PROCEEDINGS OF SCIENCE

Measurement of B meson mixing phases at LHCb

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Measuring the mixing phases of the B_s^0 mesons is crucial to validate the CP violation paradigm of the Standard Model and to search for new physics beyond it. Golden modes to measure these quantities are those governed by tree-level $b \to c\bar{c}q$ transitions, that allow precise and theoretically clean determinations to be performed. In addition, measuring the mixing phases with modes receiving major contributions from penguin diagrams open the possibility to reveal new physics appearing in the loops. In these proceedings we show the most recent measurements of B_s^0 mixing phases at LHCb.

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1. Introduction

Violation of charge-parity (CP) symmetry is one of the key conditions required to explain the observed asymmetry between matter and antimatter in the Universe. This is realised in the Standard Model by the CKM mechanism [1, 2]. The mixing of quark flavours is described by a 3×3 matrix, the CKM matrix. This matrix is fully described by four parameters, of which one is the complex CP-violating phase. Studies of heavy flavour provide access to many of the elements of the CKM matrix, which allows us to probe the CP-violation in the Standard Model. With precision measurements of the CKM parameters, we may probe for and constrain new physics models that could enhance CP-violation.

The LHCb experiment is a forward-arm spectrometer at the Large Hadron Collider [3]. Its design is optimised for the study of b- and c-hadrons, and the detector collected 9 fb^{-1} of data between 2011 and 2018 at centre-of-mass energies of 7, 8 and 13 TeV. By deploying a dedicated tracking detector, the VErtex LOcator (VELO), up to 7 mm from the beam, the characteristic displaced vertices of b-hadron decays may be reconstructed with a precision of 13 µm in the transverse plane [4]. Dedicated tracking stations downstream of the LHCb magnet provide track reconstruction and a measure of the momentum of charged tracks, with a resolution of 0.5% for low momentum tracks and a resolution of 1% for tracks up to a momentum of 200 GeV/c. The LHCb experiment also exploits Cherenkov radiation in two Ring Imaging CHerenkov (RICH) detector stations to provide particle identification of tracks, using additional information from the electromagnetic and hadronic calorimeters and dedicated muon stations. With all of these key tools combined the LHCb experiment is able to reconstruct b- and c- decays with high precision and efficiency, with an effective flavour tagging efficiency of between 4 and 5% and a decay time resolution of around 45 fs [5]. These proceedings discuss the recent results of two measurements of the CP-violation in the interference between mixing and decay by performing flavour-tagged, time-dependent angular analyses, and a measurement of the parameter $\Delta\Gamma_s$.

2. Measurement of mixing phase ϕ_s

The CP-violating phase, ϕ_s, is related to the CKM angle $\beta_s \equiv -V_{ts}V_{tb}^*/V_{cs}V_{cb}^*$ as $\phi_s = -2\beta_s$. The value of ϕ_s is very precisely predicted in the Standard Model to be $\phi_s = -0.0376^{+0.0005}_{-0.0006}$ rad [6], and can be extracted from a flavour-tagged time-dependent analysis of $B_s^0 \to J/\psi\phi$ decays. $B_s^0 \to J/\psi\phi$ decays provide an excellent laboratory to probe this CKM angle as this process occurs in large quantities at LHCb and can be very cleanly reconstructed with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. Using data taken during 2015 - 2018 (Run 2) of LHCb, corresponding to 6 fb^{-1}, a new result for the value of ϕ_s was calculated [7]. A sample of 349,000 signal events is used to extract ϕ_s, split into 48 independent samples; six $m(K^+K^-)$ ranges, two trigger categories and four data-taking years. Using an extended maximum likelihood fit to the invariant mass distribution, each event is given a signal weight using the $sPlot$ method. CP-even and CP-odd modes are disentangled and physics parameters are extracted by performing a weighted simultaneous fit to the decay-time distribution and the three decay angles in the helicity basis. The decay-time and angular distributions are shown for the combined sample in Figure 1 with the fit projection overlaid. In this analysis, ϕ_s is measured

