Asymmetries in mixed beauty decays

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6 Discussion

The measurements of a_{sl}^{d} and a_{sl}^{s} in this thesis provide an improved understanding of *CP* violation in mixing of B mesons. The current experimental status is summarized in Sec. 6.1, followed by a discussion of other potential sources of *CP* violation that may contribute to the D0 dimuon anomaly besides the mixing parameters a_{sl}^{d} and a_{sl}^{s} in Sec. 6.2. Finally, Sec. 6.3 evaluates the potential of the measurements presented in this thesis with future improvements.

6.1 The picture after LHCb run 1

The measurements of a_{sl}^{d} and a_{sl}^{s} are the most precise measurements of these parameters to date, and both are found to be compatible with the SM. Figure 6.1 displays all current measurements in the a_{sl}^{d} versus a_{sl}^{s} plane, which is an update of Fig. 1.8, where the LHCb measurements are now added in red. The world averages of the individual measurements of a_{sl}^{d} and a_{sl}^{s} are

$$\begin{aligned} a_{sl}^{d} &= (0.02 \pm 0.20)\% \\ a_{sl}^{s} &= (0.17 \pm 0.30)\%. \end{aligned} \tag{6.1.1}$$

The correlation between the LHCb measurements is $\rho = +0.13$, due to common systematic effects in the muon detection asymmetry, and the contribution of the B^0 background in the a_{sl}^{s} analysis [108]. This results in a correlation between the world-averaged values of $\rho = +0.07$. The world averages of a_{sl}^{d} and a_{sl}^{s} are only marginally compatible with the D0 dimuon result, with a p-value of 0.5%. This indicates that the observed D0 dimuon anomaly cannot be explained by new physics in *CP* violation in mixing alone. It might be a statistical fluctuation, or caused by other contributions that are not yet taken into account, as will be discussed in the following.

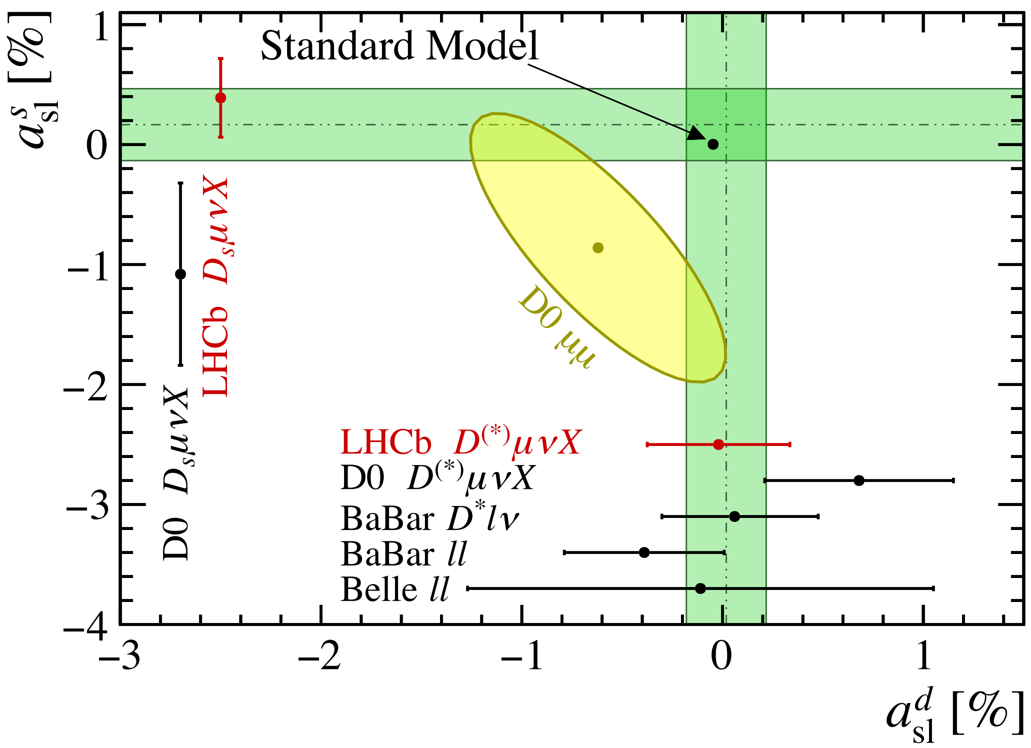

Figure 6.1: Overview of a_{sl}^d and a_{sl}^s measurements after the run-1 LHCb results presented in this thesis, indicated with red points. The black points represent the other individual measurements of a_{sl}^d or a_{sl}^s. The D0 dimuon measurement is shown in the yellow ellipse. The green bands indicate the averages of measurements, excluding the D0 dimuon result.

