Detection asymmetries

The main challenge in the measurements of $a_{sl}^d$ and $a_{sl}^s$ is to quantify the charge asymmetry of the detection efficiency between the final states $f$ and $\bar{f}$, given by

$$A_{det} = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}. \quad (3.0.1)$$

In the $a_{sl}^d$ analysis, the visible final states are $f = D^- (\rightarrow K^+ \pi^- \pi^-) \mu^+$, and in the $a_{sl}^s$ analysis $f = D_s^- (\rightarrow K^+ K^- \pi^-) \mu^+$. Various parts of the detection process can contribute to the detection asymmetry. The size of these contributions are assessed with calibration samples; samples with high statistics that allow to measure particle detection efficiencies directly in data. The simulation is not guaranteed to describe the data at the precision required, which is $O(0.1\%)$, but is a crucial tool to understand the asymmetry.

One can think of many causes of a detection asymmetry at permille-level precision. Local effects (e.g. an inefficient channel or a slightly higher bias voltage in a sensor) contribute to changes in efficiency in specific locations of the detector. On a larger scale, a misalignment of a module or even a whole station can contribute to a difference in left-right detector efficiency. Specific causes of detection inefficiencies and asymmetries are discussed in detail in Sec. 2. Most importantly, hadronic cross-sections of particles and antiparticles traversing detector material are not necessarily charge symmetric. In addition, a different amount of material traversed by particles of opposite charge, increases the probability of having a detection asymmetry. This can be caused by a left-right asymmetric placement of material in the detector setup, as is the case for cables connected to the IT. Finally, the crossing angle of the colliding beams in the LHCb interaction point directly affects the left-right occupancy in the detector, as discussed in Sec. 2.1.

The vertical magnetic dipole field bends positively and negatively charged particles to horizontally opposite directions. This transforms any difference between the detection efficiency on the left and right side of LHCb, downstream of the magnet, into a charge detection asymmetry. It is expected that these effects are dependent on where the particle passes through the detector, and therefore on the momentum and other kinematic variables. The strategy is to determine the detection asymmetries as a function of kinematic variables $(p_T, p, \eta, \phi)$ using the calibration samples. These are used to determine the asymmetry of the signal samples, based on their kinematic distributions. Effectively, this is done by...
applying event weights to the calibration samples, such that the kinematic distributions match those of the signal sample. Assuming the detection asymmetry only depends on these distributions, the detection asymmetry of the calibration sample then matches that of the signal sample, modulo statistical variations in these distributions.

A key feature of LHCb is the regular flip of the magnet polarity, such that charged particles predominantly traverse opposite sides of the spectrometer. As a net effect, the left-right asymmetries are expected to change sign, while constant terms such as the material cross-section differences will not, allowing to disentangle these contributions. The idea is to determine $a_{sl}^d$ and $a_{sl}^s$ separately for data taken with each magnet polarity, after correcting for detection asymmetries, and check for consistency of these results. After that, the arithmetic average over both magnet polarity samples is taken to reduce any possible left-right asymmetry that might remain.

The individual efficiencies are expected to mostly factorize since they represent unrelated segments of the reconstruction and selection, and are determined with separate calibration samples. On top of that, the asymmetries are small, and any existing correlation is expected to not depend on the charge of the final state. Hence, the total detection asymmetry $A_{det}$ is obtained as the sum of the individual asymmetries, as long as the product of the asymmetries is below the experimental sensitivity of the measurement ($O(10^{-5})$). The total detection asymmetry is then

$$A_{det} = A_{track} + A_{PID} + A_{trigger},$$

where $A_{track}$ is the asymmetry due to tracking and related effects, $A_{PID}$ is the asymmetry due to hadron PID criteria, and $A_{trigger}$ is the asymmetry due to the trigger. In the $a_{sl}^d$ analysis, only the muon triggers the event and $A_{trigger}$ is called $A_{\mu}$. In the $a_{sl}^s$ analysis, the software-level trigger asymmetry is determined separately, which is called $A_{Hlt}$. $A_{track}$ is then divided into charge-neutral pairs of the final-state tracks in the $a_{sl}^d$ and $a_{sl}^s$ analyses, $A_{track} = A_{\mu} + A_{K^\pi} (A_{KK} for a_{sl}^s)$, as illustrated in Fig. 3.1.

This chapter introduces the methods used in assessing various detection asymmetries, see Table 3.1 for an overview, including the decay modes that are used as calibration samples. The application of the detection asymmetry methods to the $a_{sl}^d$ and $a_{sl}^s$ measurements will be discussed in subsequent chapters.

### 3.1 The asymmetry of $\mu^+\pi^-$ pairs

The muon and the pion are almost identical particles in terms of mass ($m_{\mu^+} \approx 106$ MeV, $m_{\pi^+} \approx 140$ MeV). Therefore the tracking asymmetry of the $\mu^+\pi^-$ pair is believed to
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Table 3.1: Overview of the various detection asymmetries that are calculated with calibration samples in this chapter, including the decay modes that are used and a reference to the section. For comparison, the bottom two rows display the signal modes in the $a_{sl}^d$ and $a_{sl}^s$ analyses. Charge conjugate modes are implicitly included.

Figure 3.1: The detection asymmetry due to tracking is split up into two pairs of opposite-charge tracks, shown here for the $B^0 \rightarrow D^-\mu^+\nu_\mu X$ decay.

Largely cancel when the kinematic distributions are in agreement. However, pions do undergo nuclear interactions with the detector material, so small differences in efficiency between detecting muons and pions can be expected. Since the charge asymmetry in the pion–nuclear cross-section is small, the asymmetry of $\mu^+\pi^-$ pairs,

$$A_{\mu\pi} = \frac{\epsilon(\mu^+\pi^-) - \epsilon(\mu^-\pi^+)}{\epsilon(\mu^+\pi^-) + \epsilon(\mu^-\pi^+)}$$

is small. $A_{\mu\pi}$ is determined in two ways: first using a sample of muons to determine the tracking efficiency (Sec. 3.1.1) and assuming the pion behaves as a muon, and second using a sample of pions (Sec. 3.1.2) and assuming the muon behaves as a pion. A comparison between both methods is made in Sec. 3.1.3.
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3.1.1 The $J/\psi$ tag-and-probe method

The $J/\psi$ tag-and-probe method employs the large sample of $B \rightarrow J/\psi (\mu^+ \mu^-) X$ decays that LHCb has collected, to measure the tracking efficiency of muons. The decays are triggered on a special calibration line, as is explained in detail in Ref. [92]. In total, about 300,000 decays are collected.

