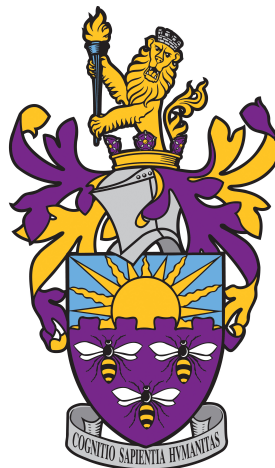


Measurements of CP violation in mixing of B_s^0 mesons and the D_s^+ production asymmetry at LHCb

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voor mama

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Abstract

This thesis reports two measurements performed using proton-proton collision data collected by the LHCb detector in 2011 and 2012, corresponding to an integrated luminosity of 3 fb^{-1} and centre-of-mass energies of 7 and 8 TeV respectively.

The first measures the CP asymmetry in B_s^0 - $\bar{B}_s^0$ oscillations, called a_{sl}^s . This is measured in inclusive B_s^0 and $\bar{B}_s^0$ to $D_s^\mp \mu^\pm \bar{\nu}_\mu X$ decays, where the $D_s^\mp$ meson is reconstructed in the final state $K^\mp K^\pm \pi^\mp$. The measurement is performed in three regions in the Dalitz phase space of the $D_s^\mp$ decay, and corrected for detection and background asymmetries. A value of

$$a_{\text{sl}}^s = (0.39 \pm 0.26 \text{ (stat)} \pm 0.20 \text{ (syst)})\%$$

is found, which is the world's most precise measurement of a CP asymmetry in B meson mixing and is consistent with the Standard Model prediction.

The second measurement determines the production asymmetry of $D_s^\pm$ mesons, and probes non-perturbative QCD models. It is performed in bins of transverse momentum and pseudorapidity in the kinematic region $2.5 < p_T < 25.0 \text{ GeV}$ and $2.0 < y < 4.5$. The $D_s^\pm$ mesons are reconstructed in the $K^\pm K^\mp \pi^\pm$ final state, where the $K^\pm K^\mp$ pair goes through the ϕ resonance. The result is corrected for detection and background asymmetries using similar techniques as for the measurement of a_{sl}^s . The resulting value is

$$A_P(D_s^\pm) = (-0.48 \pm 0.10 \text{ (stat)} \pm 0.10 \text{ (syst)})\%,$$

which is in agreement with the previous measurement from LHCb. No dependence on the $D_s^\pm$ kinematics is found.

In addition, a study on the performance of three adhesives for the assembly of vertex modules for the LHCb upgrade is performed and reported in this thesis. These are two liquid glues, Araldite 2011 and Stycast 2850FT, and one double-sided adhesive tape, 3M 9461P, which are all tested for shear strength and thermal conductivity. Stycast 2850FT is proposed to be utilised.

Declaration

The work described in Chapter 3 was conducted together with two MPhys students, Antoni Shtipliyski and Guy Stelmasiak, who wrote this in their MPhys reports in support of their MPhys degree awarded by the University of Manchester. This was published in a public LHCb note [1].

No portion of the work referred to in other chapters of this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Preface

This thesis starts with an introduction to the theory describing the Standard Model of particle physics in Chapter 1. This chapter continues to lay the foundation of the two physics analyses that are reported in this thesis: the measurement of CP violation in mixing of B_s^0 mesons, and the measurement of the D_s^+ production asymmetry. The former probes differences in matter and antimatter, whereas the latter examines non-perturbative QCD processes.

Chapter 2 describes the LHCb experiment at the LHC at CERN, close to Geneva. This is the detector that is used to collect the data that are analysed in this thesis. It also describes part of the trigger and reconstruction software.

In 2019 and 2020, the LHC will be shut down for an upgrade. During that time, the LHCb detector will also be upgraded. Chapter 3 describes the changes of the upgraded detector and reports on a study of adhesives for the assembly of vertex detector modules for the LHCb Upgrade.

The remainder of the thesis describes data analysis with data recorded in 2011 and 2012 by the LHCb experiment. The main challenge for both analyses is controlling detection asymmetries, which are described in Chapter 4. The measurement of CP violation in B_s^0 meson mixing is described in Chapter 5.

Originally started as a cross-check, and now grown into a full analysis, is the measurement of the D_s^+ production asymmetry, which is reported in Chapter 6. Finally, the conclusion of both measurements and the adhesive studies are given in Chapter 7. This chapter also gives an outlook for the future of the measurements.

The work presented in this thesis is based on the combined efforts of the LHCb collaboration. In particular, the analyses in Chapters 5 and 6, and the corresponding detection asymmetries in Chapter 4, are performed by six PhD students, Laurent Dufour, Christos Hadjivasiliou, Matthew Kelsey, Marian Stahl, Jacco de Vries and the author, and their supervisors, Marina Artuso, Marco Gersabeck, Chris Parkes, Sheldon Stone, Jeroen van Tilburg and Mika Vesterinen.

The content of this thesis thus reflects the work of a group of scientists, in particular that of the PhD students. The author determined the detection asymmetries coming from the hardware trigger as is described in Section 4.2.3, and from the software trigger, which is reported in Section 4.2.2. She also developed a new method for determining combined muon-pion detection asymmetries, which is reported in Section 4.5. In addition, the author led the analysis described in Chapter 6 and performed the majority of that analysis using the input from the other analysts for the determination of the detection asymmetries.

Throughout this thesis, the inclusion of charge-conjugate processes is implied and natural units with $\hbar = c = 1$ are used.

1 Theoretical introduction

This chapter gives an overview of the Standard Model of particle physics in Section 1.1, which describes fundamental particles and their interactions. Section 1.2 and Section 1.3 lay the foundation for the analyses that are presented in this thesis and respectively describe theoretical models for CP violation in neutral meson mixing and production asymmetries of D_s^+ mesons. Additionally, it gives an overview of the experimental status of both quantities.

1.1 Introduction to the Standard Model

The information in this section is based on References [2–4]. The Standard Model of particle physics (SM) describes fundamental particles and their interactions due to the electromagnetic, strong and weak forces. Since its formulation in the 1960s, the SM has known many successes. It passed numerous precision tests, and correctly predicted the existence of the $W^\pm$, Z and Higgs bosons, the gluon, the top, bottom and charm quarks, and the tau neutrino.

The SM is a quantum field theory (QFT) that contains two types of particles: spin-1/2 particles called fermions and spin-0 or spin-1 particles called bosons. The spin-1 bosons are the carriers of the forces: the photon (γ) carries the electromagnetic force, the $W^\pm$ and Z bosons the weak force, and the strong force is carried by eight gluons (g). So far, only one fundamental boson with spin-0 has been observed, which is the Higgs boson that was discovered in 2012 by the ATLAS and CMS collaborations [5, 6]. An overview of the properties of the bosons is given in Table 1.1.