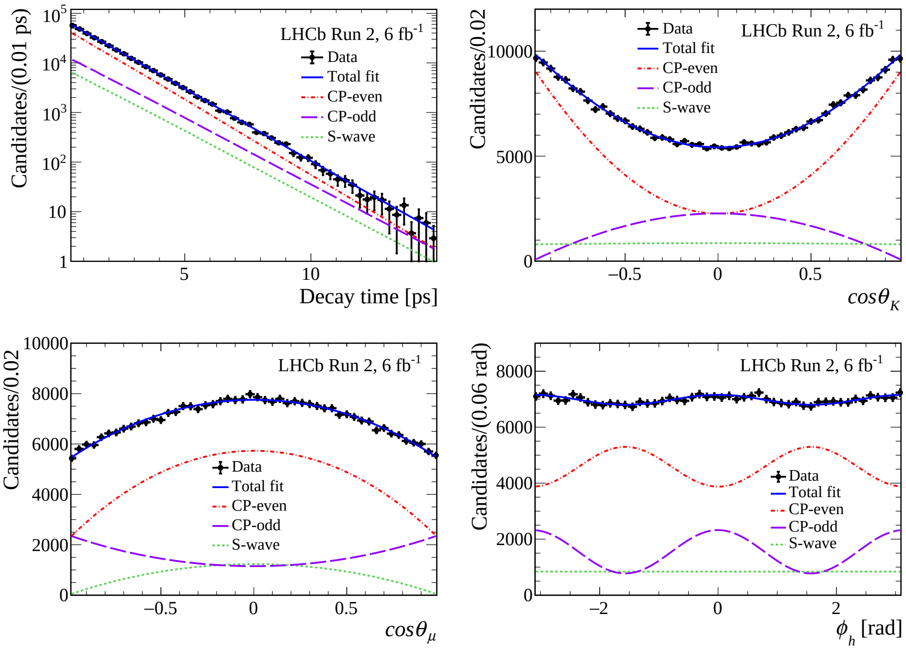

Figure 1: Distributions of decay time and helicity angles for background subtracted $B_s^0 \to J/\psi\phi$ data, with one-dimensional fit projection overlaid. The data categories are combined.

to be $-0.039 \pm 0.022 \pm 0.006$ rad. This is the single most precise determination of ϕ_s to date and is consistent with the prediction from the Standard Model.

3. Measurement of mixing phase $\phi_s^{s\bar{s}s}$

A similar analysis can be performed with $B_s^0 \to \phi\phi$ decays, but in this channel the CP violating phase, $\phi_s^{s\bar{s}s}$, is predicted to be zero in the Standard Model [8]. In this mode, a measured value of $\phi_s^{s\bar{s}s}$ significantly different from zero is a clear signature of new physics. This decay proceeds predominantly via penguin transitions and is susceptible to new physics contributions in loops. Using full Run 2 data from 2015 to 2018, corresponding to a sample of 6 fb^{-1}, LHCb published an updated measurement of $\phi_s^{s\bar{s}s}$ in this mode. With a sample size of 15,800 signal events, the value of $\phi_s^{s\bar{s}s}$ is extracted from a flavour-tagged, four-dimensional fit to the decay time and helicity angle distributions and is measured to be $-0.042 \pm 0.075 \pm 0.009$ rad [9]. This measurement is combined with the measurement from Run 1, with a sample size of 3 fb^{-1}, to give $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad. To date, this is the single most precise measurement of a time-dependent CP asymmetry in penguin-dominated B-decays, and is consistent with the prediction from the Standard Model.

