Measurement of the flavour-specific CP-violating asymmetry $a_{s\ell}$ in $B[0 \over s]$ decays

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th>Citation</th>
<th>Aaij, R. et al. “Measurement of the Flavour-Specific CP-Violating Asymmetry $a_{s\ell}$ in $B[0 \over s]$ Decays.” Physics Letters B 728 (January 2014): 607–615.</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1016/j.physletb.2013.12.030">http://dx.doi.org/10.1016/j.physletb.2013.12.030</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>Elsevier</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Sat Dec 08 07:25:37 EST 2018</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/87572">http://hdl.handle.net/1721.1/87572</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Creative Commons Attribution</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td><a href="http://creativecommons.org/licenses/by/4.0/">http://creativecommons.org/licenses/by/4.0/</a></td>
</tr>
</tbody>
</table>
Measurement of the flavour-specific $CP$-violating asymmetry $a^s_{sl}$ in $B^0_s$ decays

LHCb Collaboration

ARTICLE INFO

Article history:
Received 5 August 2013
Received in revised form 25 October 2013
Accepted 9 December 2013
Available online 16 December 2013

ABSTRACT

The $CP$-violating asymmetry $a^s_{sl}$ is studied using semileptonic decays of $B^0_s$ and $\bar{B}^0_s$ mesons produced in $pp$ collisions at a centre-of-mass energy of 7 TeV at the LHC, exploiting a data sample corresponding to an integrated luminosity of 1.0 fb$^{-1}$. The reconstructed final states are $D^+_s \mu^+$, with the $D'^+_s$ particle decaying in the $\phi\tau^+$ mode. The $D^+_s\mu^+$ yields are summed over $B^0_s$ and $\bar{B}^0_s$ initial states, and integrated with respect to decay time. Data-driven methods are used to measure efficiency ratios. We obtain $a^s_{sl} = (-0.06 \pm 0.50 \pm 0.36)\%$, where the first uncertainty is statistical and the second systematic.

1. Introduction

The $CP$ asymmetry in $B^0_s - \bar{B}^0_s$ mixing is a sensitive probe of new physics. In the neutral $B$ system ($B^0$ or $B^0_s$), the mixing of the flavour eigenstates (the neutral $B$ and its antiparticle $\bar{B}$) is governed by a $2 \times 2$ complex effective Hamiltonian matrix [1]

\[
\left( \begin{array}{cc}
M_{11} - \frac{1}{2} \Gamma_{11} & M_{12} - \frac{1}{2} \Gamma_{12} \\
M_{12}^* - \frac{1}{2} \Gamma_{12}^* & M_{22} - \frac{1}{2} \Gamma_{22}
\end{array} \right),
\]

which operates on the neutral $B$ and $\bar{B}$ flavour eigenstates. The mass eigenstates have eigenvalues $M_1$ and $M_2$. Other measurable quantities are the mass difference $\Delta M$, the width difference $\Delta \Gamma$, and the semileptonic (or flavour-specific) asymmetry $a_{sl}$. These quantities are related to the off-diagonal matrix elements and the phase $\phi_{12} \equiv \arg(-M_{12}/\Gamma_{12})$ by

\[
\Delta M \equiv M_H - M_L = 2|M_{12}| \left( 1 - \frac{1}{8} \frac{\Gamma_{12}^2}{|M_{12}|^2} \sin^2 \phi_{12} + \cdots \right),
\]

\[
\Delta \Gamma \equiv \Gamma_L - \Gamma_H = 2|\Gamma_{12}| \cos \phi_{12} \left( 1 + \frac{1}{8} \frac{\Gamma_{12}^2}{|M_{12}|^2} \sin^2 \phi_{12} + \cdots \right),
\]

\[
a_{sl} \equiv \frac{\Gamma(\bar{B}(t) \rightarrow f) - \Gamma(B(t) \rightarrow f)}{\Gamma(\bar{B}(t) \rightarrow f) + \Gamma(B(t) \rightarrow f)} \approx \frac{\Delta \Gamma}{\Delta M} \tan \phi_{12},
\]