There are two types of fundamental fermions in the Standard Model, which are quarks and leptons, and their antiparticles with opposite charge. They can be left- or right-handed. Both can be arranged in three generations. Within a generation of leptons, there is a charged particle (the electron, muon, or tau), and a light neutral

1. Theoretical introduction

Table 1.1: Bosons in the Standard Model, with their spin, charge (Q), and observed masses. The masses are experimental averages taken from the Particle Data Group [7], except for the gluon mass, which is a theoretical value.

boson	force	mass [GeV]	spin	Q/e
γ	electromagnetic	$< 10^{-27}$	1	1
$W^\pm$	weak	80.385 ± 0.015	1	± 1
Z		91.1876 ± 0.0021	1	0
g	strong	0	1	0
H^0	N/A	125.09 ± 0.24	0	0

particle (the corresponding neutrinos). Leptons interact with the electromagnetic and weak force. The quarks are called up, down, strange, charm, top and beauty (or bottom), and interact with all forces. They therefore also carry colour. Due to the confinement of the strong force, quarks never exist on their own, but are always coupled into colour-neutral hadrons. This can be mesons, comprising a quark and antiquark, or baryons, comprising three quarks or three antiquarks. All leptons and quarks in the Standard Model are listed in Table 1.2.

Table 1.2: Quarks and leptons in the Standard Model, with their masses and electric charge (Q). In the SM, neutrinos are massless. However, neutrino oscillations show that they must be massive, but the actual masses are still unknown. The masses of the quarks and leptons are the experimental averages taken from the Particle Data Group [7].

		1 st generation			2 nd generation			3 th generation	
		mass [MeV]			mass [MeV]			mass [GeV]	Q/e
quarks	u	$2.2^{+0.6}_{-0.4}$	c	$(1.27 \pm 0.03) \times 10^3$	t	173.21 ± 0.87			$2/3$
	d	$4.7^{+0.5}_{-0.4}$	s	96^{+8}_{-4}	b	$4.18^{+0.04}_{-0.03}$			$-1/3$
leptons	e	$0.511 \pm 1.6 \times 10^{-8}$	μ	$106 \pm 2.4 \times 10^{-6}$	τ	$1.78 \pm 1.2 \times 10^{-4}$			-1
	ν_e	—	ν_μ	—	ν_τ	—			0

The quantum field theory of the SM can be parametrised by the product of the gauge groups $SU(3)_C \times SU(2)_L \times U(1)_Y$. The group $SU(3)_C$ describes the strong interaction, $SU(2)_L$ the weak interaction, and $U(1)_Y$ the electromagnetic interaction. The unified $SU(2)_L \times U(1)_Y$ groups represent electroweak theory. There are as many bosons as there are generators of a group, which means that there are eight gluons in $SU(3)$, and the photon and $W^\pm$ and Z bosons arising from $SU(2)_L \times U(1)_Y$.

Since the groups must be gauge invariant, the bosons cannot have a mass. This is not in agreement with the observations listed in Table 1.1, and a scalar field is introduced to the electroweak theory which spontaneously breaks the electroweak symmetry and gives rise to the $W^\pm$ and Z masses through the Higgs mechanism. In addition, this predicts the Higgs boson.

The Lagrangian for the Standard Model can be derived by imposing gauge invariance. This is explained in the case of quantum electrodynamics in Section 1.1.1, and then generalised to electroweak theory in Section 1.1.2, which also discusses spontaneous symmetry breaking and the origin of masses through the Higgs mechanism. Quantum chromodynamics is described in Section 1.1.4.

1.1.1 Quantum electrodynamics

Quantum electrodynamics (QED) is described by the gauge field $U(1)$, which has one generator, hence one force-carrying boson. The Lagrangian for electromagnetic interactions is defined by requiring local gauge invariance, and explained here.

The Dirac Lagrangian that describes a free fermion field, ψ is

$$\mathcal{L}_{\text{Dirac}} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi, \quad (1.1)$$

where m is the fermion mass, and γ_μ are the Dirac gamma matrices with μ running from 0 to 3.¹ $\mathcal{L}_{\text{Dirac}}$ is not invariant under a local gauge transformation

$$\psi(x) \rightarrow \psi'(x) = e^{i\alpha(x)}\psi(x). \quad (1.2)$$

However, it can be made gauge invariant by replacing the ordinary derivative ∂_μ by the covariant derivative D_μ , which is defined as

$$D_\mu \equiv \partial_\mu + ieA_\mu. \quad (1.3)$$

The gauge field A_μ transforms as

$$A_\mu \rightarrow A'_\mu = A_\mu - \frac{1}{e}\partial_\mu\alpha(x) \quad (1.4)$$

under a local gauge transformation, where e is the electric charge.

¹In this chapter, the Einstein summation convention is used.

1. Theoretical introduction

The QED Lagrangian can be obtained by adding a kinetic energy term $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$, such that

$$\mathcal{L}_{\text{QED}} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi - e\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}. \quad (1.5)$$

The group U(1) is Abelian, such that the field strength tensor $F_{\mu\nu}$ is defined as

$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu. \quad (1.6)$$

The Lagrangian thus describes the interaction between a charged fermion and the photon field A_μ . The electric charge e determines the coupling strength of QED, which is defined as $\alpha = e^2/4\pi$.

1.1.2 Electroweak theory

The QED U(1) group can be expanded to the $SU(2)_L \times U(1)_Y$ group, which describes electroweak theory, including the weak interactions in addition to the electromagnetic interactions. The generators of the $SU(2)_L$ group couple to left-handed doublets, and give rise to three weak isospin vector fields $\vec{W}_\mu$. The $U(1)_Y$ group is generated by the parameter Y , which is the weak hypercharge, defined as $Y = 2(Q - T_3)$, where Q is charge, and T_3 the third component of the weak isospin.

Fermions have a left- and right-handed component, respectively ψ_L and ψ_R , and can be split as follows:

$$\psi = \psi_L + \psi_R = \frac{1 - \gamma_5}{2}\psi + \frac{1 + \gamma_5}{2}\psi, \quad (1.7)$$

where $\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$. This gives rise to left-handed doublets, which are called Q_L^i for the quark sector, and L_L^i for the lepton sector:

$$Q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b \end{pmatrix}_L; \quad L_L^i = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L. \quad (1.8)$$

In addition, there are right-handed singlets, for the up-type quarks (u_R^i), down-type quarks (d_R^i), and charged leptons (ℓ_L^i):

$$u_R^i = u_R \quad c_R \quad t_R; \quad d_R^i = d_R \quad s_R \quad b_R; \quad \ell_R^i = e_R \quad \mu_R \quad \tau_R. \quad (1.9)$$

Since right-handed neutrinos do not couple to any fields, they are not considered.