The event is triggered by the presence of a single muon. This “tag” muon is reconstructed as a long track and has a minimum $p_T$ of 1.3 GeV/c. In order to remove background tracks originating from the PV, the muon is required to originate from a secondary vertex by demanding that the Impact Parameter (IP) exceeds 0.5 mm, and the difference of the fit quality of the PV with and without the muon track is $\chi^2_{IP} > 200$. The other muon from the $J/\psi$ decay is called the “probe”, and is initially reconstructed without making use of hits in (part of) the tracking system. The tag and probe muons are required to combine into an invariant mass around the $J/\psi$ mass, with a vertex quality of $\chi^2$/dof < 5. If the standard long-track-finding algorithm finds the partially reconstructed probe muon, the candidate is considered efficient, and flagged “pass”. Otherwise, it is flagged as “fail”. The long track is required to have $p_T > 5$ GeV/c in order for the probe to be counted as efficient. The track finding efficiency of the subsystem that is not used in the partial reconstruction, is the fraction of candidates in the “pass” category, over the sum of “pass” and “fail”. Using the information of the precisely reconstructed tag track and the partially reconstructed probe track with less momentum precision, the invariant mass spectrum of the $J/\psi$ is calculated. The efficiency fraction is obtained from the ratio of yields in a maximum likelihood fit to the $J/\psi$ invariant mass peaks in both categories.

Three methods are used to probe the tracking efficiencies in various subsystems, called the “VELO”, “T-station” and “long” method. See Fig. 3.2 for an illustration.

The **VELO method** uses a downstream track (reconstructed in the TT and T-stations) to probe the VELO tracking efficiency. The downstream track is compared to reconstructed long tracks, and a long track is identified as coming from the same particle as the downstream track when 50% of the hits in the T-stations are the same. If such a long track is found, the event is considered “pass”. Otherwise, it is considered as “fail”.

The **T-station method** builds a probe candidate by making use of a stand-alone track reconstruction in the muon stations and combining these tracks with VELO segments, to test the efficiency of the T-stations. If a long track shares the same VELO segment and extrapolates to at least two of the same hits in the muon stations, they are identified as coming from the same particle, and the event is considered as “pass”.

The **long method** builds probe candidates by matching TT hits to muon tracks. A matching long track is found if at least 70% of muon hits are shared, and 60% of TT hits in case they exist. This directly probes the long track reconstruction efficiency, which requires only hits in the VELO and T-stations.
3.1. The asymmetry of $\mu^+\pi^-$ pairs

The total (long) tracking efficiency can also be found by multiplying the efficiency obtained from the VELO and T-station methods, assuming that the long tracking efficiency factorizes. Due to the smaller uncertainty, this is the default method used to determine the tracking efficiency and asymmetry, while the long method serves as a cross-check. Agreement within statistical errors between both methods is found. The invariant mass fits using the three methods described above are shown in Fig. 3.3 and the efficiencies are shown in Fig. 3.4.

In 2012 the efficiency is slightly lower, which is partially attributed to the higher detector occupancy [92].

As discussed above, the track-finding efficiency is expected to depend on the kinematic properties of the probe track and detector occupancy. Therefore, the efficiencies are determined as a function of the probe momentum $p$, transverse momentum $p_T$, pseudorapidity $\eta$ and projected azimuthal angle in the $x-y$ detector plane, $\phi$, as well as the event track multiplicity. Details of the obtained efficiencies can be found in Ref. [92].

The charge asymmetry of the tracking efficiency is obtained by determining the tracking efficiency separately for probes with a positive and negative charge. It is defined as

$$A_{\text{track}} = \frac{\epsilon^+ - \epsilon^-}{\epsilon^+ + \epsilon^-},$$

and is shown as a function of transverse momentum in Fig. 3.5. There is no evidence for a particular trend, and data taken in 2011 and 2012 display a comparable tracking asymmetry. However, around $p_T \approx 2.5 \text{ GeV/c}$ there is an indication for a magnet polarity-dependent effect.

The application of the $J/\psi$ tag-and-probe method in the $a^d_{sl}$ and $a^s_{sl}$ analyses is to determine the asymmetry in the tracking efficiency of $\mu^+\pi^-$ pairs. First, the kinematic distributions of the positively charged probe track in the $J/\psi$ sample are weighed to match those of the $\mu^+$ in the signal sample, and similarly for the negatively charged probe track and the signal $\mu^-$ distributions. The tracking asymmetry of the signal muon is then determined as in Eq. 3.1.2. Second, the same procedure is followed to obtain the tracking asymmetry of the signal pion, assuming it behaves as a muon. Finally, the tracking asymmetry of $\mu^+\pi^-$ pairs is calculated as

$$A_{\mu\pi} = A_{\text{track}}^{\mu_{\text{sig}}} + A_{\text{track}}^{\pi_{\text{sig}}} = \frac{\epsilon^+_{\text{sig}} - \epsilon^-_{\text{sig}}}{\epsilon^+_{\text{sig}} + \epsilon^-_{\text{sig}}} + \frac{\epsilon^+_{\text{sig}} - \epsilon^-_{\text{sig}}}{\epsilon^+_{\text{sig}} + \epsilon^-_{\text{sig}}},$$

where the superscripted $\mu_{\text{sig}}$ and $\pi_{\text{sig}}$ indicate which particle was used to weigh the calibration sample. The signal pion asymmetry has an opposite sign, due to it having the opposite charge of the muon in the final state. The correlation between both weighed samples is obtained by calculating the kinematic overlap between the signal muon and pion, and is taken into account in the determination of the total statistical error.

An incomplete matching of the probe-track kinematic distributions to those of the signal tracks might be a potential source of bias on the result. It is investigated by varying the choice of binning used to match the kinematic distributions to those of the signal. The deviation with respect to the nominal result is assigned as a systematic error.
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Figure 3.2: Illustration of the VELO, T-station and long methods for determining the tracking efficiency using the $J/\psi$ tag-and-probe method. The red dots indicate hits that are used to form a partially reconstructed probe track candidate. The solid line represents the part of the track that is reconstructed. The figure is taken from Ref. [70].

The size of this effect depends on the kinematic distributions of the signal, and is discussed in Chapters 4 and 5.

Alternatively, the $\mu^+\pi^-$ asymmetry is calculated by subtracting the amount of signal $\mu^+$ candidates from the amount of signal $\pi^-$ candidates in each bin of kinematic phase-space ($p_T$, $\eta$), and multiplying by the tracking asymmetry in that particular bin,

$$A_{\mu\pi} = \frac{1}{N_{\text{sig}}} \sum_{\text{bins } i} (N_i^{\mu^+} - N_i^{\pi^-}) \times A^i_{\text{track}}, \quad (3.1.4)$$
3.1. The asymmetry of $\mu^+\pi^-$ pairs

![Figure 3.3](image)

Figure 3.3: Fits to the $J/\psi$ invariant mass used in the $J/\psi$ tag-and-probe method, using the partially reconstructed probe track, in the (a) VELO method, (b) T-station method, and (c) long method. For comparison the $J/\psi$ invariant mass fit where the probe is fully reconstructed is shown in the bottom right. The effect of the partial reconstruction on the momentum resolution is clearly visible by the wider peaks in (a), (b) and (c) compared to (d). Figure is taken from Ref. [52].

