHCb reconstructed 349×10^3 signal events [8]. The data is divided in 6 bins of $m(K^+K^-)$, and a multidimensional maximum likelihood fit is applied on decay time and the three angular variables of the decay, $\cos\theta_K$, $\cos\theta_\mu$, and ϕ_h, shown in Fig. 2. As a reference channel, a large sample of $B^0 \to J/\psi K^{*0}$ decays is fit alongside the B^0_s data. A total of 9 physics parameters are extracted, amongst which $\phi_s = -0.039 \pm 0.022 \pm 0.006$ and the lifetime difference between the B^0_s mass eigenstates $\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024\,\mathrm{ps}^{-1}$. These results are consistent with, but improve significantly upon previous measurements, but the precision is not yet high enough to distinguish between no CP violation and SM CP violation.

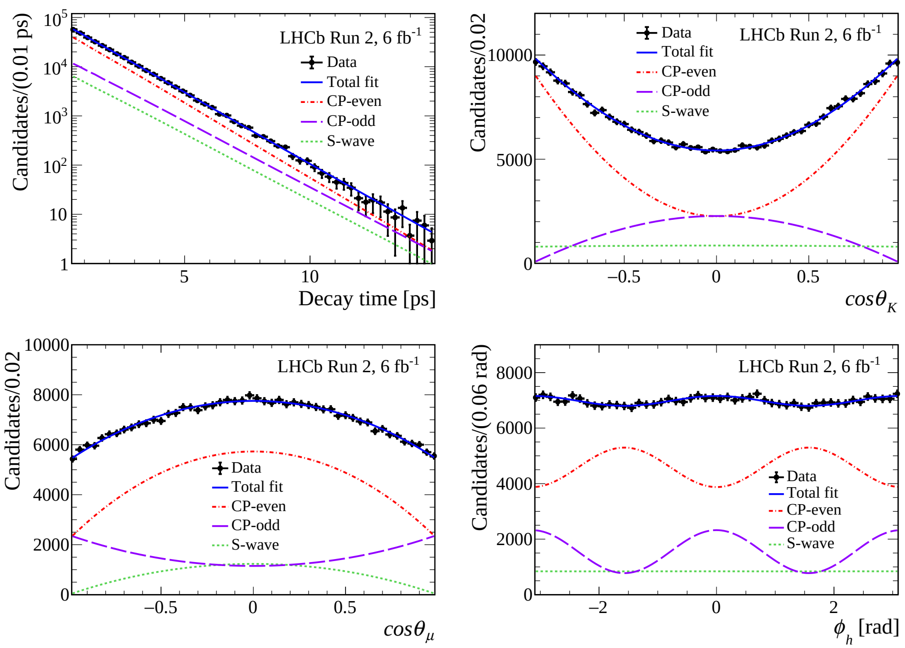

Fig. 2. Reconstructed decay time (top left), kaon angle (top right), muon angle (bottom left), and angle between the muon and hadron decay planes (bottom right).

6. Measurement of the CKM angle γ using $B^- \to DK$

Charged B mesons can interfere in the $B^- \to DK^-$ decay through common decay modes of the D^0 and the $\bar{D}^0$ meson, resulting in a nonzero value of $A^{\rm CP} \equiv \frac{\Gamma(B^-)-\Gamma(B^+)}{\Gamma(B^-)+\Gamma(B^+)}$. The three most common methods use CP eigenstates, *e.g.* $\pi^+\pi^-$, K^+K^-, $K^0_{\rm S}\pi^0$ (GLS method), favoured and double-suppressed decays such as $K^-\pi^+$ and $K^-\pi^+\pi^0$ (ADS method), and self-conjugate decays $K^0_{\rm S}\pi^+\pi^-$ and $K^0_{\rm S}K^+K^-$ (BPGGSZ method). As these decays are strongly dominated by tree diagrams, the theoretical uncertainty in the extraction of γ is tiny, $\mathcal{O}(10^{-7})$. While other methods exist to measure γ, the world average value $\gamma = (63.8^{+3.5}_{-3.7})^\circ$ is dominated by B^- decays from LHCb, and agrees with the SM prediction based on other CKM observables, $\gamma = (65.7^{+1.3}_{-1.2})^\circ$ [9].