Before symmetry breaking, the Lagrangian describing the weak interactions is given by

$$\begin{aligned} \mathcal{L}_{\text{EW, before}} = & \bar{L}_L^i \gamma^\mu \left(i\partial_\mu - \frac{g}{2} \vec{\tau} \cdot \vec{W}_\mu - g' \frac{Y}{2} B_\mu \right) L_L^i \\ & + \bar{\ell}_R^i \gamma^\mu \left(i\partial_\mu - g' \frac{Y}{2} B_\mu \right) \ell_R^i - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \vec{W}_{\mu\nu} \vec{W}^{\mu\nu}, \end{aligned} \quad (1.10)$$

where τ are the Pauli matrices, and g and g' are the coupling strengths for the $\vec{W}_\mu$ and B_μ fields. This Lagrangian describes the interaction of left-handed fermions with the B_μ and $\vec{W}_\mu = (W_\mu^1, W_\mu^2, W_\mu^3)$ fields, whereas right-handed fermions only couple to the B_μ field. Moreover, the fields B_μ and $\vec{W}_\mu$ are all massless. The field strength tensors are defined as

$$B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu, \quad (1.11)$$

$$\vec{W}_{\mu\nu} \equiv \partial_\mu \vec{W}_\nu - \partial_\nu \vec{W}_\mu - g \vec{W}_\mu \times \vec{W}_\nu. \quad (1.12)$$

Similar as for the QED Lagrangian, the gauge invariance of the EW Lagrangian is ensured by introducing the covariant derivative

$$D_\mu \equiv i\partial_\mu - \frac{g}{2} \vec{\tau} \cdot \vec{W}_\mu - \frac{g'}{2} Y B_\mu. \quad (1.13)$$

In the Standard Model, the fields B_μ and $\vec{W}_\mu$ correspond to the massless photon and the massive $W^\pm$ and Z bosons. To make the fields massive, an additional doublet of scalar fields must be introduced to the electroweak Lagrangian, which is known as the Higgs Lagrangian and keeps the model gauge invariant:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad (1.14)$$

where the last two terms are the Higgs potential. In this expression, ϕ is an isospin doublet:

$$\phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}. \quad (1.15)$$

1. Theoretical introduction

After inserting a vacuum expectation value v and considering fluctuations $h(x)$, the symmetry is spontaneously broken, and ϕ becomes

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}. \quad (1.16)$$

This mechanism gives rise to the mass of the B_μ and $\vec{W}_\mu$ fields, which can be combined to make the $W^\pm$, Z and photon fields as follows:

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2), \quad (1.17)$$

$$A_\mu = B_\mu \cos(\theta_W) + W_\mu^3 \sin(\theta_W), \quad (1.18)$$

$$Z_\mu = -B_\mu \sin(\theta_W) + W_\mu^3 \cos(\theta_W). \quad (1.19)$$

Here, $W_\mu^\pm$ are the massive $W^\pm$ boson and Z_μ the massive Z boson, which together describe the weak force, and A_μ is the massless photon field. The angle θ_W is the weak mixing angle, which can be determined experimentally from the $W^\pm$ and Z masses using $\cos \theta_W = M_W/M_Z$. It is usually expressed as $\sin^2 \theta_W$, which is measured to be 0.23 [7].

The Higgs field also gives mass to the fermions. To accomplish this, the Yukawa Lagrangian is added to the EW Lagrangian:

$$\begin{aligned} -\mathcal{L}_{\text{Yukawa}} &= Y_{ij} \bar{\psi}_L^i \phi \psi_R^j + h.c. \\ &= Y_{ij}^d \bar{Q}_L^i \phi d_R^j + Y_{ij}^u \bar{Q}_L^i \tilde{\phi} u_R^j + Y_{ij}^\ell \bar{L}_L^i \phi \ell_R^j + h.c., \end{aligned} \quad (1.20)$$

where $h.c.$ indicates the hermitian conjugate, and $\tilde{\phi}$ is defined as

$$\tilde{\phi} = i \tau_2 \phi^* = \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix}. \quad (1.21)$$

The matrices Y_{ij}^u , Y_{ij}^d and Y_{ij}^ℓ are complex matrices that give rise to couplings between different families. After spontaneous symmetry breaking, the mass terms for fermions are

$$M_{ij}^d = \frac{v Y_{ij}^d}{\sqrt{2}}; \quad M_{ij}^u = \frac{v Y_{ij}^u}{\sqrt{2}}; \quad M_{ij}^\ell = \frac{v Y_{ij}^\ell}{\sqrt{2}}. \quad (1.22)$$

The mass matrices M_{ij} can have off-diagonal elements, allowing mixing between quark or lepton families.

In the quark sector, diagonalising the mass matrices to obtain proper mass terms is done using the unitary matrices V^d , for example

$$M_{\text{diagonal}}^d = V_L^d M^d V_R^{d\dagger}, \quad (1.23)$$

$$M_{\text{diagonal}}^u = V_L^u M^d V_R^{u\dagger}. \quad (1.24)$$

This allows to introduce the Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$V_{\text{CKM}} = (V_L^u V_L^{d\dagger})_{ij}. \quad (1.25)$$

The flavour (interaction) and mass eigenstates of the quarks are chosen such that they are equal for up-type quarks, while the down-type quarks are rotated using the CKM matrix [8]. This matrix defines the probability of a quark of flavour i to decay into a flavour j , which is $|V_{ij}|^2$:

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{flavour}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}}. \quad (1.26)$$

In the lepton sector, there is a similar mixing matrix called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. However, here the neutrinos mix rather than the charged leptons.

The CKM matrix can be parametrised in different ways. The first one discussed here expresses the matrix using three Euler angles θ_{ij} , where i and j are denoting the generations. To simplify the expression $c_{ij} = \cos(\theta_{ij})$ and $s_{ij} = \sin(\theta_{ij})$. The CP -violating phase δ is chosen to be between the first and third generation, such that

$$V_{\text{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}. \quad (1.27)$$

1. Theoretical introduction

From experiments, it is known that $s_{13} \ll s_{23} \ll s_{12} \ll 1$. Therefore, another popular notation, which emphasises this hierarchy of V_{CKM} , is the Wolfenstein parametrisation. This uses the definitions

$$\sin(\theta_{12}) = \lambda, \quad (1.28)$$

$$\sin(\theta_{23}) = A\lambda^2, \quad (1.29)$$

$$\sin(\theta_{13})e^{-i\delta_{13}} = A\lambda^3(\rho - i\eta), \quad (1.30)$$

to express V_{CKM} as

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \quad (1.31)$$

The experimentally determined values of the Wolfenstein parameters are averaged by the Particle Data Group [7], and yield $\lambda = 0.23$, $A = 0.81$, $\rho = 0.13$, and $\eta = 0.37$.