![Figure 3.4](image)

Figure 3.4: Tracking efficiency as determined with the $J/\psi$ tag-and-probe VELO + T-station method, as a function of (left) momentum and (right) number of reconstructed tracks in the detector, split by data-taking year. Figures are taken from Ref. [54].
Figure 3.5: Tracking asymmetries determined using the $J/\psi$ tag and probe method, split by (top) magnet polarity and (bottom) data-taking year, as a function of (left) $p_T$ and (right) $p$.

where $A_{\text{track}}$ is the tracking asymmetry as obtained in Eq. 3.1.2 in a specific bin, and $N_{\text{sig}}$ is the total number of signal candidates. Both methods of determining the $\mu^+\pi^-$ asymmetry from the single-track asymmetry are found to be statistically compatible.

The resulting asymmetries for the $a_{\text{sl}}^d$ and $a_{\text{sl}}^s$ analyses are discussed in the appropriate sections in Chapters 4 and 5.

### 3.1.2 The $D^*$ partial-and-full method

The second method uses partially reconstructed $D^{**} \rightarrow D^0(\rightarrow K^-\pi^+\pi^-\pi^+)\pi^+$ decays to determine the charge asymmetry of reconstructing pions, and was also employed in an earlier measurement of $a_{\text{sl}}^s$ by LHCb [48]. The method is described in detail in Ref. [93].

When requiring the $D^{**}$ to originate from the primary vertex (PV), there are enough kinematic constraints to form a peak in the invariant mass difference, $\Delta M = m(\pi^+D^0) - m(D^0)$, even when one of the pions from the $D^0$ decay is not reconstructed. The missing pion, called the “probe”, is any one of the $\pi^+$ or $\pi^-$ from the $D^0$ decay. A maximum-likelihood fit to $\Delta M$ with a missing probe gives the total yield, while a fit to $\Delta M$ in the fully reconstructed case gives the “pass” yield. When fully reconstructed, the pion considered as “probe” is required to have $p > 2 \text{ GeV}/c$ and $p_T > 300 \text{ MeV}/c$ in order to
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be counted as efficient. The efficiency is then the ratio of “pass” and “total”. The pion detection asymmetry is constructed by calculating the efficiency separately for a positively and negatively charged probe track, and using Eq. 3.1.2.

The background yield in the invariant mass fits is constrained by a fit to the same $\Delta M$ variable constructed using combinations of pions and kaons with a wrong charge sign to form the $D^0$ candidate, i.e. $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$. These combinations are only formed by combinatorial background, plus a small contribution from $D^0$ mixing and doubly-Cabibbo-suppressed decays of a $D^0$, which result in a real “wrong-sign” final state. This small contribution is taken into account by an additional component in the fit. An example of such a fit is shown in Fig. 3.6. In total, about 11 million partially reconstructed decays are found.

The charge asymmetry of the pion detection efficiency is measured as a function of momentum of the probe pion. In the case that the pion is not reconstructed, the momentum of the missing pion is inferred from a kinematic fit using the PV constraint, constraining the $D^{*+}$ and $D^0$ mass to their world-average masses [94], and using the momenta of the other tracks. This decreases the momentum resolution, compared to that of a fully reconstructed pion. To determine the migration of the probe pions into neighbouring bins of momentum, a matrix is constructed by comparing the momentum of the pion in the fully reconstructed sample to the inferred momentum from the kinematic fit, assuming one pion is missing. Using this matrix, the effect of the worse pion momentum resolution is statistically unfolded, and the tracking asymmetry as function of $p$ is obtained. Alternatively, the procedure can be done in bins of $p_T$. The pion charge asymmetry as function of $p$ and $p_T$ is shown in Fig. 3.7. The asymmetry split by magnet polarity goes up to about 0.5% and shows little features, although some evidence for a magnet-dependent

![Figure 3.6: Example of fits to the (left) fully- and (right) partially-reconstructed $D^{*+}$ decays in 2011 data, in the momentum range 15 – 20 GeV/c. The reduced mass resolution of the partially reconstructed events still allows to determine the signal component.](image-url)
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cross-over point exists around $p \approx 40$ GeV/c. In 2012 data, the pion asymmetry for momenta below 5 GeV/c is somewhat larger than for 2011, which is partially attributed to the higher detector occupancy in 2012. The average of the magnet polarity split results is consistent with zero.

The $\mu^+\pi^-$ asymmetry is obtained from the charge-split efficiencies in the same way as the $J/\psi$ method, see Eq. 3.1.3, only using a single-track pion asymmetry instead of that of a muon. The unfolding procedure requires the inversion of the migration matrix, and small variations might induce instabilities. Different matrix inversion regularization methods are used to assess a possible systematic bias.

Since a two-dimensional unfolding in $p$ and $p_T$ would become too complicated, only a one-dimensional binning in $p$ is used when weighting the kinematic distributions of the probe pion. As a check, the weighting to signal data is repeated using the binning in $p_T$. The obtained values are compatible with the default method within their statistical error. The resulting $\mu^+\pi^-$ asymmetry in the $\alpha^a_{sl}$ and $\alpha^s_{sl}$ analyses will be described in the appropriate sections in Chapters 4 and 5.

![Figure 3.7: Tracking asymmetries as obtained with the $D^*$ method in (left) 2011 data and (right) 2012 data, as a function of (top) $p$ and (bottom) $p_T$.](image-url)
3.1. The asymmetry of $\mu^+\pi^-$ pairs

### 3.1.3 Comparing the methods

The tracking asymmetries obtained with the $J/\psi$ tag-and-probe method (Fig. 3.5) and $D^{*+}$ partial-and-full method (Fig. 3.7) are similar, although some differences can be observed in the results split by magnet polarity. The $J/\psi$ method requires at least part of the probe track to be reconstructed in a subdetector. This implies that the track must be in LHCb geometrical acceptance; the efficiency of which is thus not taken into account. When the particles originating from the PV have a symmetric angular spread, this does not affect the charge asymmetry. However, due to the non-zero beam-crossing angle an effect can be expected, as explained in Sec. 2. Especially due to the magnet polarity dependence of the horizontal beam-crossing angle in 2011, this effect can be different in size between magnet polarities. This might be responsible for the small difference between 2011 and 2012 data in Fig. 3.7 compared to the overlap in 2011 and 2012 data in Fig. 3.5. The effect that the acceptance has on the $J/\psi$ tag-and-probe tracking asymmetry is determined with simulated events. These are weighed to match the angular spread observed in data, in order to take into account the effect of the beam-crossing angle. Depending on the kinematic distribution, the correction to the VELO + T station method is found to range from $-0.05\%$ to $+0.05\%$ with a statistical error of about $0.01\%$, but the correction is negligible in the magnet average.