4. Measurement of $\Delta\Gamma_s$

These analyses are a measure of CP-violation in the interference between B_s^0 meson mixing and decay. Therefore, a key component for understanding CP-violation in these modes is the decay-width difference between the heavy and light B_s^0 eigenstates, $\Delta\Gamma_s$. The value of $\Delta\Gamma_s$ is free

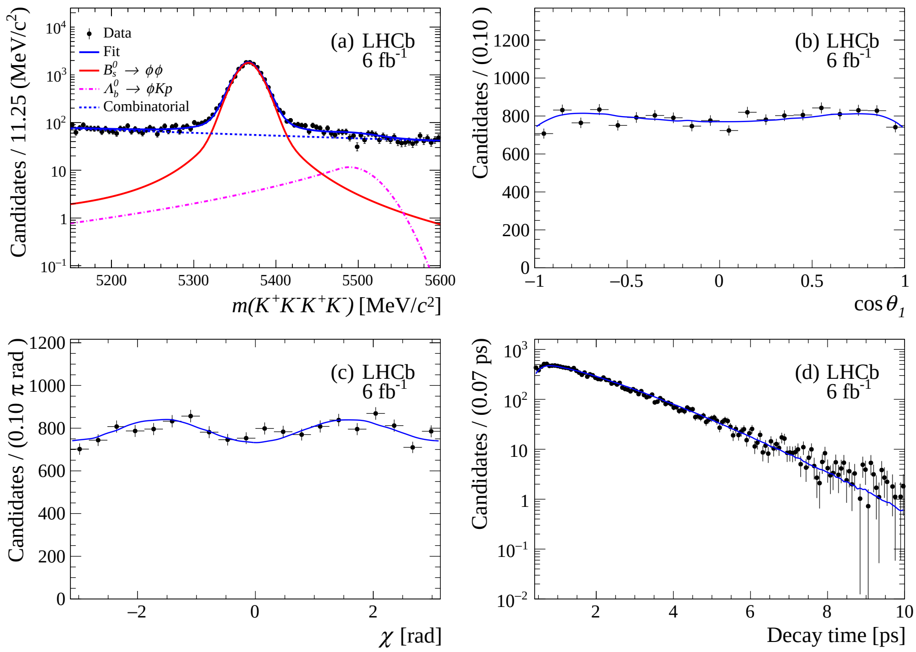

Figure 2: Distributions of four-kaon invariant mass, and background-subtracted distributions of decay time and helicity angles for $B_s^0 \to \phi\phi$ data. The one-dimensional fit projections are overlaid. The data categories are combined.

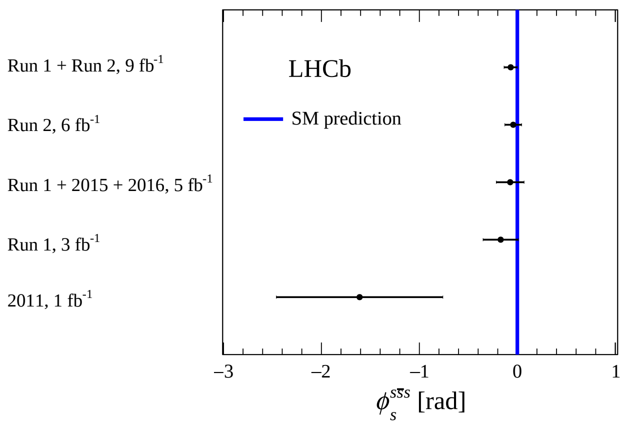

Figure 3: Measured values of $\phi_s^{s\bar{s}s}$ from LHCb analyses, including the latest result for Run 2, 6 fb^{-1} and the combination of Run 1 + Run 2, 9 fb^{-1}.

parameter in the 4D fit to $B_s^0 \to J/\psi\phi$ decays, and there exists a tension in the value obtained by the LHCb [7], ATLAS [10] and CMS [11] collaborations. As cross-check, the LHCb Collaboration have measured $\Delta\Gamma_s$ independently using decays of $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$. Since ϕ_s is small, to a good approximation CP-even decays measure the light lifetime and CP-odd decays measure the heavy lifetime. The value of $\Delta\Gamma_s$ is taken from the decay-with difference between the CP-even mode $B_s^0 \to J/\psi\eta'$ and the mode $B_s^0 \to J/\psi\pi^+\pi^-$, which is CP-odd via the $f(980)$ resonance. This analysis makes use of data taken between 2011 and 2018, corresponding to 9 fb^{-1}