1.1.3 CP violation

There are three important discrete symmetries in the Standard Model. The first is the parity transformation P , which inverts the spatial coordinates of a system, but not the spin and hence it changes the chirality of particles. The second is the charge conjugate transformation C , which converts a particle into its antiparticle and vice versa. The third is time transformation T , which reverses the time direction and thus both the momentum and spin of particles.

The strong and electromagnetic interactions are invariant under each of these three transformations, but the weak interactions are not. Although the combination of CPT transformations is a symmetry in the SM, the combination CP is violated by the weak interaction. This can be explained by the Yukawa part of the Lagrangian:

$$\begin{aligned} -\mathcal{L}_{\text{Yukawa}} &= Y_{ij} \overline{\psi_L^i} \phi \psi_R^j + h.c. \\ &= Y_{ij} \overline{\psi_L^i} \phi \psi_R^j + Y_{ij}^* \overline{\psi_R^j} \phi^\dagger \psi_L^i. \end{aligned} \quad (1.32)$$

Performing the CP operation on a spinor field yields the following:

$$CP(\overline{\psi_L^i} \phi \psi_R^j) = \overline{\psi_R^j} \phi^\dagger \psi_L^i, \quad (1.33)$$

which means that $\mathcal{L}_{\text{Yukawa}}$ is invariant under the CP transformation if $Y_{ij} = Y_{ij}^*$.

Due to the complex phase in the CKM matrix, this is not the case, and this is the origin of CP violation in the Standard Model.

There are three types of CP violation in the Standard Model, which are described here. To discuss these, it is useful to define the decay amplitudes of a particle P (and $\bar{P}$) to a final state f (and $\bar{f}$):

$$\begin{aligned} A_f &= \langle f|S|P\rangle, & \bar{A}_f &= \langle f|S|\bar{P}\rangle, \\ A_{\bar{f}} &= \langle \bar{f}|S|P\rangle, & \bar{A}_{\bar{f}} &= \langle \bar{f}|S|\bar{P}\rangle, \end{aligned} \quad (1.34)$$

where S is the scattering matrix relating the initial and final state.

CP violation often concerns neutral mesons. These do not necessarily have the same mass as flavour eigenstates. Instead, their mass eigenstates, called $|P_1\rangle$ and $|P_2\rangle$, can be expressed as linear combinations of their flavour eigenstates, $|P^0\rangle$ and $|\bar{P}^0\rangle$, as follows:

$$\begin{aligned} |P_1\rangle &= p|P^0\rangle + q|\bar{P}^0\rangle, \\ |P_2\rangle &= p|P^0\rangle - q|\bar{P}^0\rangle, \end{aligned} \quad (1.35)$$

with $|p|^2 + |q|^2 = 1$. Using the parameters p and q , the complex parameters λ_f and $\lambda_{\bar{f}}$ are defined as

$$\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f}, \quad \lambda_{\bar{f}} = \frac{q}{p} \frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}}. \quad (1.36)$$

CP violation in decay

CP violation in decay occurs when the decay width of a particle P to a final state f is not the same as that of the antiparticle $\bar{P}$ to the CP -conjugated final state $\bar{f}$. This can be expressed as

$$\Gamma(P \rightarrow f) \neq \Gamma(\bar{P} \rightarrow \bar{f}), \quad (1.37)$$

or in terms of the decay amplitudes

$$\left| \frac{\bar{A}_{\bar{f}}}{A_f} \right| \neq 1. \quad (1.38)$$

This type of CP violation can occur both in charged or neutral particles, and is also called direct CP violation, whereas the two other types involve the mixing of neutral mesons and are called indirect CP violation.

1. Theoretical introduction

CP violation in mixing

Neutral mesons can oscillate into their own antiparticle in a process called mixing. When the probability of P^0 to $\bar{P}^0$ is not the same as the reverse process:

$$\mathcal{P}(P^0 \rightarrow \bar{P}^0) \neq \mathcal{P}(\bar{P}^0 \rightarrow P^0). \quad (1.39)$$

This is called CP violation in mixing. The process of mixing in neutral B mesons and the measurements of CP violation in mixing are explained in more detail in Section 1.2 to introduce the measurement of CP violation in B_s^0 mixing, which is reported in Chapter 5.

CP violation in the interference of mixing and decay

The last type of CP violation occurs when both neutral mesons P^0 and $\bar{P}^0$ can decay into a final state f , which can thus be reached in two ways: $P^0 \rightarrow f$ and $P^0 \rightarrow \bar{P}^0 \rightarrow f$. There is CP violation in the interference of mixing and decay when the following statement holds:

$$\Gamma(P^0(\rightarrow \bar{P}^0) \rightarrow f) \neq \Gamma(\bar{P}^0(\rightarrow P^0) \rightarrow f). \quad (1.40)$$

This can also be expressed in terms of λ_f , as

$$\text{Im}(\lambda_f) = \text{Im}\left(\frac{q}{p} \frac{\bar{A}_f}{A_f}\right) \neq 0. \quad (1.41)$$

1.1.4 Quantum chromodynamics

The strong interaction is described by quantum chromodynamics (QCD), which is represented by the $SU(3)_C$ gauge group. This group describes interactions between quarks and gluons. It is experimentally determined that there are three colours in the SM, usually called red, green and blue (R, G, B), and that there are eight gluons. A quark carries a colour, while an antiquark carries an anticolour. Gluons have both a colour and anticolour and can therefore also interact with other gluons.

The QCD Lagrangian is similar to the QED Lagrangian, and is given by

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi + g_s(\bar{\psi}\gamma^\mu T_a \psi)G_\mu^a - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}. \quad (1.42)$$

In this expression, the generators of the $SU(3)$ group are $T_a = \lambda_a/2$, where λ_a are the Gell-Mann matrices, and a runs from 1 to 8, to represent eight gluons. The

Gell-Mann matrices satisfy the Lie algebra:

$$[T_a, T_b] = if_{abc}T_c, \quad (1.43)$$

where f_{abc} are fully antisymmetric structure constants.

The field strength tensor $G_{\mu\nu}^a$ is defined as

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c, \quad (1.44)$$

which is very similar to the field tensor $F_{\mu\nu}$ for QED, but also includes an extra term, which is responsible for gluon three- and four-point interactions and makes the group non-Abelian. G_μ^a represents the massless gluon field, and g_s is the QCD coupling constant.