On the other hand, the $D^{*+}$ method correctly takes into account the acceptance asymmetry, but has limited precision for higher momenta. When a significant amount of momentum of the $D^0$ is carried by the missing pion, the mass resolution broadens and the uncertainty on the asymmetry increases. In addition, due to the one-dimensional unfolding any correlation between kinematic variables (e.g. $p, \eta$) is not taken into account in the procedure. This limits the sensitivity of the $D^{*+}$ method. For these reasons a combination of both methods is made.

Pions are different than muons in the sense that they undergo nuclear interactions. The cross-section of $\pi^+$ and $\pi^-$ on protons are slightly different, but the asymmetry in the cross-section with deuterium is almost negligible, as is shown in Fig. 2.9. Although various materials are used in the setup of the LHCb detector, one can reasonably assume that it is an isoscalar target, meaning that it consists of an equal amount of protons and neutrons. The most precise measurement of the cross sections with deuterium have been done in the 1970s \[^95,97\]. The asymmetry in pion momenta ranging from 23 to 280 GeV/c was found to be

\[ 1 - \frac{\sigma^{\pi^+d}}{\sigma^{\pi^-d}} = (0.14 \pm 0.09)\%. \quad (3.1.5) \]

As a rough estimate, about 20% of all charged pions undergo a hadronic interaction in the spectrometer, integrating the material from VELO up to RICH2. Assuming every hadronic interaction results in an inefficient reconstruction, this results in a charge asymmetry of $(0.03 \pm 0.02)\%$, but depends on the kinematic distribution of the sample. Using the kinematic distributions of the $a^d_{\pi}$ signal sample, the maximal effect is found to be 0.07%.

A more detailed study is done using simulation and a full material description of the LHCb detector. This also takes into account the non-isoscalar properties of the different materials used in the detector.
Chapter 3. Detection asymmetries

materials, and an asymmetry in the amount of material traversed by positive and negative pions depending on the magnet configuration. The total effect on the tracking asymmetry is found to range between $-0.04\%$ and $+0.03\%$ with a statistical error of about $0.01\%$, using the kinematic distributions of the $a^{s}_{3}$ signal sample. In the average over magnet polarities the effect is found to be negligible.

The combination of the $J/\psi$ and $D^{*+}$ methods is made by weighting the tracking asymmetries by their relative uncertainties, while correcting the $J/\psi$ method for the acceptance and material effects. For large momenta of the probe track, the $\Delta M$ distribution in the $D^{+}$ partial-and-full method becomes very broad and the extracted yield becomes more uncertain. Hence, the $J/\psi$ method dominates in the combination of both methods at large momenta. The effect of the acceptance and material corrections on the combined $\mu^{+}\pi^{-}$ asymmetry depends on the signal kinematics, and will be discussed in Chapter 5, and a numerical comparison including material and acceptance corrections is made in Table 5.5.

3.2 The asymmetry of $K^{+}\pi^{-}$ pairs

The other charge-neutral pair in the final state of the $a^{d}_{3}$ analysis is the $K^{+}\pi^{-}$ pair. In contrast to pions, a sizeable difference in cross section with material is expected for $K^{+}$ and $K^{-}$ mesons, as was discussed in Sec. 2.2.6. The charge asymmetry of the $K^{+}\pi^{-}$ pair is determined using prompt charm decays, as illustrated in Fig. 3.8. The idea is to obtain the charge asymmetry in $D^{-}\rightarrow K^{+}\pi^{-}\pi^{-}$ decays and subtract the asymmetry in $D^{-}\rightarrow K_{S}^{0}(\rightarrow \pi^{+}\pi^{-})\pi^{-}$ decays. As is discussed below, the $K_{S}^{0}\rightarrow \pi^{+}\pi^{-}$ decays have only a small detection asymmetry, such that in the subtraction the $D^{-}$ production asymmetry and the $\pi^{-}$ asymmetry cancel, and only the $K^{+}\pi^{-}$ asymmetry remains. The events are required to be triggered independently of the presence of the $D^{-}$ daughter particles at the hardware level, to minimize a possible bias. Both decays can be triggered at the first software stage by the $\pi^{-}$ originating directly from the $D^{-}$ meson (two possibilities for the $K^{+}\pi^{-}\pi^{-}$ mode, only one for the $K_{S}^{0}\pi^{-}$ mode). This is called the “tag” pion. When the kinematic distributions of the $D^{-}$ meson and triggered $\pi^{-}$ meson are identical between the $K^{+}\pi^{-}\pi^{-}$ and $K_{S}^{0}\pi^{-}$ modes, any production and trigger asymmetry cancels in the difference of the observed asymmetry. This method has been used before in measurements of $CP$ violation in $D^{0}$ mesons [98], and includes asymmetries due to acceptance, reconstruction, material and particle identification.

In the selection of the $D^{-}\rightarrow K^{+}\pi^{-}\pi^{-}$ and $D^{-}\rightarrow K_{S}^{0}\pi^{-}$ candidates, the tag pion has to satisfy $p_{T} > 1.6$ GeV/c as well as a pion PID requirement ($DLL_{K^{-}\pi} < 0$). On the $K^{+}\pi^{-}$ pair used in the determination of the asymmetry, $p_{T} > 250$ MeV/c and $p > 2$ GeV/c is required on both tracks, as well as a kaon PID cut ($DLL_{K_{S}^{0}\pi} > 7$) on the $K^{+}$ and pion PID cut ($DLL_{K^{-}\pi} < 3$) on the $\pi^{-}$. The $K_{S}^{0}$ candidates are reconstructed from two long tracks, forcing the $K_{S}^{0}$ to have decayed inside the VELO. This happens in about a third of the $K_{S}^{0}$ decays. The detection asymmetry of $K_{S}^{0}$ candidates is small due to
3.2. The asymmetry of $K^+\pi^-$ pairs

\[ A_{K\pi} = \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi^+)} = A_{D^-\rightarrow K^+\pi^-} - A_{D^-\rightarrow K^0\pi^-} - A_{K^0\pi}, \quad (3.2.1) \]

where $A_{D^-\rightarrow K^+\pi^-}$ and $A_{D^-\rightarrow K^0\pi^-}$ are determined from the charge asymmetry in the observed yields, while for $A_{K^0\pi}$ the above value is used. The observed yields are obtained from a maximum-likelihood fit to the invariant mass, shown in Fig. 3.9. In total, about 50 million $D^- \rightarrow K^+\pi^-\pi^-$ decays and 3.5 million $D^- \rightarrow K^0\pi^-\pi^-$ decays pass the selection. The measured asymmetries of the $D^- \rightarrow K^+\pi^-\pi^-$ and $D^- \rightarrow K^0\pi^-\pi^-$ samples before

Figure 3.8: Illustration of the weighting procedure used in the determination of the $K^+\pi^-$ asymmetry (note the swapped signs in the illustration with respect to the text). The particles in the dashed circles from different decays are matched in their kinematic distributions. In addition, the kinematic distributions of the $D^+$ mesons are matched such that they have the same production asymmetry.