where $B(t)$ is the state into which a produced $B$ meson has evolved after a proper time $t$ measured in the meson rest frame, and $f$ indicates a flavour-specific final state. The term flavour-specific means that the final state is only reachable by the decay of the $B$ meson, and consequently reachable by a meson originally produced as a $\bar{B}$ only through mixing. We use the semileptonic flavour specific final state and thus refer to this quantity as $a_{sl}$. Note that $a_{sl}$ is decay time independent. Throughout the Letter, mention of a specific channel implies the inclusion of the charge-conjugate mode, except in reference to asymmetries.

The phase $\phi_{12}$ is very small in the Standard Model (SM), in particular, for $B^0_s$ mixing, $\phi_{12}$ is approximately $0.2^\circ$ [2]. New physics can affect this phase [3,4] and therefore $a_{sl}$. The D0 Collaboration has reported evidence for a decay asymmetry $A^B_{sl} = (-0.787 \pm 0.172 \pm 0.093)\%$ in a mixture of $B^0$ and $B^0_s$ semileptonic decays, where the first uncertainty is statistical and the second systematic [5]. This asymmetry is much larger in magnitude than the SM predictions for semileptonic asymmetries in $B^0$ and $B^0_s$ decays, namely $a^B_{sl} = (1.9 \pm 0.3) \times 10^{-3}$ and $a^B_{sl} = (-4.1 \pm 0.6) \times 10^{-4}$ [4]. More recently D0 published measurements of $a^B_{sl} = (0.68 \pm 0.05 \pm 0.04)\%$ [6], and $a^B_{sl} = (-1.12 \pm 0.74 \pm 0.17)\%$ [7], consistent both with the anomalous asymmetry $A^B_{sl}$ and the SM predictions for $a^B_{sl}$ and $a^B_{sl}$. If the measured value of $A^B_{sl}$ is confirmed, this would demonstrate the presence of physics beyond the SM in the quark sector. The $e^+e^-$ $B$-factory average asymmetry in $B^0$ decays is $a^B_{sl} = (0.02 \pm 0.31)\%$ [8], in good agreement with the SM. A measurement of $a^B_{sl}$ with comparable accuracy is important to establish whether physics beyond the SM influences flavour oscillations in the $B^0_s$ system.

When measuring a semileptonic asymmetry at a $pp$ collider, such as the LHC, particle–antiparticle production asymmetries, denoted as $a_P$, as well as detector related asymmetries, may bias the measured value of $a^B_{sl}$. We define $a_P$ in terms of the numbers of produced $b$-hadrons, $N(B)$, and anti-$b$-hadrons, $N(\bar{B})$, as
\[
\Delta p = \frac{N(B) - N(\bar{B})}{N(B) + N(\bar{B})},
\]
where \(\Delta p\) may in general be different for different species of \(b\)-hadron.

In this Letter we report the measurement of the asymmetry between \(D_s^0 X_\mu^+\overline{\tau}\) and \(D_s^0 X_\mu^-\overline{\nu}\) decays, with \(X\) representing possible associated hadrons. We use the \(D_s^+ \rightarrow \phi \pi^+\) decay. For a time-integrated measurement we have, to first order in \(\Delta p\),
\[
A_{\text{meas}} = \frac{\Gamma[D_s^+ \mu^+]}{\Gamma[D_s^+ \mu^-]} + \frac{\Gamma[D_s^- \mu^-]}{\Gamma[D_s^- \mu^+]}
= \frac{a_{\text{sl}}^2}{2} + \left[ a_{\text{sl}}^2 \int_{-\infty}^{\infty} e^{-t^2} \cos(\Delta M t) e^{i \phi} dt \right]
\]
where \(\Delta M = m_{D_s} - m_{D_s}^\text{phys}\) and \(\Gamma\) are the mass difference and average decay width of the \(B^0\overline{B}^0\) meson system, respectively, and \(\epsilon\) is the decay time acceptance function for \(B^0\overline{B}^0\) mesons. Due to the large value of \(\Delta M\), \(17.768 \pm 0.024\) ps\(^{-1}\), the oscillations are rapid and the integral ratio in Eq. (4) is approximately 0.2%. Since the production asymmetry within the detector acceptance is expected to be at most a few percent\(^{10–12}\), this reduces the effect of \(\Delta p\) to the level of a few \(10^{-4}\) for \(B^0\overline{B}^0\) decays. This is well beneath our target uncertainty of the order of \(10^{-3}\), and thus can be neglected, therefore yielding \(A_{\text{meas}} = 0.5a_{\text{sl}}^2\).

