Measurement of time-dependent CP violation in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays with LHCb

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In $B_s^0 \to D_s^{\mp} K^{\pm}$ decays CP violation in the interference between direct decay and decay after mixing results in a time-dependent asymmetry of the decay rates. From a measurement of this asymmetry five CP observables can be determined, which are themselves sensitive to the CKM angle γ. In order to probe the unitarity of the CKM matrix it is crucial to improve on the precision of γ, as it is the least well known CKM angle. The presented analysis [1] uses the full Run I dataset of $3\,\mathrm{fb}^{-1}$ of pp collisions that was collected at centre-of-mass energies of 7 and 8 TeV with the LHCb detector.

1 Introduction

All fundamental particles that were predicted by the Standard Model of particle physics (SM) have been experimentally discovered, which proves the SM to be an extremely successful theory. Nevertheless, there are a couple of observations the SM lacks explanations for. One of these is the asymmetry between matter and anti-matter visible in today's universe, whose existence requires the violation of the CP symmetry. Though CP violation is well established in the SM, it is only described at an extent far too small to explain the size of the observed matter-anti-matter asymmetry. The sole origin of CP violation in the SM lies in a single irreducible complex phase of the Cabbibo-Kobayashi-Maskawa (CKM) quark mixing matrix. The CKM matrix, whose matrix elements V_{xy} describe the transition from a quark of type x to type y, is unitary in the SM and connects the observables of various decay modes via its unitarity conditions. One of these conditions is given by the equation

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0, \tag{1}$$

which can be interpreted as a triangle in the complex plane. Measuring the sides and the angles of this so-called CKM triangle conducts an indirect test of the SM, as the triangle needs to close if the quark mixing matrix is unitary in nature. The presented analysis [1] aims to measure

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right), \tag{2}$$

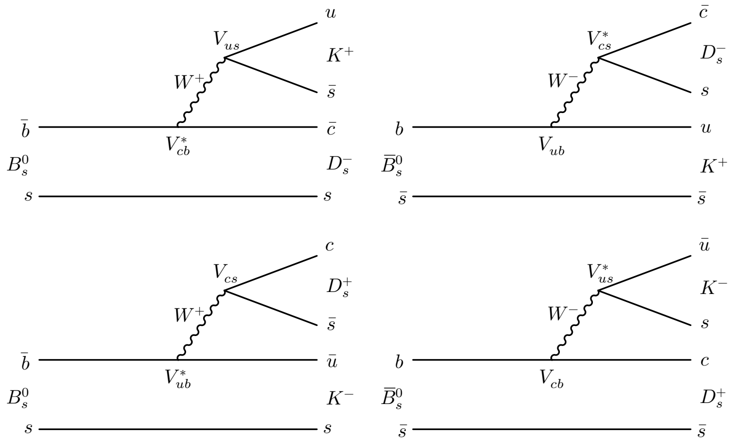

Figure 1 – Tree-level diagrams of the four direct decay transitions in $B_s^0 \to D_s^{\mp} K^{\pm}$.

which is currently measured to be $(73.2^{+6.3}_{-7.0})^{\circ}$ [2]. The world average is dominated by the wide range of LHCb γ measurements, of which a recent combination resulted in $\gamma = (72.2^{+6.8}_{-7.3})^{\circ}$ [3]. This combination also includes a time-dependent measurement of *CP* violation in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays [4] using $1\,\text{fb}^{-1}$, which precedes the presented analysis that uses the full Run I dataset of $3\,\text{fb}^{-1}$.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range of $2 < \eta < 5$, designed to study hadrons containing b or c quarks. It includes a high-precision tracking and vertexing system, which consists of a silicon-strip vertex detector that surrounds the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet, and three tracking stations placed downstream of the magnet that each feature an inner silicon-strip detector and an outer straw drift tube detector. A fundamental requirement for the presented analysis is LHCb's excellent decay-time resolution of about 45 fs, which makes it suitable for measuring *CP* violation in the B_s^0 system despite the fast oscillation frequency of these mesons. Another crucial ingredient for the analysis is the differentiation between kaons, pions, and protons, which the LHCb detector accomplishes with two ring-imaging Cherenkov detectors that are part of the particle identification (PID) system. LHCb's trigger system features a hardware and a software stage, which together reduce the event rate to about 5 kHz (3.5 kHz) in 2012 (2011). More details about the LHCb detector can be found elsewhere [5].