the charge-symmetric final state. However, the $K^0_S$ itself has a significant lifetime, such that material, $CP$-violating and mixing effects can create a charge asymmetry of the flavour eigenstates $K^0$ and $\bar{K}^0$, as produced from the respective decays $D^- \rightarrow K^0\pi^-$ and $D^+ \rightarrow \bar{K}^0\pi^+$. The $K^0_S$ asymmetry due to all these effects has been extensively studied in Ref. [99] and is found to be $A_{K^0_S} = (-0.054 \pm 0.014)\%$. Finally, direct $CP$ violation in these Cabibbo-favoured tree charm decays is expected to be small due to the large suppression of alternative diagrams, and is ignored. Taking the above into account, we are left with the $K^+\pi^-$ asymmetry

$$ A_{K\pi} = \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi^+)} = A_{D^-\rightarrow K^+\pi^-} - A_{D^-\rightarrow K^0\pi^-} - A_{K^0\pi}, \quad (3.2.1) $$

where $A_{D^-\rightarrow K^+\pi^-}$ and $A_{D^-\rightarrow K^0\pi^-}$ are determined from the charge asymmetry in the observed yields, while for $A_{K^0\pi}$ the above value is used. The observed yields are obtained from a maximum-likelihood fit to the invariant mass, shown in Fig. 3.9. In total, about 50 million $D^- \rightarrow K^+\pi^-\pi^-$ decays and 3.5 million $D^- \rightarrow K^0\pi^-\pi^-$ decays pass the selection. The measured asymmetries of the $D^- \rightarrow K^+\pi^-\pi^-$ and $D^- \rightarrow K^0\pi^-\pi^-$ samples before
The results of the fits are overlaid. Production and detection asymmetries depend on the kinematic distributions of the particles involved. Since the momentum distributions of the particles in the signal and background are different, alternative variables are used in the weighting in order to determine the size of a potential bias due to the choice of variables. In addition, alternative variables are used in the weighting in order to determine the asymmetries between the two magnet polarities. Part of this is explained by the magnet-dependent PID asymmetry introduced by the selection on these samples, which is determined with the method described in Sec. 3.3 and contributes about 0.1%. The rest is attributed mostly to the kaon material interaction asymmetry, but also includes effects from tracking, acceptance and amount of material traversed.

There are three weighting steps involved in the determination of the $K^+\pi^-$ asymmetry, illustrated by Fig. 3.8. The distributions that are matched to each other are described below. In addition, alternative variables are used in the weighting in order to determine the size of a potential bias due to the choice of variables.

**First**, the kinematic distributions of the $K^+$ and $\pi^-$ (that is not used to trigger the event) of the $D^- \rightarrow K^+\pi^-\pi^-$ sample are matched to the kaon and pion in the signal sample. This is done by applying weights to the events in the $D^- \rightarrow K^+\pi^-\pi^-$ sample. Three variables are considered simultaneously: the $p_T$ and pseudorapidity $\eta$ distributions of the pion, and the $p_T$ distribution of the kaon. Alternatively, the $p_T$ and $\eta$ distributions of the kaon, and $p_T$ distribution of the pion are used.

### Table 3.2: The unweighed asymmetries of the $K^+\pi^-\pi^-$ and $K^0_{\pi^+}\pi^-$ data samples.

<table>
<thead>
<tr>
<th></th>
<th>$A_{K^+\pi^-}$ [%]</th>
<th>$A_{K^0_{\pi^+}\pi^-}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1.82 ± 0.01</td>
<td>0.84 ± 0.06</td>
</tr>
<tr>
<td>2011, Up</td>
<td>2.36 ± 0.04</td>
<td>0.85 ± 0.18</td>
</tr>
<tr>
<td>2011, Down</td>
<td>1.52 ± 0.02</td>
<td>0.64 ± 0.15</td>
</tr>
<tr>
<td>2012, Up</td>
<td>2.10 ± 0.02</td>
<td>0.87 ± 0.09</td>
</tr>
<tr>
<td>2012, Down</td>
<td>1.52 ± 0.03</td>
<td>0.89 ± 0.09</td>
</tr>
<tr>
<td>2011 (linear av.)</td>
<td>1.94 ± 0.02</td>
<td>0.74 ± 0.12</td>
</tr>
<tr>
<td>2012 (linear av.)</td>
<td>1.81 ± 0.02</td>
<td>0.88 ± 0.07</td>
</tr>
<tr>
<td>Weighted av.</td>
<td>1.86 ± 0.01</td>
<td>0.85 ± 0.06</td>
</tr>
</tbody>
</table>

Figure 3.9: Fits to the invariant mass of the (left) $D^- \rightarrow K^+\pi^-\pi^-$ and (right) $D^- \rightarrow K^0_{\pi^+}\pi^-$ candidates, used in the determination of the $K^+\pi^-$ asymmetry. Figures are taken from Ref. [98].
The second weighting step consists of matching the $\phi$ distribution of the kaon in the $D^- \to K^+\pi^-\pi^-$ sample to that of the kaon in the signal sample. This weighting is found to not affect the distributions in the previous step. Alternatively, this step is left out.

Finally, weights are applied to the $D^- \to K^0\pi^-$ sample in order to match the $D^- \to K^+\pi^-\pi^-$ sample, in the distributions of $p_T$ and $\eta$ of the $D^-$, and the $p_T$ of the trigger pion. This cancels the $D^-$ production asymmetry and the $\pi^-$ detection asymmetry in the $D^- \to K^+\pi^-\pi^-$ sample. Alternatively, the three variables whose distributions are matched are the $p_T$ of the $D^-$, and the $p_T$ and $\eta$ of the $\pi^-$. Another variation of the weighting is done by using the $\phi$ angle of the $D^-$ meson instead of $\eta$.

When using only the last weighting step — matching the $D^- \to K^0\pi^-$ sample to the $D^- \to K^+\pi^-\pi^-$ sample — and subtracting the $K^0$ asymmetry, the $K^+\pi^-$ asymmetry can be shown as a function of momentum of the kaon. This is done in Fig. 3.10. A clear decrease in the absolute asymmetry as a function of momentum is observed, as is expected from the decreasing kaon interaction asymmetry as was shown in Fig. 2.9.

Using the alternative variables in the weighting steps described above, the potential bias due to the choice of these variables is determined. The deviation from the resulting $K^+\pi^-$ charge asymmetry using these alternative schemes, with respect to the result using the nominal variables, are assigned as systematic errors. The amount of material encountered in the VELO by tracks originating from a $D^-$ meson that is promptly produced in the PV, might be somewhat different than that for tracks originating from $B^0 \to D^-$ decays. This effect is studied in simulation and found to be negligible. The resulting values for the asymmetries depend on the kinematic distributions of the $K^+\pi^-$ pair in the $a_1^d$ signal

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![Figure 3.10: The $K^+\pi^-$ charge asymmetry as function of momentum of the kaon, averaged over both magnet polarities. Note the swapped signs in the figure with respect to the text. The shaded area is the average of the individual bins. The figure is taken from Ref. [98.]](image-url)
sample, and will be discussed in Chapter 4. In the $a^4_{sl}$ analysis, the final state involves a $K^+K^-$ pair instead. The next section describes how to use the above method to determine the $K^+K^-$ asymmetry.

