PROCEEDINGS OF SCIENCE

CP violation in mixing at LHCb

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Measurements of *CP* violation in mixing in the B^0 and B_s^0 systems at LHCb are presented, using the full Run 1 dataset corresponding to $3\,\mathrm{fb}^{-1}$. Semileptonic decays are used to measure the amount of *CP* violation in the B_s^0 and B^0 systems, denoted a_{sl}^s and a_{sl}^d, respectively. The focus lies on the new measurement of $a_{\mathrm{sl}}^s = (0.39 \pm 0.26 \pm 0.20)\%$, where the first error is statistical and the second systematic. This is the most precise measurement of *CP* Violation in mixing in the B_s^0 system to date. Combinations with measurements of a_{sl}^s and a_{sl}^d from other experiments are made, and the results are consistent with the Standard Model predictions.

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1. Introduction

Neutral mesons are mainly created in their interaction (or flavour) eigenstates, B or $\bar{B}$. The free propagation before the decay of these mesons, however, happens in their mass (or Hamiltonian) eigenstates, B_H or B_L. They can be expressed by a rotation in the $(B,\bar{B})$ eigenstate basis. Due to the difference in the decay widths, $\Delta\Gamma$, and masses, Δm, of these mass eigenstates, the flavour of neutral B mesons can change between creation and decay [1]. *CP* violation in this mixing process occurs if $P(B \to \bar{B}) \neq P(\bar{B} \to B)$. So far, *CP* violation in mixing has only been observed in the kaon system, where it is a 0.2% effect [2].

There are two neutral B systems, B^0 and B^0_s. The corresponding observables for the amount of *CP* violation in mixing in these systems are

$$a_{\rm sl}^{s,d} = \frac{P(\bar{B}_{s,d} \to B_{s,d}) - P(B_{s,d} \to \bar{B}_{s,d})}{P(\bar{B}_{s,d} \to B_{s,d}) + P(B_{s,d} \to \bar{B}_{s,d})} \, . \tag{1.1}$$

The Standard Model (SM) predictions for these parameters are $a^s_{\rm sl} = (2.22 \pm 0.27) \times 10^{-5}$ and $a^d_{\rm sl} = (-4.7 \pm 0.6) \times 10^{-4}$ [1,3], which is effectively zero within the current experimental sensitivity. Contributions from unknown particles in both the virtual loops and real intermediate states contributing to the mixing process can enhance these values [4]. These measurements thus make an excellent null-test of the SM.

2. Method

In order to measure $a_{\rm sl}$, one needs to know the flavour the B mesons are created in, and in which flavour they decay. The latter requirement is achieved by looking at flavour-specific decays. Semileptonic decays $B_{(s)} \to D^-_{(s)}\mu^+\nu_\mu X$, where X can be any number of particles, are flavour specific and have high branching ratios, and are thus well-suited for these measurements. These channels are, however, only partially reconstructed as $D^-_{(s)}\mu^+$ pairs, and include backgrounds from other B mesons decaying to the same inclusive final state.

The initial flavour of the B meson could be obtained using a procedure called flavour-tagging [5, 6]. This is difficult to perform at a hadron machine and suffers from a small effective efficiency, and possibly introduces additional asymmetries. What is done instead is to measure the raw untagged asymmetry of $D^\mp_{(s)}\mu^\pm$ candidates,

$$A_{\rm raw} = \frac{N(D^-_{(s)}\mu^+) - N(D^+_{(s)}\mu^-)}{N(D^-_{(s)}\mu^+) + N(D^+_{(s)}\mu^-)} \, . \tag{2.1}$$

The raw asymmetry is sensitive to $a_{\rm sl}/2$ due to the contribution of both wrong-sign $(\bar{B} \to f)$ decays that have mixed to another flavour, and right-sign decays $(B \to f)$ which have not. Since the untagged asymmetry only considers final states, it is also sensitive to any production asymmetry between B and $\bar{B}$ mesons (A_P) in the pp collisions of the LHC. In addition, there can be an asymmetry between the detection efficiencies of the $D^-_{(s)}\mu^+$ and $D^+_{(s)}\mu^-$ final states (A_D). This can for instance be because oppositely charged tracks are bent into different directions of the LHCb detector due do the dipole magnet. These detection asymmetries are expected to change sign with

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data taken under a reversed magnet polarity. Calibration samples are used to assess the detection asymmetries in a data-driven way. Comparing results between data taken with the reversed magnet polarity provides an excellent consistency check.