2 Time-dependent *CP* violation in $B_s^0 \to D_s^{\mp} K^{\pm}$

Both the B_s^0 and the $\overline{B}_s^0$ meson are able to directly decay into the final states $D_s^- K^+$ and $D_s^+ K^-$, which are symbolised with f and $\bar{f}$, respectively. All four direct decays are tree-level processes, as illustrated in Figure 1. Furthermore, all diagrams are of the same order λ^3 with respect to the parameter of the Wolfenstein parametrisation of the CKM matrix. Due to the oscillation of B_s^0 mesons between the particle and anti-particle states with the frequency Δm_s, it is possible that initially produced B_s^0 mesons decay as $\overline{B}_s^0$ mesons and vice versa. Therefore, all requirements for *CP* violation in the interference between direct decay and decay after mixing are fulfilled. This type of *CP* violation manifests in an asymmetry between the time-dependent decay widths, given by

$$\mathcal{A}_f(t) = \frac{\Gamma(\overline{B}_s^0(t) \to f) - \Gamma(B_s^0(t) \to f)}{\Gamma(\overline{B}_s^0(t) \to f) + \Gamma(B_s^0(t) \to f)} = \frac{-C_f \cos(\Delta m_s t) + S_f \sin(\Delta m_s t)}{\cosh(\Delta\Gamma t/2) - A_f^{\Delta\Gamma} \sinh(\Delta\Gamma t/2)}. \tag{3}$$

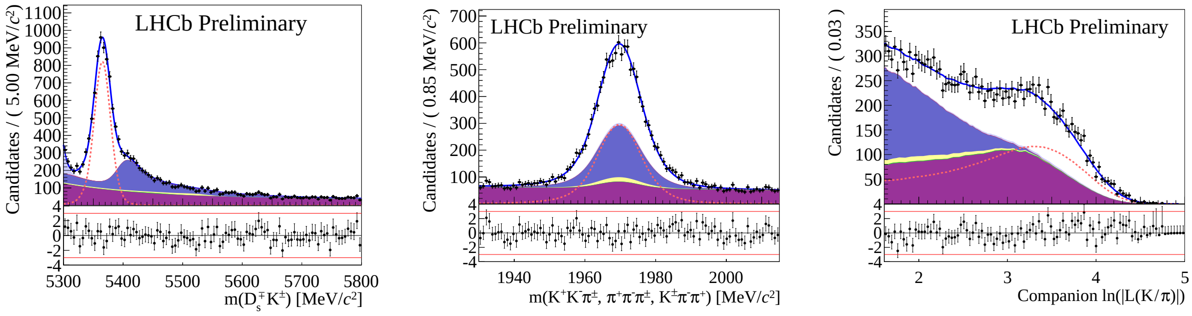

Figure 2 – Results of the fit to the B_s^0 invariant mass (left), $D_s^\pm$ invariant mass (middle) and distribution of the bachelor particle PID hypothesis (right). The sum of all components is represented by the blue solid line, while the signal is illustrated by the red dashed line. Different background components are plotted as shaded areas.

An equivalent asymmetry exists for the charge-conjugated final state $\bar{f}$. Thus, there are in total six measurable *CP* observables, which are defined as

$$\begin{aligned} A_f^{\Delta\Gamma} &= \frac{-2r_{D_sK}\cos(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, & A_{\bar{f}}^{\Delta\Gamma} &= \frac{-2r_{D_sK}\cos(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}, & C_f &= \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2}, \\ S_f &= \frac{2r_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, & S_{\bar{f}} &= \frac{2r_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}, & C_{\bar{f}} &= -C_f. \end{aligned} \quad (4)$$

Here, the relation $C_f = -C_{\bar{f}}$ originates from neglecting direct *CP* violation. Furthermore, r_{D_sK} is the amplitude ratio $|A(\overline{B}_s^0 \to D_s^- K^+)/A(B_s^0 \to D_s^- K^+)|$, while δ is the strong phase difference between the favoured and the suppressed amplitudes. The *CP* parameters give access to $\gamma - 2\beta_s \approx \gamma + \phi_s$, where ϕ_s is the weak phase measurable in $B_s^0 \to J/\psi\phi$ decays.

3 Analysis outline

The reconstruction starts by forming $D_s^\pm$ candidates from the final states $K^+K^-\pi^\pm$, $K^\pm\pi^-\pi^+$, and $\pi^+\pi^-\pi^\pm$ and subsequently combining them with a charged kaon or a charged pion to form $B_s^0 \to D_s^\mp K^\pm$ and $B_s^0 \to D_s^-\pi^+$ decays. The flavour-specific decay mode $B_s^0 \to D_s^-\pi^+$ has a higher branching ratio than the signal decay and is kinematically very similar, which makes it suitable to optimise the selection and to use it as a control mode throughout the analysis. Pre-selected $B_s^0 \to D_s^-\pi^+$ data is used to train a boosted decision tree that suppresses combinatorial background. Furthermore, a combination of PID information and kinematic vetoes is used to distinguish the different $D_s^\pm$ final states from each other and from cross-feed backgrounds such as $B^0 \to D^-K^+$ or $\overline{\Lambda}_b^0 \to \overline{\Lambda}_c^- K^+$. After all selection steps, there are about 6000 $B_s^0 \to D_s^\mp K^\pm$ and 97000 $B_s^0 \to D_s^-\pi^+$ candidates.