### 3.2.1 The asymmetry of $K^+K^-$ pairs

If the kinematic distributions of a $K^+K^-$ pair nearly overlap, such as in $D^-_s \rightarrow \phi \pi^-$ decays where the $\phi$ decays as $\phi \rightarrow K^+K^-$, the $K^+K^-$ asymmetry is expected to be very small. For other decays to a $K^+K^-\pi^-$ final state, i.e. $D^-_s \rightarrow K^{*0}K^-$, where $K^{*0} \rightarrow K^+\pi^-$, and non-resonant decays, this is not necessarily the case.

In order to determine the $K^+K^-$ asymmetry, the first weighting step in the $K^+\pi^-$ asymmetry method — which matches the distributions of the $K^+\pi^-$ pair in the $D^- \rightarrow K^+\pi^-\pi^-$ decay to the signal distributions — is replaced by only weighting the kaon from the $D^- \rightarrow K^+\pi^-\pi^-$ sample to the kaon in the signal with the same sign (SS) as the $D^+_s$ meson. The distributions that are required to match are the $p_T$ and $\eta$ of the kaon. This procedure is then repeated for the opposite-sign (OS) kaon. The second step — where the azimuthal angles $\phi$ of the kaons are matched — is skipped. Finally, the third step that matches the kinematic distributions of the $D^-$ mesons in the $D^- \rightarrow K^+\pi^-\pi^-$ and $D^- \rightarrow K^0\pi^-$, is identical. The $K^+K^-$ asymmetry is calculated as

$$A_{KK} = A_{K\pi}^{OS} - A_{K\pi}^{SS}.$$  

In the determination of the statistical error, the large correlation (93\%–99\%) between $A_{K\pi}^{OS}$ and $A_{K\pi}^{SS}$ is taken into account. Any residual pion asymmetry from the unweighed $\pi^-$ in the $D^- \rightarrow K^+\pi^-\pi^-$ sample is likely to be small in the magnet-average result. As a check, an additional weighting step is done for the pion by matching the distributions in the samples used for $A_{K\pi}^{OS}$ and $A_{K\pi}^{SS}$ to those of the pion in the $a^4_{sl}$ signal sample. The effect is found to be around ±0.03\% for data taken with a given magnet polarity, and is included as a systematic error to the magnet separate results. It is found to be negligible in the magnet average. Due to the large overlap between the $A_{K\pi}^{OS}$ and $A_{K\pi}^{SS}$ samples, the effect of $A_{K\pi}^{SS}$ on the $K^+K^-$ asymmetry is estimated to be smaller than $10^{-5}$ and neglected. The $K^+K^-$ asymmetry depends on the signal kinematic distributions, and will be further discussed in Chapter 5.

### 3.3 Hadron identification asymmetry

In the stripping and offline selection, particle identification (PID) criteria are placed on the $D^-$ ($D^+_s$) daughter particles. The efficiency of these selection criteria depend on the performance of RICH1 and RICH2, which can vary depending on the position and momentum of the particles as discussed in Chapter 2. As a consequence, a charge asymmetry could be created by the PID requirements.

The possible asymmetries introduced by the PID criteria in the $a^4_{sl}$ and $a^4_{sl}$ signal selections are measured using a large sample of $D^0 \rightarrow K^-\pi^+$ decays that originate from
3.3. Hadron identification asymmetry

a $D^{*-} \to D^0 \pi^-$ decay. The pions and kaons from the $D^0$ decay are required to have $p_T > 1.2 \text{GeV/c}$ and $p > 2 \text{GeV/c}$. The charge of the pion in the $D^{*-}$ decay identifies the charges of the kaon and pion from the $D^0$ decay, without requiring input from PID-sensitive variables. This allows to determine the efficiency of a cut on PID variables on the kaon or pion in an unbiased way. The total yield can be obtained by performing a maximum-likelihood fit to the invariant mass difference of the $D^{*-}$ and $D^0$ candidates. This is shown in Fig. 3.11 (left).

This fit is used to calculate signal weights for the events using the $sPlot$ method [100]. This method allows to subtract combinatorial background in kinematic distributions of signal candidates. As the efficiencies depend on the kinematic properties of the particles, the sample is split up into bins in $n$ kinematic variables. For each bin, the efficiency is determined as the sum of signal weights for events where the particle passes the PID criterium, over the total signal weights in this bin. The efficiencies obtained with this method are discussed in Ref. [73], and shown in Fig. 3.11 for two typical PID criteria. The efficiency of correct identification using standard PID criteria is about 95% for momenta between 10 and 40 GeV/c, but drops quickly above or below this range. For tighter PID requirements the drop is significantly faster. Hence, a larger PID asymmetry is expected for particles with very high or low momenta.

In order to calculate the PID efficiency of signal particles, the $n$-dimensional histogram is used as a look-up table, and an iteration over all signal events is made to determine the total PID efficiency for that signal particle. The charge asymmetries of the hadron PID efficiencies are defined as

$$A_{\text{PID}} = \frac{\epsilon_{\text{PID}}(D^+_{(s)}) - \epsilon_{\text{PID}}(D^-_{(s)})}{\epsilon_{\text{PID}}(D^+_{(s)}) - \epsilon_{\text{PID}}(D^-_{(s)})},$$

and are shown in Fig. 3.12 and Fig. 3.13 as a function of momentum for PID criteria that are used in the $a_0^+$ analysis. The variation of the asymmetry displays opposite behaviour for

Figure 3.11: (left) A fit to the $D^0 \to K^- \pi^+$ invariant mass, used to determine signal weights and PID efficiencies. (right) Kaon (mis)identification efficiency for two typical PID criteria. Figures are taken from Ref. [73].
the two magnet polarities around $p = 40\text{ GeV}/c$, and diverges rapidly above $p = 60\text{ GeV}/c$. This is the momentum range in which most sensitivity in the PID variables originates from RICH2, which is positioned after the magnet. This effect increases with stronger PID requirements. The amount of signal candidates in the $a_{sl}^d$ and $a_{sl}^s$ analyses with momenta in this highly-asymmetric range is small. In addition, the average asymmetry of both magnet polarities remains close to zero.