The measurement could be affected by a detection charge-asymmetry, which may be induced by the event selection, tracking, and muon selection criteria. The measured asymmetry can be written as
\[
A_{\text{meas}} = A_{\mu}^\text{\scriptsize LHCb} - A_{\text{track}} - A_{\text{bkg}},
\]
where \(A_{\mu}^\text{\scriptsize LHCb}\) is given by
\[
A_{\mu} = \frac{N(D_s^+ \mu^+) - N(D_s^+ \mu^-) \times \epsilon(\mu^+)}{N(D_s^- \mu^+) + N(D_s^- \mu^-) \times \epsilon(\mu^-)}.
\]
\(N(D_s^+ \mu^+)\) and \(N(D_s^+ \mu^-)\) are the measured yields of \(D_s\mu\) pairs, \(\epsilon(\mu^+)'s\) and \(\epsilon(\mu^-)'s\) are efficiency corrections accounting for trigger and muon identification effects, \(A_{\text{track}}\) is the track-reconstruction asymmetry of charged particles, and \(A_{\text{bkg}}\) accounts for asymmetries induced by backgrounds.

2. The LHCb detector and trigger

We use a data sample corresponding to an integrated luminosity of 1.0 fb\(^{-1}\) collected in 7 TeV pp collisions with the LHCb detector.\(^{13}\) This detector is a single-arm forward spectrometer covering the pseudorapidity range \(2 < \eta < 5\), designed for the study of particles containing \(b\) or \(c\) quarks. The detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the \(pp\) interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift-tubes placed downstream. The combined tracking system has momentum resolution \(\delta p/p\) that varies from 0.4% at 5 GeV to 0.6% at 100 GeV.\(^2\) Charged hadrons are identified using two ring-imaging Cherenkov (RICH) detectors.\(^{14}\) Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and pre-shower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.\(^{15}\) The LHCb coordinate system is a right handed Cartesian system with the positive z-axis aligned with the beam line and pointing away from the interaction point and the positive x-axis following the ground of the experimental area, and pointing towards the outside of the LHC ring.

The trigger system\(^{16}\) consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage which applies a full event reconstruction. For the \(D_s\mu\) signal samples, the hardware trigger (L0) requires the detection of a muon of either charge with transverse momentum \(p_T > 1.64\) GeV. In the subsequent software trigger, a first selection algorithm confirms the \(L0\) candidate muon as a fully reconstructed track, while the second level algorithm includes two possible selections. One is based on the topology of the candidate muon and one or two additional tracks, requiring them to be detached from the primary interaction vertex. The second category is specifically designed to detect inclusive \(\phi \rightarrow K^+ K^-\) decays. We consider all candidates that satisfy either selection algorithm. We also study two mutually exclusive samples, one composed of candidates that satisfy the second trigger category, and the other satisfying the topological selection of events including a muon, but not the inclusive \(\phi\) algorithm. Approximately 40% of the data were taken with the magnetic field up, oriented along the positive y-axis in the LHCb coordinate system, and the rest with the opposite down polarity. We exploit the fact that certain detection asymmetries cancel if data from different magnet polarities are combined.