The coupling strength of QCD, α_s , is defined as $\alpha_s = g_s^2/4\pi$. This is dependent on the energy of the process and becomes smaller at higher energies. This means that QCD is a perturbative theory only at high energies, while at energies below a certain energy scale Λ_{QCD} , it is non-perturbative. Several models for non-perturbative QCD are presented in Section 1.3 in the context of production asymmetries.

1.2 CP violation in mixing

The mixing of neutral mesons in the Standard Model can occur through a second order weak amplitude, which is shown for the B_s^0 meson in Figure 1.1. Since these processes are heavily suppressed in the Standard Model and occur through loop diagrams, they are sensitive to new physics. Mixing in the B_s^0 system is sensitive to contributions of physics beyond the standard model in $b \rightarrow s$ transitions, and a measurement of CP violation in B_s^0 meson mixing is reported in Chapter 5.

This section describes the principles of neutral meson mixing in Section 1.2.1 and CP violation in the mixing of B mesons in Section 1.2.2. Theoretical predictions are summarised in Section 1.2.3, and the current experimental status is outlined in Section 1.2.4.

1.2.1 Neutral meson mixing

For B mesons, the mass eigenstates as defined in Equation (1.35) are called $|B_L\rangle$ and $|B_H\rangle$, the L and H respectively denoting light and heavy mass eigenstates. As before, they are expressed in terms of their flavour eigenstates $|B\rangle$ and $|\bar{B}\rangle$:

$$\begin{aligned} |B_L\rangle &= p|B\rangle + q|\bar{B}\rangle, \\ |B_H\rangle &= p|B\rangle - q|\bar{B}\rangle, \end{aligned} \quad (1.45)$$

with $|p|^2 + |q|^2 = 1$. This section explains how this definition leads to neutral meson mixing.

In quantum mechanics, the time evolution of a decaying particle P , with mass m_P , and lifetime $\tau_P = 1/\Gamma_P$ is given by

$$|P(t)\rangle = e^{-im_P t} e^{-\Gamma_P t/2} |P(0)\rangle, \quad (1.46)$$

where Γ_P is the total decay rate of P . In a system with two neutral mesons, this decay can be described by the time-dependent Schrödinger equation [9]:

$$i \frac{d}{dt} \begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \Sigma \begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}. \quad (1.47)$$

Here, Σ is a 2×2 complex Hamiltonian matrix which can be written as the sum of a hermitian and an antihermitian matrix:

$$\begin{aligned} \Sigma &= \mathbf{M} - i \frac{\mathbf{\Gamma}}{2} \\ &= \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}, \end{aligned} \quad (1.48)$$

where $\mathbf{M}$ is the mass matrix, and $\mathbf{\Gamma}$ the decay matrix. Naively, if the flavour eigenstates are the same as the mass eigenstates, one expects the diagonal entries in the matrix $\mathbf{M}$ to be equal to the B mass, the diagonal entries in the $\mathbf{\Gamma}$ matrix to be the decay rates of the B , and the off-diagonal entries to be zero. However, the flavour eigenstates B and $\bar{B}$ can transform into their own antipartners through weak interactions. Figure 1.1 shows the Feynman diagrams corresponding to such interactions for B_s^0 to $\bar{B}_s^0$ mixing.

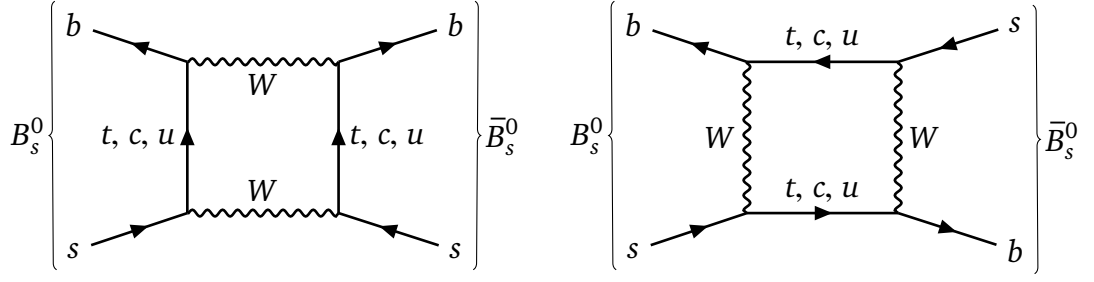


Figure 1.1: Feynman diagrams showing mixing of B_s^0 mesons into $\bar{B}_s^0$ mesons. The box diagrams containing the top quarks dominate over those containing the charm and up quarks, because the amplitudes of the diagrams are dependent on the internal quark mass [9].

The components contributing to the mixing process are M_{12} and Γ_{12} . These respectively describe the off-shell states in the box diagrams in Figure 1.1 which have an internal t quark, and the on-shell states with the internal u or c quarks [10]. The latter can be interpreted as an intermediate state f , accessible to both B and $\bar{B}$ mesons: $B \rightarrow f \rightarrow \bar{B}$, such as $D_s^+ D_s^-$ for B_s^0 mixing. Assuming CPT symmetry, $M_{11} = M_{22} = m$, and $\Gamma_{11} = \Gamma_{22} = \Gamma$. In addition, $M_{21} = M_{12}^*$ and $\Gamma_{21} = \Gamma_{12}^*$, such that Equation (1.48) reduces to

$$\Sigma = \begin{pmatrix} m - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & m - \frac{i}{2}\Gamma \end{pmatrix}. \quad (1.49)$$

Both M_{12} and Γ_{12} can be complex, due to the CKM structure, and can thus be written as

$$M_{12} = |M_{12}|e^{i\phi_m}, \quad (1.50)$$

$$\Gamma_{12} = |\Gamma_{12}|e^{i\phi_\Gamma}, \quad (1.51)$$

where CKM phases ϕ_m and ϕ_Γ are non-physical phases.