![Figure 3.12](image)

Figure 3.12: Kaon PID asymmetry as function of (top) momentum and (bottom) transverse momentum in (left) 2011 and (right) 2012 for PID criteria used in the $a_{sl}^s$ analysis (see Sec. 5), with the loose PID selection that is used for the $D_s^- \rightarrow \phi\pi^-$ resonant decay region ($\text{DLL}_{K-\pi} > -5$ and $\text{ProbNNK} > 0.1$).
3.3. Hadron identification asymmetry

![Graphs showing Kaon PID asymmetry as function of momentum and transverse momentum for 2011 and 2012](image)

Figure 3.13: Kaon PID asymmetry as function of (top) momentum and (bottom) transverse momentum in (left) 2011 and (right) 2012 for PID criteria used in the $a_s$ analysis (see Sec. 5), with the more stringent selection that is used for the decay region outside of the $D_{s}^{+}$ resonance ($\text{DALL}_K > 4$ and $\text{ProbNNK} > 0.15$).

The PID efficiency of a signal candidate is determined by multiplying the PID efficiencies for the individual final-state particles (e.g. $K^+$, $\pi^+$, $\pi^-$). Since the same samples are probed when determining the individual efficiencies, the statistical error of the combination is correlated. Therefore a toy method is used to determine the overall statistical uncertainty. To do this, the efficiencies in each bin of the $n$-dimensional histograms are independently varied, by drawing a random value from a Gaussian distribution with a width equal to the error on the efficiency. The new efficiency histograms are used to re-determine the total PID asymmetry. This procedure is repeated 100 times, and the standard deviation of these values is taken as the statistical error.

A possible bias due to the choice of binning is determined by varying the binning, as well as changing the binning variables to both 2-dimensional and 3-dimensional schemes in $p_T$, $p$, $\eta$ and $\phi$. The maximal difference with respect to the nominal result is taken as a systematic error. In addition, a possible bias might originate from the usage of the $s$Plot method, and is investigated as follows.

As described above, the efficiencies are calculated from the ratio of signal weights, which are determined with the $s$Plot method. These weights depend on the signal shape...
used in the fit to the invariant mass distributions. However, the invariant mass shape is affected by the kinematic properties of the particles. For the result on the asymmetry, this effect is expected to be small since the kinematic distributions of the charge-conjugate final state are almost identical. Nonetheless, in order to test the validity of the sPlot method an alternative method is used. Here the data is first divided into kinematic bins, after which a fit is performed in each bin to obtain the “pass” and “fail” yields and efficiencies. The resulting differences between both methods varies between $-0.02\%$ and $+0.02\%$ depending on the kinematic bin, which is included in the systematic uncertainties.

3.4 Trigger and muon PID asymmetry

The semileptonic final states used in the $a_{sl}^d$ and $a_{sl}^s$ analyses are mainly triggered by the muon. The efficiency of triggering on the signal muon (TOS) is determined with a $J/\psi$ tag-and-probe method, similar to the method used for the tracking asymmetry, but in this case both muons are fully reconstructed as long tracks offline and the samples have a negligible overlap. The event is triggered on one muon which acts as the “tag”, while the trigger information on the “probe” muon is used to determine the trigger and muon PID efficiency. Candidate $J/\psi$ decays are obtained from loosely selected $B \rightarrow J/\psi X$ decays in order to suppress backgrounds directly originating from the PV, and the event is triggered on the tag muon by the muon system ($L0Muon$, see Chapter. 2.4). Both muons are required to have $p > 6\text{ GeV}/c$ and $p_T > 1.2\text{ GeV}/c$ and minimum $\chi^2_{IP} > 4$. They should form a $J/\psi$ vertex with $\chi^2/\text{ndf} < 4$ which should be significantly detached from the PV, and the resulting momentum vector should have a $p_T > 500\text{ MeV}/c$ and point towards the PV within an angle $\cos(\phi) > 0.99$. Another track is loosely combined with this vertex to form a $B$ candidate.

This selects about 30 million events in total. The requirements that are probed by this method are the muon hardware trigger, the first software-stage trigger ($Hlt1TrackMuon$) and the muon identification requirement ($\text{DLL}_{\mu-\pi} > 0$), given that the probe track is reconstructed as a long track. An event is categorized as “pass” if the probe track meets all the requirements, and as “fail” if it does not. The muon trigger- and PID asymmetry is defined as

$$A_{\mu} = \frac{\epsilon^+_{\mu} - \epsilon^-_{\mu}}{\epsilon^+_{\mu} + \epsilon^-_{\mu}},$$

and from now on referred to as the muon asymmetry.

The efficiencies are determined from the ratio of pass to total yields, obtained from a binned maximum-likelihood fit to the $J/\psi$ invariant mass, shown in Fig. 3.14. The shape used for the fit is the sum of a Crystal Ball (CB) function and a Gaussian function. The CB is a Gaussian function with a power-law tail on the left side, with a continuous and smooth transition. It is defined as

$$f_{\text{CB}}(x, \alpha, n, \mu, \sigma) = N \cdot \begin{cases} \frac{e^{-\left(\frac{x-\mu}{\sigma}\right)^2}}{2\pi}, & \text{for } \frac{x-\mu}{\sigma} > \alpha \\ A \cdot (B - \frac{x-\mu}{\sigma})^{-n}, & \text{for } \frac{x-\mu}{\sigma} \leq \alpha, \end{cases}$$

(3.4.2)
3.4. Trigger and muon PID asymmetry

where \( A = (\frac{n}{|\alpha|})^n \cdot e^{-\frac{|\alpha|^2}{2}} \) and \( B = \frac{n}{\alpha} - |\alpha| \). Here \( N \) is the normalization factor, \( x \) is the invariant mass, \( \mu \) is the mean, \( \sigma \) the Gaussian width, \( \alpha \) is the point where the shape changes from Gaussian to a power-law tail in units of \( \sigma \), and \( n \) is the decay strength of the power-law tail. The tail on the left side is required to describe radiative energy losses of the tracks, while the two Gaussian functions allow to describe two different contributions to the momentum resolution, typically from tracks traversing either through the IT or the OT. The Gaussian and CB share the same parameter for the mean. The CB tail parameters \( \alpha \) and \( n \) are fixed from a fit to simulated events without background, but are varied within their error to determine the systematic bias of this choice on the muon asymmetry. The shape used for the background is a first-order Chebychev polynomial, the parameters of which are found to be less correlated with the CB tail parameters than an exponential background shape. The fit is performed simultaneously for positive and negative “pass” candidates, sharing all free parameters but the normalization. The same is done for the “fail” candidates. The results of the fits for 2012 data are shown in Fig. 3.14.