3. Selection requirements

Additional selection criteria exploiting the kinematic properties of semileptonic \(b\)-hadron decays\(^{17–19}\) are used. In order to minimize backgrounds associated with misidentified muons, additional selection criteria on muons are that the momentum, \(p\), be between 6 and 100 GeV, that the pseudorapidity, \(\eta\), be between 2 and 5, and that they are inconsistent with being produced at any primary vertex. Tracks are considered as kaon candidates if they are identified by the RICH system, have \(p_T > 0.3\) GeV and \(p_T > 2\) GeV. The impact parameter (IP), defined as the minimum distance of approach of the track with respect to the primary vertex, is used to select tracks coming from charm decays. We require that the \(\chi^2\), formed by using the hypothesis that each track’s IP is equal to 0, which measures whether a track is consistent with coming from the PV, is greater than 9. To be reconstructed as a \(\phi\) meson candidate, a \(K^+ K^-\) pair must have invariant mass within \(\pm 20\) MeV of the \(\phi\) meson mass. Candidate \(\phi\) mesons are combined with charged pions to make \(D_s\) meson candidates. The sum of the \(p_T\) of \(K^+\), \(K^-\) and \(\pi^\pm\) candidates must be larger than 2.1 GeV. The vertex fit \(\chi^2\) divided by the number of degrees of freedom (ndf) must be less than 6, and the flight distance \(\chi^2\), formed by using the hypothesis that the \(D_s^+\) flight distance is equal to 0, must be greater than 100. The \(B^0\) candidate, formed from the \(D_s\) and the muon, must have vertex fit \(\chi^2/\text{ndf} < 6\), be downstream of the primary vertex, have \(2 < \eta < 5\) and have invariant mass between 3.1 and 5.1 GeV. Finally, we include some angular selection criteria that require that the \(B\) candidate have a momentum aligned with the measured flight direction. The cosine of the angle between the \(D_s\mu\) momentum direction and the vector from the primary vertex to the \(D_s\mu\) origin must be larger than 0.999. The cosine of the angle between the \(D_s\) momentum and the vector from the primary vertex to the \(D_s\) decay vertex must be larger than 0.99.

4. Analysis method

Signal yields are determined by fitting the \(K^+ K^-\pi^+\) invariant mass distributions shown in Fig. 1. We fit both the signal \(D_s^+\) and

\[2\] We work in units with \(c = 1\).
$D^+$ peaks with double Gaussian functions with common means. The $D^+$ channel is used only as a component of the fit to the mass spectrum. The average mass resolution is about 7.1 MeV. The background is modelled with a second-order Chebychev polynomial. The signal yields from the fits are listed in Table 1.

Table 1

| Yields for $D_s^+\mu^-$ and $D_s^-\mu^+$ events separately for magnet up and down data. These yields contain very small contributions from prompt $D_s$ and $b$-hadron backgrounds. |
|---|---|
| Magnet up | Magnet down |
| $D_s^+\mu^-$ | 38 742 ± 218 | 53 768 ± 264 |
| $D_s^-\mu^-$ | 38 055 ± 223 | 54 252 ± 259 |

The detection asymmetry is largely induced by the dipole magnet, which bends particles of different charge in different detector halves. The magnet polarity is reversed periodically, thus allowing the measurement and understanding of the size of this effect. We analyze data taken with different magnet polarities separately, deriving charge asymmetry corrections for the two data sets independently. Finally, we average the two values in order to cancel any residual effects. We use two calibration samples containing muons to measure the relative trigger efficiencies of $D_s^+\mu^-/D_s^-\mu^+$ events, and the relative $\mu^-/\mu^+$ identification efficiencies. The first sample contains $b \rightarrow J/\psi(\rightarrow \mu^+\mu^-)X$ decays triggered independently of the $J/\psi$ meson, and where the $J/\psi$ is selected by requiring two particles of opposite charge have an invariant mass consistent with the $J/\psi$ mass. This sample is called the kinematically-selected (KS) sample. The second sample is collected by triggering on one muon from a $J/\psi$ decay that is detached from the primary vertex. It is called muon selected (MS) as it relies on the presence of a well identified muon.