Some physics backgrounds remain after the selection, of which some overlap with the signal in the invariant B_s^0 mass distribution. In order to improve the separation of the signal from these backgrounds, a three-dimensional fit of the B_s^0 invariant mass, the $D_s^\pm$ invariant mass and the PID hypothesis distribution of the bachelor hadron is performed. Projections of the distributions of the data in all dimensions are shown in Fig. 2. The shapes used to model the different components are taken from simulated data, which is corrected for kinematic differences between simulations and data. From the three-dimensional fit signal weights are extracted, which enable a quasi background subtracted decay-time fit.

To determine the *CP* observables from the decay-time fit it is necessary to know the production flavour of the B_s^0 mesons. At LHCb this information is inferred by so-called flavour tagging algorithms, which are in this case calibrated using $B_s^0 \to D_s^-\pi^+$ data. Another important analysis ingredient is the modelling of decay time inefficiencies caused by the selection. These inefficiencies are taken care of with a cubic-spline based decay-time acceptance function that is modelled using $B_s^0 \to D_s^-\pi^+$ data. Figure 3 shows the result of the decay-time fit, with

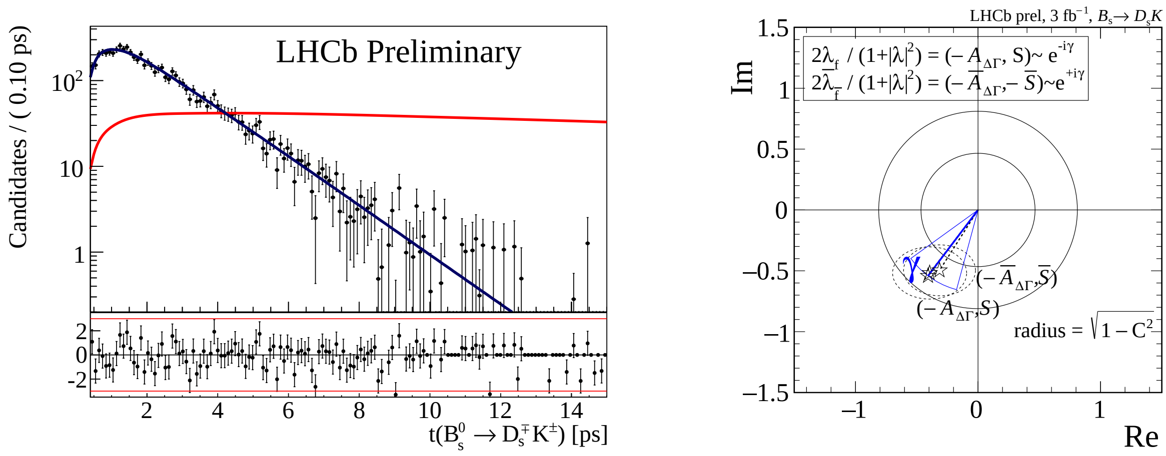

Figure 3 – Decay-time fit (left) and illustration of the *CP* parameters as well as γ in the complex plane (right).

the decay-time acceptance plotted as red line. The decay-time fit measures the *CP* observables

$$\begin{array}{llll} A_f^{\Delta\Gamma} = & 0.395 \pm 0.277 \pm 0.122, & A_{\bar{f}}^{\Delta\Gamma} = & 0.314 \pm 0.274 \pm 0.107, \\ S_f = & -0.518 \pm 0.202 \pm 0.073, & S_{\bar{f}} = & -0.496 \pm 0.197 \pm 0.071, \\ C_f = & 0.735 \pm 0.142 \pm 0.048. & & \end{array} \tag{5}$$

Here, the first uncertainties are statistical, while the second are systematic. The systematic uncertainties, which are smaller than the statistical ones throughout, were primarily determined using simulated pseudo-experiments. Neglecting correlations among the observables of the multidimensional fit is found to be the leading systematic uncertainty. Using the obtained *CP* parameters in a likelihood based on the Eqs. 4 results in

$$\gamma = (127^{+17}_{-22})^\circ, \qquad \delta = (358^{+15}_{-16})^\circ, \qquad r_{D_sK} = 0.37^{+0.10}_{-0.09}. \tag{6}$$

In order to obtain the result for γ, the value $\phi_s = (0.010 \pm 0.039)$ rad is taken from a recent LHCb measurement [6] as an external input. Figure 3 illustrates the results in the complex plane.

4 Conclusion

A time-dependent measurement of γ using $B_s^0 \to D_s^\mp K^\pm$ decays has been performed [1]. The result shows a $2.15\,\sigma$ compatibility with a combination of LHCb's time-integrated γ measurements [3]. The change in log-likelihood, when forcing $\gamma - 2\beta_s$ to 0, indicates an evidence for *CP* violation in $B_s^0 \to D_s^\mp K^\pm$ at the level of $3.6\,\sigma$. Superseding analyses will profit from LHCb's increasing dataset, as the presented one is still statistically limited.

Acknowledgments

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