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6.2 Thoughts about the dimuon anomaly

The D0 dimuon measurement is obtained by counting events in which two same-sign muons are present, and calculating the corresponding charge asymmetry $A_{\mu\mu}$ (see Eq. 1.2.31). The motivation for this measurement is primarily due to the contribution of a_{sl}^d and a_{sl}^s to $A_{\mu\mu}$, but since no explicit reconstruction of a B-meson decay is done, there are additional contributions to $A_{\mu\mu}$ that need to be considered.

In the 2011 D0 result [45], contributions from backgrounds and detection asymmetries are taken into account. The contribution from b-hadron decays that can also produce a same-sign dimuon final state without mixing, such as $b \to c$ decays as e.g. $B^0 \to D^-(\to K^0\mu^-\overline{\nu}_\mu)\pi^+$ decays (while the other b-hadron decays semileptonically), is also included. These decays contribute equally to the number of $\mu^+\mu^+$ and $\mu^-\mu^-$ final states, and dilute the sensitivity of $A_{\mu\mu}$ to a_{sl}^d and a_{sl}^s.

Other contributions to $A_{\mu\mu}$ have been considered since the 2011 D0 result was published. In Ref. [46] the potential contribution from CP violation in the interference between mixing and decay in the B^0 and B_s^0 systems is estimated. This can contribute to $A_{\mu\mu}$ when one b hadron decays semileptonically, while the other decays as e.g. $B_{(s)}^0 \to D_{(s)}^+ D_{(s)}^-$, where the $D^-_{(s)}$ meson subsequently decays semileptonically. Due to *CP* violation in interference, $P(B^0_{(s)} \to D^+_{(s)} D^-_{(s)})(t) \neq P(\overline{B}^0_{(s)} \to D^-_{(s)} D^+_{(s)})(t)$ resulting in a charge asymmetry. These contributions depend on the values of Δm, $\Delta\Gamma$ and the amount of *CP* violation in interference in these decays given by $\sin(2\beta_{(s)})$ [3]. The integrated contributions are found to be negligible for the B^0_s system due to the small value of $\sin(2\beta_s)$ and the dilution due to the high mixing frequency Δm_s. The contribution of *CP* violation in interference of B^0 mesons is taken into account by the D0 collaboration in the 2013 update [47] as follows. Since experimentally only an upper bound on the value of $\Delta\Gamma_d$ exists, the SM value is used. This results in a 3.6σ deviation from the SM prediction. However, there is ample room for new-physics contributions to $\Delta\Gamma_d$, for instance through decays such as $B^0 \to \tau^+\tau^-$ [115]. When allowing the values of $a^d_{\rm sl}$, $a^s_{\rm sl}$ *and* $\Delta\Gamma_d$ free in the fit to the observed $A_{\mu\mu}$, the discrepancy with the SM predictions of $a^d_{\rm sl}$, $a^s_{\rm sl}$ and $\Delta\Gamma_d$ reduces to 3.0σ, with large correlations between the parameters.

In addition, decays where direct *CP* violation can be expected, but is not yet measured, can contribute to $A_{\mu\mu}$. An example is the decay $B^+ \to \overline{D}^0(\to \mu^- X)D^+$. The SM contribution of such decays is expected to be negligible [46], but new-physics contributions can enhance this effect. The same argument holds for decays where no sizeable direct *CP* violation is expected in the SM, such as in semileptonic decays of b- and c-hadrons [116, 117]. Such new-physics contributions might also explain the D0 dimuon anomaly.