In order to measure the relative $\pi^+$ and $\pi^-$ detection efficiencies, we use the ratio of partially reconstructed and fully reconstructed $D^{\ast+} \rightarrow \pi^+ D^0$, $D^{\ast-} \rightarrow K^- \pi^+ \pi^- (\pi^\mp)$ decays. The former sample is gathered without explicitly reconstructing the $\pi^\mp$ particle, and then the efficiency of finding this track in the event is measured. The same procedure is applied to the charge conjugate mode, so the relative $\pi^+ \rightarrow \pi^- \mu^+$ efficiency is measured. A detailed description is given in Ref. [20].

Finally, a sample of $D^{\ast+}(\rightarrow K^- \pi^+\pi^-)\mu^-$ candidates is obtained using similar triggers to the $D_s\mu$ sample. This sample is used to assess charge asymmetries induced by the software trigger.

The efficiency ratio $\epsilon_{\mu^+}/\epsilon_{\mu^-}$ in Eq. (6) accounts for losses due to the muon identification efficiency algorithm and the trigger requirements. We measure $\epsilon_{\mu^+}/\epsilon_{\mu^-}$ using the KS and MS calibration samples. There are about 0.6 million KS $J/\psi$ candidates selected in total, and about 1.2 million MS $J/\psi$ candidates. As the calibration muon spectra are slightly softer than that of the signal, we subdivide the signal and calibration samples into subsamples defined by the kinematic properties of the candidate muon. We define five muon momentum bins: $6–20$ GeV, $20–30$ GeV, $30–40$ GeV, $40–50$ GeV, and $50–100$ GeV. We further subdivide the signal and calibration samples with two binning schemes. In the first, each $\mu$ momentum bin is split into 10 rectangular regions in $q_{px}$ and $p_y$, where $q$ represents the muon charge and $p_x$ and $p_y$ are the Cartesian components of the muon momentum in the directions perpendicular to the beam axis. The second grid uses 8 regions of muon $p_T$ and azimuthal angle $\phi$ to reduce the sensitivity to differences in $\phi$ acceptance between signal and calibration samples. In this case the first and third bins in $\phi$ are flipped for negative charges, to symmetrize the acceptance in a consistent manner with the $q_{px}$ and $p_y$ binning. Signal and calibration yields are determined separately in each of the intervals both for magnet up and down data. Fig. 2 shows the $\mu^+\mu^-$ invariant mass distribution for the KS $J/\psi$ events in magnet up data.

The relative efficiencies for triggering and identifying muons in five different momentum bins are shown in Fig. 3 for magnet up and magnet down data using the KS calibration sample. They are consistent with being independent of momentum. The small difference of approximately 1% between the two samples can be attributed to the alignment of the muon stations, which affects predominantly the hardware muon trigger.

The $D_s^+\mu^-$ final state benefits from several cancellations of potential instrumental asymmetries that can arise due to the different interaction cross-sections in the detector material or to differences between tracking reconstructions of negative and positive particles. The $\mu$ and $\pi$ charged tracks have very similar reconstruction efficiencies. Using the partially-reconstructed $D^{\ast+}$ calibration sample, we found that the $\pi^+$ versus $\pi^-$ relative tracking efficiencies are independent of momentum and transverse momentum [20]. This, along with the fact that $\pi^+$ and $\pi^-$ interaction
and thus the charge asymmetry in the track reconstruction component. It is determined to be $A_{\text{track}}^{KK}$. Using the efficiency ratios

$$\epsilon_{\pi^+}/\epsilon_{\pi^-}$$

measured for pions are mistaken for muons, provide a measurement of the fake backgrounds, combined with knowledge of the probability that kaons or pions are mistaken for muons, provide a measurement of the fake background induced by prompt background equal to $(+0.14 \pm 0.07)\%$ for magnet up data, $(−0.05 \pm 0.05)\%$ for magnet down data, with an average value of $(+0.04 \pm 0.04)\%$.