The raw asymmetry as a function of the decay time of the B meson is given by

$$A_{\rm raw}(t) = \frac{N(D^-_{(s)}\mu^+,t) - N(D^+_{(s)}\mu^-,t)}{N(D^-_{(s)}\mu^+,t) + N(D^+_{(s)}\mu^-,t)} \approx A_D + \frac{a_{\rm sl}}{2} + \left(A_P - \frac{a_{\rm sl}}{2}\right)\cos(\Delta m t). \tag{2.2}$$

For the measurement of $a^d_{\rm sl}$ the time-dependence of the raw asymmetry is used to disentangle $a^d_{\rm sl}$ from A_P. Using the full 3 fb^{-1} LHCb dataset it was found to be $a^d_{\rm sl} = (-0.02 \pm 0.19 \pm 0.30)\%$ [7].

3. New measurement of $a^s_{\rm sl}$

The previous LHCb measurement of $a^s_{\rm sl} = (-0.06 \pm 0.50 \pm 0.36)\%$ [8] was performed using the 1 fb^{-1} dataset taken in 2011. The new measurement published in Ref. [9] uses the full 3 fb^{-1} dataset and supersedes the previous result. Using inclusive $\bar{B}^0_s \to D^-_s \mu^+ \nu_\mu X$ decays, $a^s_{\rm sl}$ is measured by performing an untagged, time-integrated analysis. The difference with the $a^d_{\rm sl}$ measurement is that in the B^0_s system, the mixing frequency Δm_s is so large that the amplitude of the cosine term in Eq. 2.2 is diluted by a factor 10^{-3} when integrating over B^0_s decay time [8, 10]. This implies we do not have to take the production asymmetry into account. However, detection asymmetries still play a significant role, as well as the backgrounds from real B decays that peak in the D^-_s mass, resulting in

$$a^s_{\rm sl} = \frac{2}{1 - f_{\rm bkg}}(A_{\rm raw} - A_D - f_{\rm bkg}A_{\rm bkg}), \tag{3.1}$$

where $f_{\rm bkg}$ is the fraction of the peaking background contribution, and $A_{\rm bkg}$ is the asymmetry in these backgrounds.

3.1 Selection and backgrounds

The previous analysis considered the final state $D^-_s \to (\phi \to K^+K^-)\pi^-$ where the kaon pair goes through the ϕ resonance. This analysis considers the full $D^-_s \to K^+K^-\pi^-$ decay phase space, increasing the amount of signal by almost a factor two. Three regions in the D^-_s Dalitz plane are treated separately due to various levels of background: the $\phi\pi$ region (identical to the previous analysis), the K^*K region where the decay goes through the $K^*(892)^0 \to K^+\pi^-$ resonance, and the remainder which is called the non-resonant (NR) region. Fig. 1 (**left**) shows the definitions of these regions in the Dalitz plane. Contributions from partially reconstructed or misidentified sources like $\overline{\Lambda}^-_c \to K^+\overline{p}\pi^-$ and $D^- \to K^+\pi^-\pi^-$ decays are removed, as well as D^-_s candidates that are promptly produced in the pp collision. B^0_s yields are obtained by selecting $(D^-_s\mu^+)$ combinations, and fitting the D^-_s candidates invariant mass using a binned maximum-likelihood fit as shown in Fig. 1 (**right**). The B^0_s yields obtained in this way contain contributions from other B decays, as mentioned before. These can be split up into two categories: $B \to D^-_s D$ decays, where B represents $B^+, B^0, B^0_s, \Lambda^0_b$ and D is any charmed hadron decaying semileptonically, and $B^{0,*} \to D^-_s K\mu^+\nu_\mu X$ where a kaon is produced in a D^{**} decay. These backgrounds contribute to the obtained D^-_s and D^+_s yields and hence dilute the sensitivity to $a^s_{\rm sl}$. If these backgrounds have a production asymmetry or *CP* asymmetry (e.g. a^d_{sl}) their contribution will shift the measurement of a^s_{sl}. These effects are represented by the multiplicative factor and the last term in Eq. 3.1, respectively. The background fractions are obtained from known branching ratios [2] and dedicated simulation studies. The background asymmetries are measured by LHCb [7, 11, 12]. The total effect of all backgrounds is $f_{bkg} = (18.4 \pm 6.0)\%$ and $f_{bkg}A_{bkg} = \sum_i f^i_{bkg}A^i_{bkg} = (-0.023 \pm 0.031)\%$.