The possibility of other (SM or new physics) contributions to $A_{\mu\mu}$ that would have been overlooked cannot be excluded. Unfortunately, LHCb is unable to measure the like-sign dimuon asymmetry, mainly due to possible production asymmetries originating from the pp collisions (as opposed to the $p\bar{p}$ collisions at the Tevatron). However, the currently unmeasured contributions mentioned above can be investigated by LHCb. One idea is to constrain the amount of *CP* violation in mixing using existing measurements of *CP* violation in interference [118]. Assuming that new physics contributions to the phase of $\Gamma_{12,s}$ are negligible, and new-physics contributions to penguin diagrams in $B^0_s \to J/\psi\,\phi$ are negligible [119, 120], the contribution of new physics to the *CP*-violating phase in $b \to c\bar{c}s$ transitions, called ϕ_s, should be the same as the new physics contribution to ϕ_{12} in $a^s_{\rm sl}$ [121]. Since the phase ϕ_s is measured to be consistent with zero in decays such as $B^0_s \to J/\psi\,\phi$ [28] and $B^0_s \to D^-_s D^+_s$ [122], this constrains the size of new physics contributions to ϕ_{12}. Combined with the world-average values for $\Delta\Gamma_s$ and Δm_s (Eq. 1.2.27 and 1.2.28) this results in an estimate of

$$a^s_{\rm sl} = (0.004 \pm 0.075)\%, \tag{6.2.1}$$

and the LHCb measurement of $a^s_{\rm sl}$ can potentially be used to measure other sources of *CP* violation, such as the direct *CP* violation in semileptonic B^0_s decays, which was assumed to be zero in the analyses in this thesis. Another suggestion made in Ref. [118] is to use this method to measure direct *CP* violation in Cabibbo-favoured charm decays using the measurement of $a^s_{\rm sl}$, which were also assumed to be negligible. However, this is not straightforward due to the extensive use of charm hadron decays as calibration modes throughout this thesis. Possibly in the future, one can rely on simulation studies to model the detection asymmetries with enough accuracy to make this possible.

6.3 Future prospects

The SM prediction for $a^d_{\rm sl}$ and $a^s_{\rm sl}$ (Eq. 1.2.29) is much more precise than the experimental measurements presented in this thesis. This implies that — even though *CP* violation in mixing is unlikely to fully explain the D0 dimuon anomaly — there is a potential that new-physics contributions to the mixing process exist. In order to confirm or exclude whether this is the case, a large improvement in the experimental uncertainty on $a^d_{\rm sl}$ and $a^s_{\rm sl}$ is required. The largest source of uncertainty for the $a^d_{\rm sl}$ and $a^s_{\rm sl}$ analyses is the statistical error on the signal sample. This can be improved upon with future data and by including other decay channels.

6.3.1 Additional charm decay channels

A possibility is including more decay modes of the D^- ($\overline{D}^0$) and D^-_s mesons, for example $D^-_s \to \pi^-\pi^+\pi^-$ ($\mathcal{B} = 1.1\%$) decays, which do not suffer from kaon material interactions. This mode has a branching fraction that is about 1/5 of the total $D^-_s \to K^+K^-\pi^-$ branching fraction, and would naively increase the number of $a^s_{\rm sl}$ signal decays by a factor 1.2. In addition, the $\overline{D}^0 \to K^+\pi^-\pi^+\pi^-$ mode could be considered for the $a^d_{\rm sl}$ analysis. This mode has a branching fraction of 8.1% which is twice that of the $\overline{D}^0 \to K^+\pi^-$ mode. The downside of these many-body final states is that each additional track suffers from a reconstruction inefficiency. The combined probability for a track to be within LHCb acceptance, to not have a hadronic interaction with the detector material and to be efficiently reconstructed depends on the kinematic distributions of the particle, and is roughly estimated to be about 70%. Taking that into account, the amount of $a^d_{\rm sl}$ signal decays when adding $\overline{D}^0 \to K^+\pi^-\pi^+\pi^-$ decays increases by a factor 1.2.

Finally, charm decays involving one or more neutral final-state particles have significant branching fractions. Decays involving a $K^0_{\rm S}$ suffer from a reduced reconstruction efficiency due to the additional track from the $K^0_{\rm S} \to \pi^+\pi^-$ decay, and the branching ratio of these decays is 70%. In addition, only 1/3 of the $K^0_{\rm S}$ mesons decay inside the VELO, which is required for the reconstruction of a $K^0_{\rm S}$ with two long tracks. The detection asymmetry for neutral kaons is already used in Sec. 3.2, and has been studied in Ref. [99]. Taking the above into account, adding $D^-_s \to K^-K^0_{\rm S}$ ($\mathcal{B} = 1.5\%$) decays to the $a^s_{\rm sl}$ analysis naively increases the amount of signal decays by a factor 1.1. In decays involving a π^0 or γ, the reconstruction of a narrow invariant mass peak is more challenging since neutral particles have a worse momentum resolution. However, for decays involving a π^0, such as $D^{*-} \to \overline{D}^0(\to K^+\pi^-\pi^0)\pi^-$, the delta-mass peak ($m_{D^{*-}} - m_{\overline{D}^0}$) is still narrow enough to separate the signal from the background [123]. The efficiency of reconstructing a π^0 candidate is estimated to be about 50% [124]. Adding the $\overline{D}^0 \to K^+\pi^-\pi^0$ mode