Samples of $D_s^+\mu^-X$ and $D_s^-K^+X$ events, where $X$ represents undetected particles from the same decay, are used to infer the numbers of $D_s^+$-hadron combinations from $B$ decays that could be mistaken for $D_s^+\mu^-X$ events if the hadron is misidentified as a muon. Kaons and pions are identified using the RICH. These numbers, combined with knowledge of the probability that kaons or pions are mistaken for muons, provide a measurement of the fake hadron background. These misidentification probabilities are also calculated in the five momentum bins using $D_s^{++} \rightarrow \pi^+D^0$ decays, with $D^0$ decaying into the $K^-\pi^+$ final state. The net effect on the asymmetry is below $10^{-4}$ and thus the $D_s^+$-hadron background can be ignored.

We also consider the background induced by $D_s^+\mu^-X$ events deriving from $b \rightarrow c\bar{c}s$ decays where the $D_s^+$ hadron originates from the virtual $W^+$ boson and the muon originates from the charm-hadron semileptonic decay. These backgrounds are suppressed since the $D$ hadron travels away from the $B$ vertex prior to its semileptonic decay. As these decays are of opposite sign to the signal, they cause a background asymmetry that is proportional to the production asymmetry of the background sources. The $B^0$ production asymmetry has been measured in LHCb to be $(-0.1 \pm 1.0)\%$ [11], and the $B^+$ production asymmetry to be $(+0.3 \pm 0.9)\%$ by comparing $B^+ \rightarrow J/\psi K^+$ and $B^- \rightarrow J/\psi K^+$ decays [21]. A small

5. Backgrounds

Backgrounds include prompt charm production, fake muons associated with real $D_s^+$ particles produced in $b$-hadron decays, and $B \rightarrow Ds$ decays where the $D$ hadron decays semileptonically. Here $B$ denotes any meson or baryon containing a $b$ (or $\bar{B}$) quark, and similarly, $D$ denotes any hadron containing a $c$ (or $\bar{c}$) quark. The prompt background is highly suppressed by the requirement of a well identified muon forming a vertex with the $D_s^+$ candidate. The prompt yield is separated from false $D_s$ backgrounds using a binned two-dimensional fit to the mass and $\ln(\text{IP}/\text{mm})$ of the $\phi\pi^+$ candidates. The method is described in detail in Ref. [19]. Fig. 4 shows the fit results for the magnet-down $D_s^+\mu^-$ candidate sample. From the asymmetry in the prompt yield normalized to the overall signal yield in the five momentum bins, we obtain an asymmetry due to prompt background equal to $(+0.02 \pm 0.13)\%$.

The efficiency ratios used in determining $A_{\text{track}}^{KK}$ are based on $\epsilon_{\pi^+}/\epsilon_{\pi^-}$ with a correction derived from the comparison between the Cabibbo-favoured decays $D^+ \rightarrow K^-\pi^+\pi^-$ and $D_s^+ \rightarrow K_s^0\pi^+$, accounting for additional charge asymmetry induced by $K$ interactions in the detector. Therefore, the total tracking asymmetry is $A_{\text{track}} = (+0.02 \pm 0.13)\%$.