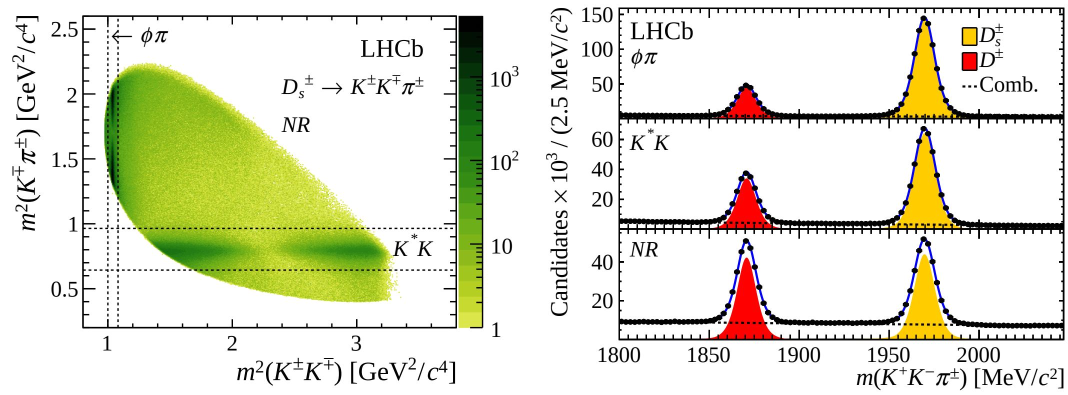


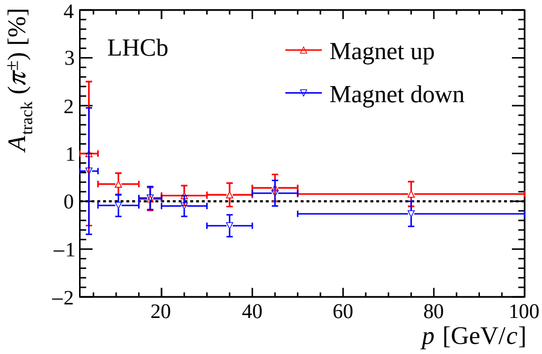
Figure 1: Left: the D_s^- decay Dalitz plane. Indicated are the three Dalitz regions into which the data is split. **Right**: Distributions of $K^+K^-\pi^\pm$ mass in the three Dalitz regions, summed over both magnet polarities and data-taking periods. Overlaid is the result of the fit.

3.2 Detection asymmetries

Contributions to the detection asymmetry are split up into three categories: the tracking asymmetry A_{track}, the particle identification (PID) asymmetry A_{PID} and the trigger asymmetry A_{trig}, of which the main contributions are briefly described below. The largest source of systematic uncertainty in the previous analysis originated from the determination of A_{track}, which is now calculated using two methods. The first uses a tag-and-probe approach with partially reconstructed $J/\psi \to \mu^+\mu^-$ decays, as described in Ref. [13]. The other method uses fully and partially reconstructed $D^{*+} \to (D^0 \to K^-\pi^+\pi^-\pi^+)\pi^+$ decays, as described in Ref. [14]. In addition, simulation studies are performed to address effects of cross-sections in the detector material and detector acceptance. The combined tracking asymmetry is shown in Fig. 2 (**left**). The PID asymmetry is obtained by using a $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ sample, where the daughters of the D^0 are identified by the charge of the pion from the D^{*+} decay, without using information from the PID systems. The asymmetry is somewhat larger for the K^*K and NR regions due to a tighter PID requirement with respect to the $\phi\pi$ region. The trigger asymmetry mostly originates from the hardware-level muon trigger and is assessed with a J/ψ tag-and-probe method. Even though the measured detection asymmetries per magnet polarity range from 0.01% up to a few %, the average of the magnet polarities is consistent with zero.