Variations of $B^- \to DK^-$ decays have also been employed to contribute to the precision measurement of γ. Two recent LHCb measurements use $B^- \to D^*K^-$ decays, where the D^{*0} decays to a D^0 and a soft photon or neutral pion. Since the energy of the soft photon or pion is small, the spectrum of reconstructed DK mass naturally displays a secondary structure at $\approx 200\,$MeV below the B^+ mass. While not as clean as the main feature from $B^- \to DK^-$ decays, the secondary structure from partially reconstructed decays has a well-understood shape, and backgrounds in the mass range of interest can be modelled accurately as well.

An analysis based on partially reconstructed $B^- \to D^*K^-$ measures $\gamma = (92^{+21}_{-17})^\circ$ [10]. Another analysis attempts to reconstruct the soft photon or neutral pion in the LHCb electromagnetic calorimeter and achieves somewhat smaller uncertainties $\gamma = (69^{+13}_{-14})^\circ$ [11]. The intricate disentanglement of the components contributing to the data is illustrated in Fig. 3.

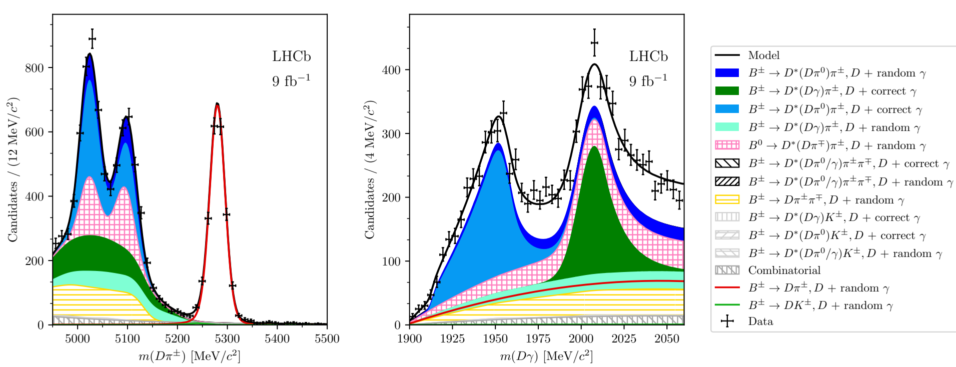

Fig. 3. Invariant mass distributions of $D\pi$ combinations and $D\gamma$ combinations in fully reconstructed $B^- \to D^*K^-$ decays.

7. CP asymmetry of B decays to double charm

Beauty mesons decay with a high probability to two charm mesons, since the process appears at tree level and without particular suppression mechanisms. It may thus not appear to be the most fruitful place to search for CP asymmetries, which require at least two amplitudes to contribute to a decay, with different weak and strong phases. For the Cabbibo-suppressed decay $B^- \to D^{(*)-}D^0$ however, it is not excluded that new physics contributions elevate the asymmetry to the $\mathcal{O}(10^{-1})$ level, making it obligatory to perform this measurement.

In 9 fb^{-1}, collisions containing a combination of a D^0 and a D_s^-, D^- or a D^{*-} were selected [12], and a Boosted Decision Tree was used to select the candidates with kinematic and geometric similarity to simulated B^- decays. As illustrated in Fig. 4 for $B^- \to D^-D^0$ decays, all three selected final states show both a sharp peak at the B^- mass and a secondary structure at lower mass corresponding to partially reconstructed decays, where the B decay involved an excited D meson and a soft photon or pion that was not reconstructed.