Cross-sections on isoscalar targets are equal, and that the detector is almost isoscalar, implies that the difference between $\pi^+$ and $\pi^-$ tracking efficiencies depend only upon the magnetic field orientation and the detector acceptance. Thus the charge asymmetry ratios measured for pions are applicable to muons as well. In the $\phi\pi^+\pi^-$ final states, the pion and muon have opposite signs, and thus the charge asymmetry in the track reconstruction efficiency induced by imperfect $\pi\mu$ cancellation, $A_{\text{track}}^{KK}$, is small. Using the efficiency ratios $\epsilon_{\pi^+}/\epsilon_{\pi^-}$ measured with the $D_s^+$ calibration sample, we obtain $A_{\text{track}}^{KK} = (+0.01 \pm 0.13)\%$. A small residual sensitivity to the charge asymmetry in $K$ track reconstruction is present due to a slight momentum mismatch between the two kaons from $\phi$ decays arising from the interference with the $S$-wave component. It is determined to be $A_{\text{track}}^{KK} = (+0.012 \pm 0.004)\%$.
subset of this background is from $\Lambda^0$ decays, whose production asymmetry is not well known, $d_\phi = (-1.0 \pm 4.0)\%$, but is consistent with zero [22]. The $B^0$ final states include $D^0$ and $D^+$ hadrons, in proportions determined according to the $D^{+}/D^{-}$ ratio in the measured exclusive final states. In addition, we consider backgrounds coming from $B^0$, $B^+ \rightarrow D^- K \mu^+$ decays, that provide a background asymmetry with opposite sign. We estimate this background asymmetry to be $+(0.01 \pm 0.04)\%$. The systematic uncertainty includes the limited knowledge of the inclusive branching fraction of the $b$-hadrons, uncertainties in the $b$-hadron production ratios, and in the charm semileptonic branching fractions, but is dominated by the uncertainty in the production asymmetry. By combining these estimates, we obtain $A_{Bkg} = (+0.05 \pm 0.05)\%$.

6. Results

We perform weighted averages of the corrected asymmetries $A_{\mu}^i$ observed in each $p_{1\phi}$ and $p_{2\phi}$ subsample, using muon identification corrections both in the KS and MS sample (see Fig. 5). In order to cancel remaining detection asymmetry effects, the most appropriate way to combine magnet up and magnet down data is with an arithmetic average [20]. We then perform an arithmetic average of the four values of $A_{\mu}^i$ obtained with the two binning schemes chosen and with the two muon correction methods, assuming the results to be fully statistically correlated, and obtain $A_{\mu} = (+0.04 \pm 0.25)\%$. The results are shown in Table 2. Finally, we correct for tracking efficiency asymmetries and background asymmetries, and obtain $A_{\text{meas}} = (-0.03 \pm 0.25 \pm 0.18)\%$, where the first uncertainty reflects statistical fluctuations in the signal yield and the second reflects the systematic uncertainties. This gives $a_{sl} = (-0.06 \pm 0.50 \pm 0.36)\%$.

We consider several sources of systematic uncertainties on $A_{\text{meas}}$ that are summarized in Table 3. By examining the variations on the average $A_{\mu}^i$ obtained with different procedures, we assign a 0.07% uncertainty, reflecting three almost equal components: the fitting procedure, the kinematic binning and a residual systematic uncertainty related to the muon efficiency ratio calculation. We study the effect of the fitting procedure by comparing results obtained with different models for signal and background shapes. In addition, we consider the effects of the statistical uncertainties of the efficiency ratios, assigning 0.08%, which is obtained by propagating the uncertainties in the average $A_{\mu}^i$. The uncertainties affecting the background estimates are discussed in Section 5. Possible changes in detector acceptance during magnet up and magnet down data taking periods are estimated to contribute 0.01%. The software trigger systematic uncertainty is mainly due to the topological trigger algorithm and is estimated to be 0.05%. These uncertainties are considered uncorrelated and added in quadrature to obtain the total systematic uncertainty.

7. Conclusions

We measure the asymmetry $a_{sl}^d$, which is twice the measured asymmetry between $D_s^- \mu^+$ and $D_s^+ \mu^-$ yields, to be $a_{sl}^d = (-0.06 \pm 0.50 \pm 0.36)\%$.

Fig. 6 shows this measurement, the $D_0$ measured asymmetries in dimuon decays in 1.96 TeV $p\overline{p}$ collisions of $A_{\mu}^d = (-0.78 \pm 0.172 \pm 0.093)\%$ [5], $a_{sl}^d = (0.68 \pm 0.45 \pm 0.14)\%$ [6], and $a_{sl}^d = (-1.12 \pm 0.74 \pm 0.17)\%$ [7], and the most recent average from $B$-factories [8], namely $a_{sl}^d = (0.02 \pm 0.31)\%$. Our result for $a_{sl}^d$ is currently the most precise measurement made and is consistent with the SM.