Defining the quantity $F = \sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)}$, the eigenvalues of Σ can be expressed as $\sigma_\pm = m - \frac{1}{2}\Gamma \pm F$. These can be interpreted as a mass and decay width for the light and heavy mass eigenstates by splitting them into real and imaginary parts:

$$m_H + \frac{i}{2}\Gamma_H = m - \text{Re}(F) - \frac{i}{2}(\Gamma - 2\text{Im}(F)), \quad (1.52)$$

$$m_L + \frac{i}{2}\Gamma_L = m + \text{Re}(F) - \frac{i}{2}(\Gamma + 2\text{Im}(F)). \quad (1.53)$$

1. Theoretical introduction

This allows to define the expressions for the mass difference Δm and decay width difference $\Delta\Gamma$ [11]:

$$\begin{aligned}\Delta m &= m_H - m_L \\ &= 2 |M_{12}| \left(1 + \frac{1}{8} \frac{|\Gamma_{12}|^2}{|M_{12}|^2} \sin^2 \phi_{12} + \dots \right) \\ &\approx 2 |M_{12}|,\end{aligned}\tag{1.54}$$

$$\begin{aligned}\Delta\Gamma &= \Gamma_L - \Gamma_H \\ &= 2 |\Gamma_{12}| \cos \phi_{12} \left(1 - \frac{1}{8} \frac{|\Gamma_{12}|^2}{|M_{12}|^2} \sin^2 \phi_{12} + \dots \right) \\ &\approx 2 |\Gamma_{12}| \cos \phi_{12},\end{aligned}\tag{1.55}$$

where ϕ_{12} is the mixing phase:

$$\phi_{12} \equiv \arg \left(-\frac{M_{12}}{\Gamma_{12}} \right) = \pi + \phi_m - \phi_\Gamma.\tag{1.56}$$

This is a physical phase, unlike ϕ_m and ϕ_Γ . The factor $\frac{1}{8} \frac{|\Gamma_{12}|^2}{|M_{12}|^2} \sin^2 \phi_{12}$ is sufficiently small (in the B_s^0 system it is of the order 6×10^{-11} [11]) with respect to the experimental precision to be safely neglected.

In addition, the variables m and Γ can now be expressed as

$$m = \frac{m_H + m_L}{2} = M_{11} = M_{12},\tag{1.57}$$

$$\Gamma = \frac{\Gamma_H + \Gamma_L}{2} = \Gamma_{11} = \Gamma_{12}.\tag{1.58}$$

Here, the mass difference between the light and heavy eigenstates is chosen such that it is positive. The width difference $\Delta\Gamma$, on the other hand, can be either positive or negative and must be determined from experiments. The Standard Model predicts positive values for $\Delta\Gamma$ in the B^0 and B_s^0 systems [9].

Using the expression for Δm , $\Delta\Gamma$, M_{12} and Γ_{12} , the ratio q/p can be expressed as

$$\frac{q}{p} = -\frac{\Delta m + i \Delta\Gamma/2}{2 M_{12} - i \Gamma_{12}} = -\frac{2 M_{12}^* - i \Gamma_{12}^*}{\Delta m + i \Delta\Gamma/2}.\tag{1.59}$$

The time-dependence of the meson oscillations can be written as

$$|B(t)\rangle = g_+(t)|B\rangle + \frac{q}{p}g_-(t)|\bar{B}\rangle, \quad (1.60)$$

$$|\bar{B}(t)\rangle = \frac{p}{q}g_-(t)|B\rangle + g_+(t)|\bar{B}\rangle, \quad (1.61)$$

where $g_{\pm}(t)$ are defined as:

$$g_+(t) = e^{-imt}e^{-\Gamma t/2} \times \left[\cosh\left(\frac{\Delta\Gamma t}{4}\right) \cos\left(\frac{\Delta m t}{2}\right) - i \sinh\left(\frac{\Delta\Gamma t}{4}\right) \sin\left(\frac{\Delta m t}{2}\right) \right], \quad (1.62)$$

$$g_-(t) = e^{-imt}e^{-\Gamma t/2} \times \left[\sinh\left(\frac{\Delta\Gamma t}{4}\right) \cos\left(\frac{\Delta m t}{2}\right) + i \cosh\left(\frac{\Delta\Gamma t}{4}\right) \sin\left(\frac{\Delta m t}{2}\right) \right]. \quad (1.63)$$

Using these expressions, the decay width of a meson in a flavour eigenstate into the same or opposite flavour eigenstate is

$$\begin{aligned} \Gamma(B(t) \rightarrow B) &= \Gamma(\bar{B}(t) \rightarrow \bar{B}) \\ &= |g_+(t)|^2 = \frac{e^{-\Gamma t}}{2} \left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \cos(\Delta m t) \right], \end{aligned} \quad (1.64)$$

$$\Gamma(B(t) \rightarrow \bar{B}) = \left|\frac{q}{p}\right|^2 |g_-(t)|^2 = \frac{e^{-\Gamma t}}{2} \left|\frac{q}{p}\right|^2 \left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta m t) \right], \quad (1.65)$$

$$\Gamma(\bar{B}(t) \rightarrow B) = \left|\frac{p}{q}\right|^2 |g_-(t)|^2 = \frac{e^{-\Gamma t}}{2} \left|\frac{p}{q}\right|^2 \left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta m t) \right]. \quad (1.66)$$

From these expressions, it becomes clear that the mass difference, Δm , between the physical eigenstates is responsible for the oscillations between mesons and antimesons. The mixing parameters for the B_s^0 and B^0 system are listed in Table 1.3. Starting from a source with only B_s^0 (or B^0) mesons, the probability of finding a B_s^0 and $\bar{B}_s^0$ (or B^0 and $\bar{B}^0$) meson after a time t is shown in Figure 1.2. It shows that the large mass difference in the B_s^0 system causes its rapid oscillations, whereas the smaller value for Δm yields slower oscillations in the B^0 system.

1. Theoretical introduction

Table 1.3: Lifetime ($\tau = 1/\Gamma$), decay width difference ($\Delta\Gamma$), mass (m), and mass difference (Δm) for the B^0 and B_s^0 meson systems. The values are the experimental averages taken from the Particle Data Group [7].

	τ [ps]	$\Delta\Gamma$ [ps^{-1}]	m [MeV]	Δm [ps^{-1}]
B_s^0	1.510 ± 0.005	0.082 ± 0.007	5366.82 ± 0.22	17.78 ± 0.02
B^0	1.520 ± 0.004	-0.002 ± 0.010	5279.62 ± 0.15	0.5096 ± 0.0034

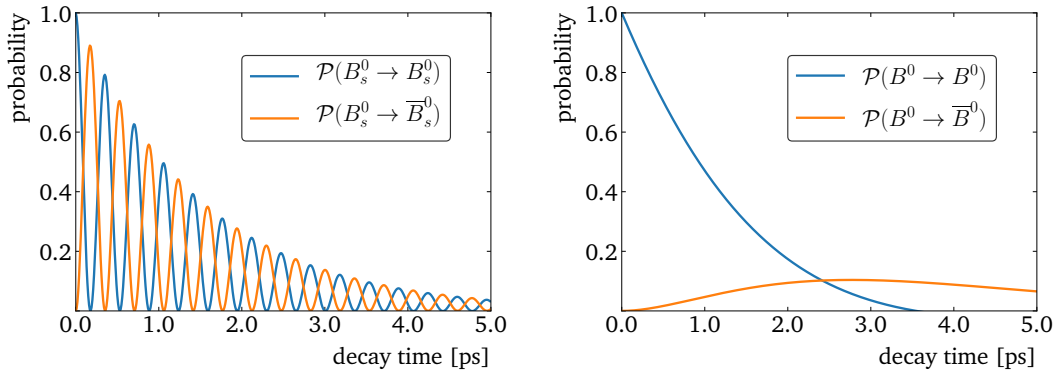


Figure 1.2: Probability of finding a B_s^0 or $\bar{B}_s^0$ meson is shown on the left, and B^0 or $\bar{B}^0$ mesons on the right, after a time t , starting from a source of only B_s^0 or B^0 mesons.