($\mathcal{B} = 14.2\%$) to the a_{sl}^{d} analysis would naively provide a factor of 1.3 increase in signal yield.

Adding these additional charm decay channels also requires to understand the background contributions in all of these, as well as measuring potential sources of detection asymmetries. If this is understood, potentially the total signal statistics in a_{sl}^{s} can be increased by a factor of 1.3, and in the a_{sl}^{d} analysis by a factor 1.4. This does not, however, provide a significant improvement to the final result, as can be seen in Table 6.1. Hence, this approach is not considered further.

6.3.2 Additional beauty decay channels

Other semileptonic decays of B^0 and B_s^0 mesons that include a D^- (D^{*-}) or D_s^- meson in the final state, for instance through higher resonances, are already included in the analyses in this thesis. Semileptonic decays that do not decay to charm hadrons are Cabibbo-suppressed and have a low branching ratio [2], so these will not be considered further. However, one could consider using the fully-reconstructible modes $B_{(s)}^0 \to D_{(s)}^- \pi^+$ (without a neutrino in the final state) to measure *CP* violation in mixing. These modes have been used at LHCb to measure the mixing frequencies Δm_d [125] and Δm_s [126]. The narrow $B_{(s)}^0$ invariant mass peak will allow to distinguish signal decays from backgrounds peaking in the $D_{(s)}^-$ mass. Decays of $B^0 \to D^- \pi^+$ are not flavour specific, and contributions from *CP* violation in interference in this decay [127] should be taken into account. In appendix D this contribution to the untagged *CP* asymmetry is estimated, and found to be negligible. However, the $B_{(s)}^0 \to D_{(s)}^- \pi^+$ branching fractions are an order of magnitude smaller, the hardware-level trigger efficiency is about 30% lower for hadrons than for muons [80], and it is more difficult to determine the hardware-level trigger detection asymmetry. This is partly due to the low granularity of the calorimeters. These modes would provide an independent measurement of a_{sl}^{d} and a_{sl}^{s}, with different detection asymmetries and backgrounds. The results will, however, not be competitive in terms of statistics.

6.3.3 Reducing errors due to calibration samples

The second- and third-largest errors originate from the statistical and systematic error on the calibration samples. The statistical error can be improved upon with additional methods or channels for determining detection asymmetries (such as was done for the J/ψ tag-and-probe and D^{*-} partial-and-full methods for the tracking asymmetry in the a_{sl}^{s} analysis). There are on-going efforts to study the use of new methods to measure the detection asymmetries. One example is to use $D^{*-} \to \overline{D}^0(\to K^+\pi^-)\pi^-$ decays where one of the tracks from the $\overline{D}^0$ decay is only required to be reconstructed in the VELO. Such a method could be used to determine the long tracking efficiency of the rest of the detector. This is useful as the charge asymmetry caused by the VELO is small. Several advantages are that the “probe” track is not required to be in the acceptance of the muon stations — as is the case with the J/ψ tag-and-probe method — and the VELO track adds a constraint that allows for a narrow partially reconstructed invariant mass peak — which is not the case for the D^{*-} partial-and-full method. A reduction of the systematic error on the detection asymmetries might be possible when the individual contributions of all possible detector effects are better understood. This would allow for a more optimal decision of the variables and bins used in the weighting of the calibration samples, or an improved selection to remove events that are expected to have a large detection asymmetry.