Table 2

<table>
<thead>
<tr>
<th>$A_{\mu}^i$ [%]</th>
<th>KS muon correction</th>
<th>MS muon correction</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet</td>
<td>$p_{1\phi}$, $p_{2\phi}$</td>
<td>$p_{1\phi}$, $p_{2\phi}$</td>
<td>$p_{1\phi}$, $p_{2\phi}$</td>
</tr>
<tr>
<td>Up</td>
<td>$+0.38 \pm 0.38$</td>
<td>$+0.30 \pm 0.38$</td>
<td>$+0.64 \pm 0.37$</td>
</tr>
<tr>
<td>Down</td>
<td>$-0.17 \pm 0.32$</td>
<td>$-0.25 \pm 0.32$</td>
<td>$-0.60 \pm 0.32$</td>
</tr>
<tr>
<td>Avg.</td>
<td>$+0.11 \pm 0.25$</td>
<td>$+0.02 \pm 0.25$</td>
<td>$+0.02 \pm 0.24$</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma(A_{\text{meas}})$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal modelling and muon correction</td>
<td>0.07</td>
</tr>
<tr>
<td>Statistical uncertainty on the efficiency ratios</td>
<td>0.08</td>
</tr>
<tr>
<td>Background asymmetry</td>
<td>0.05</td>
</tr>
<tr>
<td>Asymmetry in track reconstruction</td>
<td>0.13</td>
</tr>
<tr>
<td>Field-up and field-down run conditions</td>
<td>0.01</td>
</tr>
<tr>
<td>Software trigger bias (topological trigger)</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Fig. 6. Measurements of semileptonic decay asymmetries. The bands correspond to the central values ±1 standard deviation uncertainties, defined as the sum in quadrature of the statistical and systematic errors. The solid dot indicates the SM prediction.

Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); CNRS/IN2P3 and Region Auvergne (France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); FOM and NWO (The Netherlands); SCSR (Poland); MEN/IFA (Romania); MinES, Rosatom, MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); STFC (United Kingdom); NSF (USA). We also acknowledge support from CERN and from the national agencies: RFBR and NRC “Kurchatov Institute” (Russia); MinECo, XuntaGal (Spain); GridPP (United Kingdom); NSF (USA). We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); CNRS/IN2P3 and Region Auvergne (France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); FOM and NWO (The Netherlands); SCSR (Poland); MEN/IFA (Romania); MinES, Rosatom, MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); STFC (United Kingdom); NSF (USA). We also acknowledge support from the ERC under FP7. The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom); NSF (USA). We also acknowledge the support received from the ERC under FP7. The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom); NSF (USA). We also acknowledge the support received from the ERC under FP7.

References


LHCb Collaboration

* Corresponding author.

1 University of Bari, Bari, Italy.
2 University of Bologna, Bologna, Italy.
3 University of Cagliari, Cagliari, Italy.
4 University of Ferrara, Ferrara, Italy.
5 University of Firenze, Firenze, Italy.
6 University of Urbino, Urbino, Italy.
7 University of Modena e Reggio Emilia, Modena, Italy.
8 University of Genova, Genova, Italy.
9 University of Milano Bicocca, Milano, Italy.
10 University of Roma Tor Vergata, Roma, Italy.
11 University of Roma La Sapienza, Roma, Italy.
12 University of Basilicata, Potenza, Italy.
13 IFAE, La Salle, Universitat Ramon Llull, Barcelona, Spain.
14 University of Science, Hanoi, Viet Nam.
15 Institute of Physics and Technology, Moscow, Russia.
16 University of Pavia, Padova, Italy.
17 University of Roma, Roma, Italy.
18 Scuola Normale Superiore, Pisa, Italy.
19 Associated to European Organization for Nuclear Research (CERN), Geneva, Switzerland.