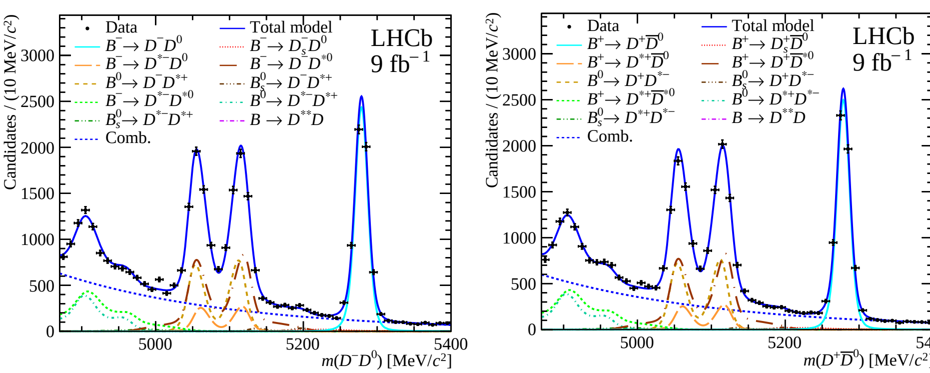

Fig. 4. Reconstructed $B^- \to D^-D^0$ (left) and $B^+ \to D^+\bar{D}^0$ candidates.

For both fully and partially reconstructed decays, the raw asymmetry $A_{\rm raw} \equiv \frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)}$ is determined from the fitted yields, shown in Fig. 4. The raw asymmetries are corrected for the B^- production asymmetry, measured in the $B^- \to J/\psi K^-$ decay, and the detection asymmetries from the trigger, particle identification, offline reconstruction, and material interactions. The resulting CP asymmetries for the fully reconstructed modes are $\mathcal{A}^{\rm CP}(B^- \to D_s^- D^0) = (0.5 \pm 0.2 \pm 0.5)\%$, $\mathcal{A}^{\rm CP}(B^- \to D^-D^0) = (2.5 \pm 1.0 \pm 0.4)\%$, $\mathcal{A}^{\rm CP}(B^- \to D^{*-}D^0) = (3.3 \pm 1.6 \pm 0.6)\%$, and for the partially reconstructed modes $\mathcal{A}^{\rm CP}(B^- \to D_s^{*-}D^0) = (-0.5 \pm 1.1 \pm 1.0)\%$, $\mathcal{A}^{\rm CP}(B^- \to D_s^- D^{*0}) = (1.1 \pm 0.8 \pm 0.6)\%$, $\mathcal{A}^{\rm CP}(B^- \to D^-D^{*0}) = (-0.2 \pm 2.0 \pm 1.4)\%$, and $\mathcal{A}^{\rm CP}(B^- \to D^{*-}D^{*0}) = (2.3 \pm 2.1 \pm 1.7)\%$. To all these results, an additional 0.3% uncertainty must be added to account for the CP violation in $B^- \to J/\psi K^-$ decays.

All measured asymmetries are consistent with zero and with the Standard Model. Several of the listed asymmetries have been measured for the first time and some of them have the precision improved by an order of magnitude.

8. Rare B decays

One intriguing discrepancy in heavy flavour physics has been the angular distribution in $B^0 \to K^{*0}\mu^+\mu^-$ decays, in particular the value of the P_5' parameter, as a function of the dimuon invariant mass, q^2. Previous analyses, which determined the angular parameters in bins of q^2, found a $3.3\,\sigma$ discrepancy in the corresponding Wilson Coefficient $\mathrm{Re}(C_9)$ [13], however, it has been argued that certain long-distance hadronic effects can mimic NP.

A recent analysis on 3 fb^{-1} of Run 1 and 1.7 fb^{-1} of Run 2 data [14, 15] takes a new approach: the data are analysed without binning in q^2, resulting in a 5-dimensional fit instead of the previous simultaneous set of 4-dimensional fits in bins of q^2. Using a polynomial expansion in q^2, this approach gives more control over long-distance contributions from the J/ψ and $\psi(2S)$ poles. With this approach, the discrepancy is reduced to less than 2σ, as shown in Fig. 5.