6.3.4 Reducing errors due to backgrounds

The next largest contribution to the error on $a_{\rm sl}^d$ and $a_{\rm sl}^s$ is the contribution from peaking backgrounds. In the $a_{\rm sl}^d$ analysis this is mostly due to the error on the production asymmetry of the B^+, which is determined from external measurements and contributes 0.12% to the total systematic error. As already mentioned in Sec. 4.4.5, this error can be halved when using an updated LHCb measurement employing $B^+ \to \overline{D}^0\pi^+$ decays [104]. The largest uncertainty on the asymmetry of the peaking background modes in the $a_{\rm sl}^s$ analysis, is due to the Λ_b^0 production asymmetry. This is currently being measured at LHCb with improved precision, as already mentioned in Sec. 5.3.2. In order to reduce the error on the background fraction $f_{\rm bkg}$, the branching fractions of the signal and background modes have to be measured more precisely. These are measured at the B-factories [2] and are difficult to improve upon at a hadron collider. Higher-precision measurements of these branching fractions could be performed at Belle II experiment in Tsukuba, Japan, which starts data-taking in 2018.

A further improved estimate of the contribution from peaking backgrounds could be made by performing a fit to a parameter that has some distinguishing power between signal and background, using template distributions for signal and every type of background (obtained e.g. from simulated events). A first attempt of this method was made as a cross-check of the B^+ fraction, using the corrected B^0 mass, in Sec. 4.3.3. In the LHCb analysis of semileptonic $B^0 \to D^{*-}\tau^+\nu_\tau$ decays, this method was successfully applied by modelling the missing B^0 mass, muon energy, and q^2 of the decay for each background type [128]. Such a method would allow to determine the background fractions directly from data. Potentially this method could even measure the asymmetry in these backgrounds directly.

6.3.5 Beyond run 1

Adding additional data taken during run 2 (2015-2018) of the LHC will reduce all statistical errors. The plan is to collect at least $5\,\text{fb}^{-1}$ at a centre-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$. The $b\bar{b}$ production cross-section at this energy is about twice that of run 1 [129]. In addition, a real-time alignment and calibration is implemented [130], which increases online performance, and an upgraded computing infrastructure and revised trigger setup [131] allows for a rate of 12.5 kHz of events written to storage (compared to 5 kHz in 2012), a significant amount of which is dedicated to charm decays. Using all data at the end of run

2, this would result in a factor of 4.3 more signal events for both $a_{\rm sl}^d$ and $a_{\rm sl}^s$. Due to the increased bandwidth for charm decays, this number is likely to be even higher for most of the calibration channels.

After 2018 the LHCb detector will be upgraded [132] to be able to deal with luminosities of 2×10^{33} cm^{-2}s^{-1} or above, corresponding to an average number of visible pp interactions per bunch crossing of $\mu_{\rm vis} = 5.2$ [133]. In order to deal with the larger detector occupancy, the sensors in the VELO will be replaced by a pixel-based silicon detector. In addition, the IT and OT will be replaced with a scintillating-fibre detector called the SciFi, with fibres and channels that are 250 μm wide (compared to the 5-mm-wide OT straws). The TT will be replaced with a finer-grained silicon-strip detector called Upstream Tracker (UT). Finally, the hardware-level trigger will be completely removed in order to avoid the 1 MHz readout bottleneck, and all detector electronics will be replaced and read out at 40 MHz [134]. The plan is to collect a total of 50 fb^{-1} with the upgraded LHCb detector. This would naively increase the amount of signal and calibration data by a factor 30 with respect to the analyses in this thesis.

Using the estimates for the errors described above, possible future measurements of LHCb are indicated in Table 6.1 and Fig. 6.2. In the run-2 estimate, a reduction of statistical errors on both the signal and calibration samples are taken into account, as well as a reduction in the systematic uncertainty of a factor 2 due to a better understanding of the detection asymmetries, and additional calibration methods. In the LHCb upgrade estimate, this is chosen to be a factor 10 smaller than the current analyses. The correlation between the $a_{\rm sl}^d$ and $a_{\rm sl}^s$ measurements is chosen to be the same as for the measurements in this thesis, $\rho = +0.13$. As can be observed in Fig. 6.2, an evidence or discovery of new physics is well possible with these future updates, while being compatible with the current measurements.