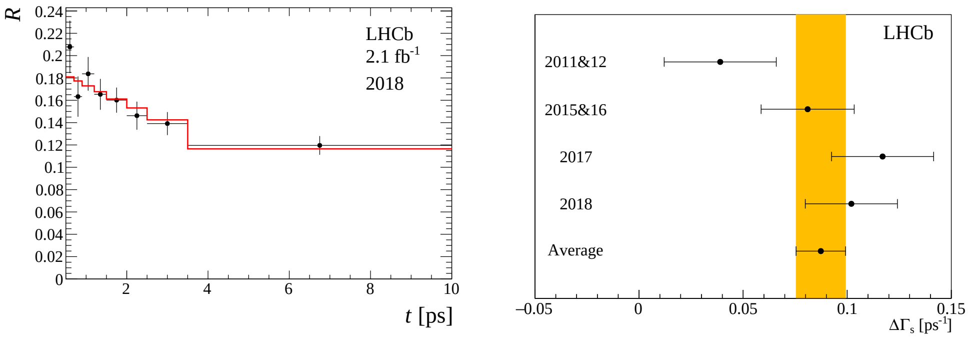

Figure 4: The left shows an example fit of the ratio of heavy and light decays as a function of decay time for the 2018 data sample, with the fit projection overlaid in red. On the right, the measured values of $\Delta\Gamma_s$ are shown for each sample, and the weighted average of all samples is shown with the yellow band.

of data. The samples are separated into four data-taking periods and then further split into bins of decay time. For each year, the ratio of heavy and light modes, corrected by a relative efficiency, is fitted to extract the value of $\Delta\Gamma_s$. Figure 4 shows an example fit to the ratio, R_i, and the fitted values for $\Delta\Gamma_s$ for each data-taking period and the weighted average of all periods. The weighted average result for $\Delta\Gamma_s$ is $0.087 \pm 0.012 \pm 0.009$ ps^{-1}, which is consistent with the value obtained from the latest LHCb analysis of $B_s^0 \to J/\psi\phi$ decays [7].

5. Looking to the future

The uncertainty on measurements of ϕ_s and $\phi_s^{s\bar{s}s}$ are still dominated by statistical uncertainty. An improvement in precision on these parameters requires more data to be taken. In 2022, the LHCb experiment recommenced data taking with a fully upgraded detector [12]. LHCb now takes data at the full bunch crossing rate of the LHC and has deployed a novel, software-only triggering system to boost the selection efficiency of modes such as $B_s^0 \to \phi\phi$ [13]. This phase of LHCb, known as Upgrade I, will be operational over Runs 3 and 4 of the LHC. In the 2030s, the LHC will start operating at high luminosity and the LHCb experiment will be further upgraded. This phase, known as LHCb Upgrade II, will replace all sub-detetctors and collect 300 fb^{-1} of data, providing unprecedented samples of $B_s^0 \to \phi\phi$ and $B_s^0 \to J/\psi\phi$. Following LHCb Upgrade I, the statistical uncertainty on ϕ_s is projected to be 14 mrad and the statistical uncertainty on $\phi_s^{s\bar{s}s}$ is to be 39 mrad, which will be further reduced to 4 mrad and 11 mrad respectively following Upgrade II [14].

6. Summary

The LHCb experiment continues to provide world-leading sensitivity to measurements of B-meson mixing phases, which the CKM picture holding. We show no evidence for new physics yet, but with all measurements still limited by statistical uncertainty the LHCb Upgrades I and II will provide unprecedented samples of these decays to further improve precision.

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