The muon asymmetry is reconstructed from the separate charge efficiencies, and is shown in Fig. 3.15. From the top row it is immediately clear that the muon asymmetry in 2011 for each magnet polarity is large, and diverges at low \( p_T \). This is due to a misalignment in the L0 muon trigger, as discussed in Sec. 2.4. Due to the misalignment, the \( p_T \) of the muon calculated in the hardware trigger (L0Muon) is underestimated for one charge. This decreases the efficiency of the trigger for that charge, and induces a charge asymmetry for low transverse momenta. Demanding a higher minimum \( p_T \) would solve this problem, but since the \( p_T \) resolution in the hardware trigger is so much worse than that of the offline reconstructed \( p_T \) of the track, this effect is smeared out over a large range of offline \( p_T \) values. Instead, the full 2011 data is used to calibrate the positions of the pads in the muon stations, after which the hardware trigger is emulated using the offline-reconstructed track parameters, using the correct positions of the pads. A look-up table is created with the correct values for the hardware-trigger \( p_T \). This look-up table is

![Figure 3.14](image-url)

Figure 3.14: Fits to the \( J/\psi \) invariant mass in 2012 data, used to measure the muon asymmetry. The “pass” and “fail” contributions are projected, split up for a (left) positive charge and (right) negative charge of the probe track.
applied to the data, and a slightly higher cut of $p_{\text{L0Muon}} > 1640$ MeV/c is made to obtain similar efficiencies for both charges. This is shown in the second row of Fig. 3.15.

In 2012 data the L0Muon $p_T$ is calibrated from the start, using the first few run numbers, which are excluded from the data in the $a_{sl}^d$ and $a_{sl}^s$ analyses. Hence, no look-up table is constructed offline. The resulting charge asymmetry is shown in the bottom row of Fig. 3.15. The effect as function of $p_T$ and $p$ is larger than the corrected 2011 data, which is explained by the difference in the procedure and the fact that not the whole 2012 data was used for a correction a-posteriori. Around $p = 40$ GeV/c the sign of the asymmetry for each magnet polarity flips. This roughly corresponds to the momentum at which most of the tracks that are either in the left- or right side of the detector before the magnet, stay on that side after the magnet. The potential sources of asymmetry described in

Figure 3.15: The muon asymmetry in bins of momentum (left) and $p_T$ (right), for 2011 data without (top) and with (middle) L0 look-up table applied, and (bottom) calibrated 2012 data.
3.4. Trigger and muon PID asymmetry

Sec. 2.3.3 are expected to be the same size but of opposite sign for each magnet polarity. This is observed when averaging over magnet polarities, which is consistent with zero in all situations.

The kinematic distributions of the probe muon in the \( B \to J/\psi X \) sample are matched to those of the muon in the signal in the \( a_{sl}^d \) and \( a_{sl}^s \) analyses. This is done by weighting in bins of kinematic variables. The resulting asymmetries will be discussed in Chapters 4 and 5. In the \( a_{sl}^d \) and \( a_{sl}^s \) signal samples, there is an additional requirement at the second software-trigger level for the event to be triggered on the muon topological lines, described in Chapter 2. The possible asymmetry in this requirement has been determined using the overlap in triggered events of the two, three-, and four-body lines, and found to be zero with a precision of 0.020%. This is added as a systematic uncertainty on the results.

In the \( a_{sl}^s \) analysis, the Hlt1 trigger requirement consists of two lines, in order to increase the signal efficiency. How the asymmetry of the combination is determined is discussed in the next section.

### 3.4.1 Asymmetry of two trigger lines

In the measurement of \( a_{sl}^s \) a combination of the software-level muon trigger (Hlt1TrackMuon) on the muon, and the general software-level single-track trigger (Hlt1TrackAllL0) on all the four final-state tracks, is used. Therefore, the total muon and trigger asymmetry is split up into two steps. First, the muon asymmetry as described in the previous section is determined, for the hardware-level trigger and muon PID requirement only. In addition, the efficiency of the requirement for the muon to have triggered on either of the first software-level trigger lines, is determined with respect to the hardware trigger and muon PID requirement. The asymmetry is shown in Fig. 3.16 for 2012 data. From the figure it is clear that the software trigger requirement contributes little to the total muon asymmetry.

The efficiency of the general software-level trigger line on the other three tracks (Hlt1TrackAllL0) is determined using a sample of prompt \( D_s^- \to \phi(\to K^+K^-)\pi^- \) decays. This sample is required to be triggered independently of the signal (i.e., on the rest of the event) at the hardware level, to minimize a possible bias due to the hardware trigger. The final-state hadrons are required to have \( p_T > 500 \text{ MeV/c} \) and \( p > 5 \text{ GeV/c} \). Two out of three final-state tracks function as “tag”, while the third track functions as the “probe”. Fits to the \( D_s^- \) invariant mass result in the single-track efficiencies for this software trigger line for kaons and pions, and the charge asymmetries for kaons and pions are shown in Fig. 3.17.

Both software trigger lines share similarities in the selection requirements, as discussed in Sec. 2.4. Therefore a large fraction of signal events is triggered on both lines — up to 80% — especially since the muon may trigger both lines. In order to calculate the combined efficiency of triggering on one or more final-state tracks, the software trigger efficiencies of muons, pions and kaons of both charges are split up in bins of kinematic variables. These histograms are then used as a look-up table for the signal tracks in the \( a_{sl}^s \) analysis. In each event a combination of all track efficiencies is made, while taking the
Chapter 3. Detection asymmetries

Figure 3.16: Charge asymmetry of either the software-level muon trigger or general single-track trigger on the muon, with respect to the muon hardware trigger and PID criterium, in 2012 data, as a function of (left) $p$ and (right) $p_T$. The asymmetries are determined with the $J/\psi$ tag-and-probe method.

Figure 3.17: Charge asymmetry of the general single-track software trigger for hadrons in 2012 data, as a function of (left) $p$ and (right) $p_T$. Displayed are (top) pion probe tracks and (bottom) kaon probe tracks as determined with the $D_s^-$ sample.

The possibility of being triggered by multiple tracks into account. A sum over all events is done as follows,

$$\varepsilon_{B^0_s} = \sum_i (\epsilon_{K^+}^i + \epsilon_{K^+}^i + \epsilon_{\pi^-}^i + \epsilon_{\pi^+}^i - \epsilon_{K^-}^i + \epsilon_{K^-}^i - \epsilon_{K^+}^i - \epsilon_{K^-}^i - \epsilon_{K^+}^i)$$

(3.4.3)

where $i$ runs over all signal events. The charges in Eq. 3.4.3 are reversed for the $B^0_s$.
efficiency. The software trigger asymmetry is then
\[
A_{\text{Hlt}} = \frac{\varepsilon_{B_d^0} - \varepsilon_{\bar{B}_d^0}}{\varepsilon_{B_d^0} + \varepsilon_{\bar{B}_d^0}}. 
\] (3.4.4)

The statistical uncertainty on \(A_{\text{Hlt}}\) is determined by varying the efficiency histograms within their error, similar to what is done for the hadronic PID asymmetry in Sec. 3.3. Variations in the binning and binning variables are made in order to determine a possible bias originating from the choice of binning. The resulting asymmetry and uncertainties for the \(a^*_\text{sl}\) signal sample is discussed in Sec. 5.4.