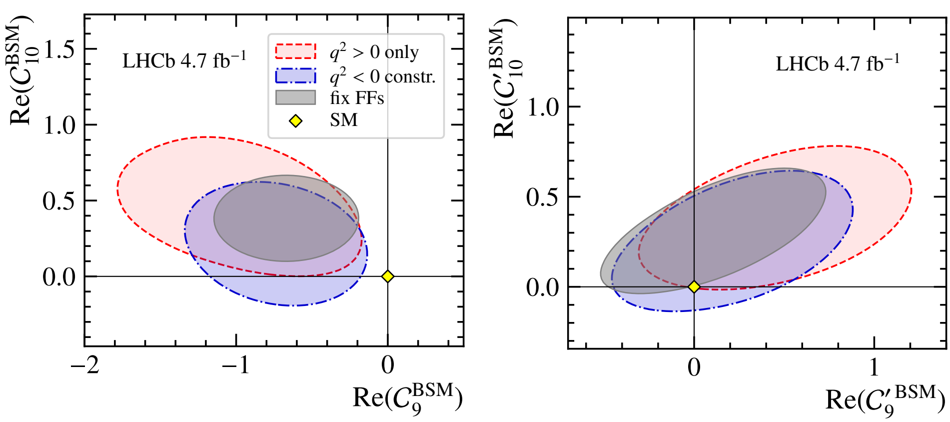

Fig. 5. Measurement of the Wilson coefficients C_9 and C_{10} (left), and C_9' and C_{10}' (right).

9. The LHCb upgrades

Since the end of Run 2 data taking in 2018, the LHCb detector has undergone a radical upgrade, which involves the replacement of almost all electronics, and several of the sub-detectors [16]. The aim of the upgrade is to be able to handle an increase in the luminosity by a factor five, and to do so with equal or higher efficiency for heavy flavour decays.

For the vertex detector, the previous silicon-strip detector has been replaced by a pixel detector. The down-stream tracker, a gas-based detector, has been replaced by scintillating fibres. In the Ring-Imaging Cherenkov detector, multi-channel PMTs replace the previous hybrid photodetectors. Also in the calorimeter and muon systems, all but the very front-end electronics has been replaced to handle the 40-fold increase in readout rate. The trigger is now completely software-based, with all sub-detectors fully read out to a trigger farm of CPUs and GPUs for every non-empty bunch crossing.

Analysis of several heavy-flavour signals has demonstrated that the upgraded detector is functional, but the data recorded in 2022 and 2023, is not considered to be of physics quality: in 2022 the detector was incomplete and in early 2023, an incident with the vacuum system of the vertex detector resulted in damage that prohibited the vertex detector to operate close to the beam line. This damage has been repaired during the end-of-year shutdown of 2023, and LHCb is on schedule to take physics quality data at the start of the 2024 run.

Currently, advanced studies are underway for a second upgrade in the high-luminosity era of the LHC, with the ultimate aim of collecting 300 fb^{-1} of pp collision data. This will require another 7-fold increase in instantaneous luminosity, reaching $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. At these values of the instantaneous luminosity, every bunch crossing will contain on average 40 collisions. To disentangle this large number of tracks in the high-density forward region, LHCb plans to make use of a vertex detector with very precise, $\mathcal{O}(50\,\mathrm{ps})$ time resolution. Several initial enhancements are foreseen to be implemented during the 3$^{\mathrm{rd}}$ LHC shutdown in 2026, while the completion of the second LHCb upgrade is planned for the 4$^{\mathrm{th}}$ LHC shutdown in 2033.

10. Conclusions

The activity levels of the LHCb Collaboration have never been higher: Analysis of the $9\,\mathrm{fb}^{-1}$ of pp collision data recorded in Run 1 and Run 2 are being completed, the upgraded detector is in the final stages of commissioning, and a vibrant research program is underway to develop detectors for the second upgrade.

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