1.2.2 CP violation in meson mixing

Starting from Equations (1.65) and (1.66), the CP asymmetry, a , between a neutral antimeson mixing into a meson, and the reverse process can be defined as

$$a = \frac{\Gamma(\bar{B}(t) \rightarrow B) - \Gamma(B(t) \rightarrow \bar{B})}{\Gamma(\bar{B}(t) \rightarrow B) + \Gamma(B(t) \rightarrow \bar{B})} = \frac{1 - \left|\frac{q}{p}\right|^4}{1 + \left|\frac{q}{p}\right|^4}. \quad (1.67)$$

Assuming that the amount of CP violation is small, $\left|\frac{q}{p}\right|^2 \approx 1$, and using a Taylor expansion, this expression reduces to

$$a \approx 1 - \left|\frac{q}{p}\right|^2. \quad (1.68)$$

Hence, when $\left|\frac{q}{p}\right| = 1$, there is no CP violation in the mixing of neutral mesons.

Multiplying the two expressions for q/p in Equation (1.59), and using Equations (1.54) to (1.56), it is found that the asymmetry in terms of Γ_{12} , M_{12} and ϕ_{12} is [9]

$$a \approx \frac{|\Gamma_{12}|}{|M_{12}|} \sin \phi_{12}. \quad (1.69)$$

When performing a measurement of the asymmetry in meson mixing, the decays of the mesons into the final states f are studied. Using Equations (1.34) and (1.36), and the definitions of $|B(t)\rangle$ and $|\bar{B}(t)\rangle$ from Equations (1.60) and (1.61), the following expressions for the decay rates of neutral meson and antimesons into the final state f are found:

$$\begin{aligned} \Gamma(B(t) \rightarrow f) = \mathcal{N}_f |A_f|^2 e^{-\Gamma t} & \left\{ -\operatorname{Re}(\lambda_f) \sinh\left(\frac{\Delta\Gamma t}{2}\right) - \operatorname{Im}(\lambda_f) \sin(\Delta m t) \right. \\ & \left. + \frac{1 + |\lambda_f|^2}{2} \cosh\left(\frac{\Delta\Gamma t}{2}\right) + \frac{1 - |\lambda_f|^2}{2} \cos(\Delta m t) \right\}, \quad (1.70) \end{aligned}$$

$$\begin{aligned} \Gamma(\bar{B}(t) \rightarrow f) = \mathcal{N}_f |A_f|^2 \frac{1}{1-a} e^{-\Gamma t} & \left\{ -\operatorname{Re}(\lambda_f) \sinh\left(\frac{\Delta\Gamma t}{2}\right) + \operatorname{Im}(\lambda_f) \sin(\Delta m t) \right. \\ & \left. + \frac{1 + |\lambda_f|^2}{2} \cosh\left(\frac{\Delta\Gamma t}{2}\right) - \frac{1 - |\lambda_f|^2}{2} \cos(\Delta m t) \right\}. \quad (1.71) \end{aligned}$$

Here $\mathcal{N}_f$ is a time-independent normalisation factor, including the results of the phase-space integration. In Equation (1.71), the term $\frac{1}{1-a}$ comes in using Equations (1.36) and (1.68). Comparing these decay modes with the corresponding decays into the final state $\bar{f}$, which is the *CP* conjugate of f , the following decay rates are found:

$$\begin{aligned} \Gamma(B(t) \rightarrow \bar{f}) = \mathcal{N}_f |\bar{A}_{\bar{f}}|^2 e^{-\Gamma t} (1-a) & \left\{ -\operatorname{Re}\left(\frac{1}{\lambda_{\bar{f}}}\right) \sinh\left(\frac{\Delta\Gamma t}{2}\right) + \operatorname{Im}\left(\frac{1}{\lambda_{\bar{f}}}\right) \sin(\Delta m t) \right. \\ & \left. + \frac{1 + |\lambda_{\bar{f}}|^{-2}}{2} \cosh\left(\frac{\Delta\Gamma t}{2}\right) - \frac{1 - |\lambda_{\bar{f}}|^{-2}}{2} \cos(\Delta m t) \right\}, \quad (1.72) \end{aligned}$$

1. Theoretical introduction

$$\Gamma(\bar{B}(t) \rightarrow \bar{f}) = \mathcal{N}_f \left| \bar{A}_{\bar{f}} \right|^2 e^{-\Gamma t} \left\{ -\operatorname{Re} \left(\frac{1}{\lambda_{\bar{f}}} \right) \sinh \left(\frac{\Delta\Gamma t}{2} \right) - \operatorname{Im} \left(\frac{1}{\lambda_{\bar{f}}} \right) \sin(\Delta m t) \right. \\ \left. + \frac{1 + |\lambda_{\bar{f}}|^{-2}}{2} \cosh \left(\frac{\Delta\Gamma t}{2} \right) + \frac{1 - |\lambda_{\bar{f}}|^{-2}}{2} \cos(\Delta m t) \right\}. \quad (1.73)$$

Logically, the term a is only present in decays where mixing occurs.

In flavour-specific decays, where $B \rightarrow f$ and $\bar{B} \rightarrow \bar{f}$ are allowed, but $\bar{B} \rightarrow f$ and $B \rightarrow \bar{f}$ are not: $\bar{A}_f = A_{\bar{f}} = 0$, such that also $\lambda_f = 1/\lambda_{\bar{f}} = 0$. In addition, when studying decays without direct CP violation: $|\bar{A}_{\bar{f}}| = |A_f|$. Semileptonic decays are expected to satisfy both criteria² and are abundant. Therefore, they provide an excellent environment for studying CP violation in mixing, which is therefore often called the semileptonic CP asymmetry, a_{sl} . This asymmetry is defined as

$$a_{sl} \equiv \frac{\Gamma(\bar{B}(t) \rightarrow f) - \Gamma(B(t) \rightarrow \bar{f})}{\Gamma(\bar{B}(t) \rightarrow f) + \Gamma(B(t) \rightarrow \bar{f})} \\ = \frac{1 - (1 - a)^2}{1 + (1 - a)^2} = a + \mathcal{O}(a^2). \quad (1.74)$$

To evaluate a_{sl} using Equation (1.74), the flavour of the meson at production must be known. At LHCb, flavour-tagging algorithms have an efficiency of a few percent [13], such that a higher statistical accuracy can be achieved using a so-called “untagged” method to measure a_{sl} . The untagged decay rates can be defined as

$$\Gamma[f, t] = \Gamma(\bar{B}(t) \rightarrow f) + \Gamma(B(t) \rightarrow f), \quad (1.75)$$

$$\Gamma[\bar{f}, t] = \Gamma(\bar{B}(t) \rightarrow \bar{f}) + \Gamma(B(t) \rightarrow \bar{f}). \quad (1.76)$$

²In fact, while corrections on this assumption are extremely small in the Standard Model, this has never been tested experimentally [12].