6.4 Closing remarks

The measurements of $a_{\rm sl}^d$ and $a_{\rm sl}^s$ presented in this thesis improve our understanding of the anomaly that was present in 2013. No significant evidence for new-physics contributions to B-meson mixing is seen yet. Due to the statistical limitations of the measurements, exciting improvements can be expected after run 2 and after the upgrade of LHCb, which

	$a_{\rm sl}^d$ [%]	$a_{\rm sl}^s$ [%]
run 1	0.39 ± 0.36	-0.02 ± 0.33
run 1+	$\pm\, 0.34$	$\pm\, 0.31$
run 2	$\pm\, 0.17$	$\pm\, 0.16$
Upgrade	$\pm\, 0.06$	$\pm\, 0.06$

Table 6.1: Potential measurement errors of $a_{\rm sl}^d$ and $a_{\rm sl}^s$ by LHCb after the considerations explained in the text.

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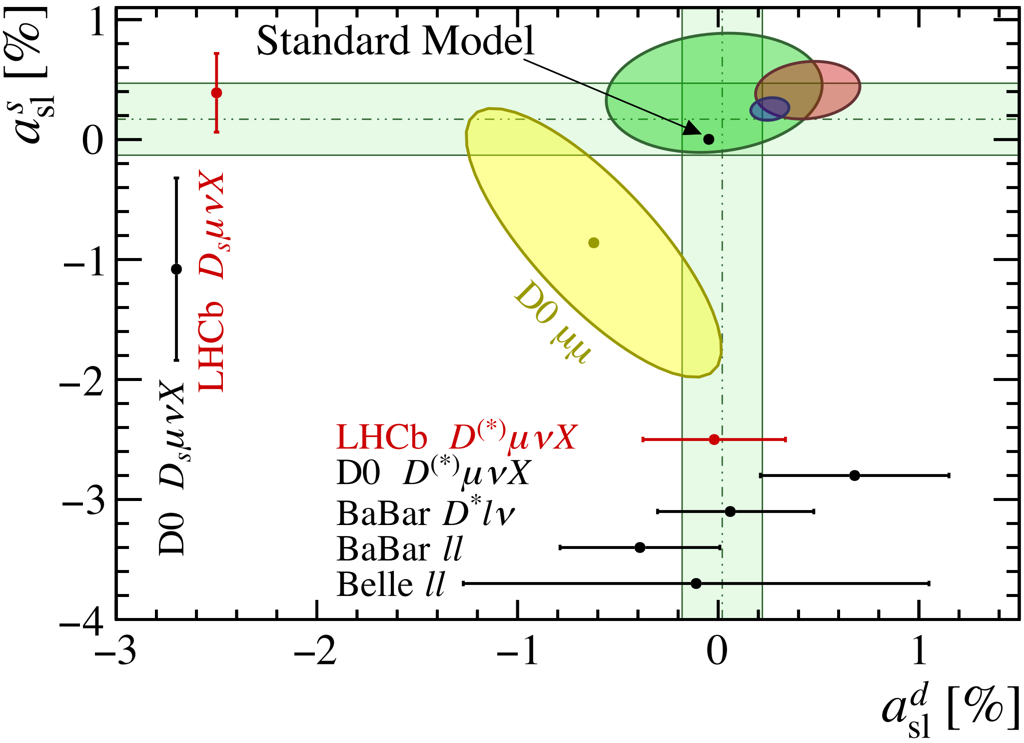

Figure 6.2: Future prospects of the $a_{\rm sl}$ analyses at LHCb overlaid on Fig. 6.1. The two-dimensional combination of the measurements provided in this thesis are indicated by the green ellipse. A possible result including run-2 data is indicated in red, where the central value is (arbitrarily) chosen such that the combined result is 3σ away from the SM. Finally, the possible result after including LHCb upgrade data is indicated in the purple ellipse, with the central value chosen to be 5σ away from the SM, indicating a discovery. The borders of the ellipses show the 68% confidence level intervals with two degrees of freedom.

have the potential to claim a new-physics discovery.

The role of $a_{\rm sl}$ in the future search for new physics will be complementary to analyses with a higher precision to the phase of M_{12}, such as *CP* violation in interference in $B_s^0 \to J/\psi\,\phi$ decays. Together, constraints on new-physics contributions from other sources can be made, such as a non-SM contribution to $\Delta\Gamma_d$ from $B^0 \to \tau^+\tau^-$ decays, which are very difficult to reconstruct. In addition, the measurements of $a_{\rm sl}$ require a precise understanding of the LHCb detector, in particular its detection asymmetries, for which this thesis shows that they can be controlled with sufficient precision.