3.3 Results

Twelve values for a^s_{sl} are obtained, split into three Dalitz regions, two magnet polarities, and two data-taking periods. These results are combined as follows. First, the weighed average of the three Dalitz regions is taken. Then, an arithmetic average is taken between the magnet polarities, in order to cancel any magnet-induced detection asymmetry that might have been overlooked. Lastly, the weighted average of the data-taking periods is taken. The result is $a^s_{\rm sl} = (0.39 \pm 0.26 \pm 0.20)\%$, where the first error is statistical and the second systematic, consistent with the previous result and the SM prediction. The largest source of statistical uncertainty originates from the raw asymmetry, while the largest systematic uncertainty is due to the peaking background fraction. Note that the sources of statistical uncertainty originating from the calibration samples, used to assess the detection asymmetry, are added to the total statistical uncertainty. This was not done in the previous measurement.



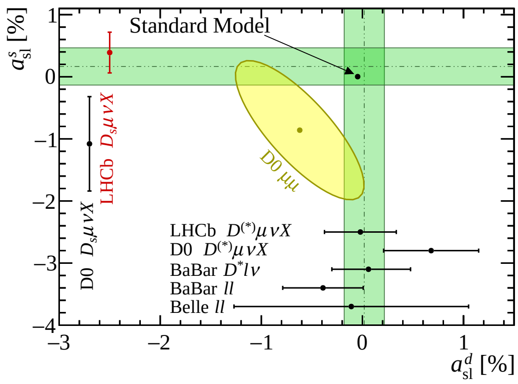


Figure 2: Left: the combined tracking detection asymmetry as function of momentum. **Right**: overview of $a^d_{\rm sl}$ and $a^s_{\rm sl}$ measurements. The points with error bars represent individual measurements of either $a^d_{\rm sl}$ or $a^s_{\rm sl}$, whose averages are shown in the green bands. The new LHCb measurement of $a^s_{\rm sl}$ is highlighted in red. The yellow ellipse represents the D0 dimuon measurement.

4. Overview

The measurements of $a^d_{\rm sl}$ and $a^s_{\rm sl}$ are summarized in Fig. 2 (**right**). The D0 dimuon measurement, represented by the yellow ellipse, is sensitive to $a^s_{\rm sl}$, $a^d_{\rm sl}$ and $\Delta\Gamma_d$ and displays a 3.6σ deviation from the SM prediction [15], when assuming a SM value for $\Delta\Gamma_d$. How much of this deviation can be attributed to a non-SM value of $\Delta\Gamma_d$ is a point of debate [16]. The green bands represent the averages of the pure measurements of either $a^d_{\rm sl}$ [17] or $a^d_{\rm sl}$, and include the LHCb results of $a^d_{\rm sl}$ and the new result for $a^s_{\rm sl}$ using the full $3\,{\rm fb}^{-1}$ dataset. They are consistent with the SM predictions, and marginally compatible with the D0 result.

5. Conclusion

LHCb has measured $a^s_{\rm sl} = (0.39 \pm 0.26 \pm 0.20)\%$, using the full Run 1 dataset corresponding to $3\,{\rm fb}^{-1}$. This is the most precise measurement of *CP* violation in mixing of B^0_s mesons, and is compatible with the SM prediction and the previous result. Since the precision of this analysis is limited by statistics, an improved measurement can be expected after collecting more data in Run 2 of the LHC.

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