Since a is small, $1/(1-a) \approx 1+a$, such that

$$\Gamma[f, t] = \mathcal{N}_f |A_f|^2 e^{-\Gamma t} \left\{ \frac{1}{2} \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \cos(\Delta m t) \right) + \frac{(1+a)}{2} \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta m t) \right) \right\}, \quad (1.77)$$

$$\Gamma[\bar{f}, t] = \mathcal{N}_f |\bar{A}_{\bar{f}}|^2 e^{-\Gamma t} \left\{ \frac{(1-a)}{2} \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta m t) \right) + \frac{1}{2} \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \cos(\Delta m t) \right) \right\}. \quad (1.78)$$

Hence, the asymmetry of the untagged decay rates is

$$\frac{\Gamma[f, t] - \Gamma[\bar{f}, t]}{\Gamma[f, t] + \Gamma[\bar{f}, t]} = \frac{a_{\text{sl}}}{2} - \frac{a_{\text{sl}}}{2} \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}. \quad (1.79)$$

1.2.3 Theoretical predictions for a_{sl}

In the Standard Model, the predictions of the semileptonic asymmetries in the B_s^0 system (a_{sl}^s) and the B^0 system (a_{sl}^d) are very small and precise. Reference [14] uses Heavy Quark Expansion (HQE) to calculate the SM predictions for a_{sl}^s and a_{sl}^d and finds the following values:

$$\begin{aligned} a_{\text{sl}}^s &= (2.0 \pm 0.3) \times 10^{-5}, \\ a_{\text{sl}}^d &= (-4.0 \pm 0.5) \times 10^{-4}. \end{aligned}$$

Since these values are so close to zero, the measurements of a_{sl}^s and a_{sl}^d provide a null test of the Standard Model, where a significant deviation of these predictions are a strong indication of New Physics [11]. This could for example enter through the phase ϕ_{12} . In the Standard Model [11], this phase is particularly small for the B_s^0 system:

$$\begin{aligned} \phi_{12}^s &= (0.26 \pm 0.07)^\circ, \\ \phi_{12}^d &= (-5.5 \pm 1.4)^\circ. \end{aligned}$$

1.2.4 Measurements of flavour-specific asymmetries

Measurements of the semileptonic CP asymmetries a_{sl}^s and a_{sl}^d have been performed by various experiments. This section briefly explains the different methods that are used, and concludes with an overview of these measurements in Figure 1.4. It does not include the older measurements of a_{sl}^d by the CLEO [15, 16], OPAL [17, 18], and ALEPH [19] collaborations, which have much larger uncertainties than the ones listed here.

Measurements of a_{sl}^d at B-factories

As mentioned in Section 1.2.2, there are two methods to measure semileptonic asymmetries. The first measures a tagged asymmetry. In the B -factories BaBar and Belle, time-integrated inclusive like-sign dilepton asymmetries $A_{\ell\ell}$, are measured. These are defined as

$$a_{sl} = A_{\ell\ell} = \frac{\Gamma(\ell^+\ell^+) - \Gamma(\ell^-\ell^-)}{\Gamma(\ell^+\ell^+) + \Gamma(\ell^-\ell^-)}. \quad (1.80)$$

This method relies on pair-production of b quarks, and requires both of the B mesons to decay semileptonically. For a like-sign lepton pair to occur, one of the B mesons must have mixed into its antipartner. Hence, selecting these like-sign pairs is a method of flavour tagging.

The B -factories BaBar and Belle are detectors located at the PEP-II and KEKB e^+e^- colliders respectively, running at a centre-of-mass energy of the $\Upsilon(4S)$ mass to produce $b\bar{b}$ pairs. This centre-of-mass energy is not high enough to produce B_s^0 mesons, thus only measurements of a_{sl}^d are performed. BaBar [20] and Belle [21] measure

$$\begin{aligned} a_{sl}^d &= (-0.39 \pm 0.35 \text{ (stat)} \pm 0.19 \text{ (syst)})\% \text{ by BaBar,} \\ a_{sl}^d &= (-0.11 \pm 0.79 \text{ (stat)} \pm 0.70 \text{ (syst)})\% \text{ by Belle.} \end{aligned}$$

These measurements are in agreement with the Standard Model predictions.

The BaBar experiment also measured a_{sl}^d [22] using a sample of $B^0 \rightarrow D^{*-} \ell^+ \nu X$ decays, in which the flavour of the B^0 is kaon-tagged. This kaon comes from the other B^0 in the event; a negatively charged kaon indicates a B^0 , and vice versa.

They find a value of

$$a_{\text{sl}}^d = (0.06 \pm 0.17 \text{ (stat)} \text{ }^{+0.38}_{-0.32} \text{ (syst)})\% .$$

Measurements of a_{sl} at D0

The D0 experiment also made a measurement of $A_{\ell\ell}$, but as this was at the high energy of the Tevatron proton-antiproton collider, both B^0 and B_s^0 mesons were produced. The mass resolution at D0 was not sufficient to easily be able to distinguish B^0 and B_s^0 mesons and hence their measurement is a linear combination of a_{sl}^s and a_{sl}^d , initially [23] thought to be equal to

$$a_{\text{sl}}^b = A_{\ell\ell}^{\text{D0}} = C_{\text{sl}}^s a_{\text{sl}}^s + C_{\text{sl}}^d a_{\text{sl}}^d . \quad (1.81)$$

The coefficients C_{sl}^s and C_{sl}^d are dependent on the production fractions f_s and f_d of the B_s^0 and B^0 mesons, their mixing probabilities, and the impact parameter of the muons that are studied [23], and add up to unity. In 2011, D0 published their anomalous like-sign dimuon paper, where they found a value of [23]

$$a_{\text{sl}}^b = (-0.79 \pm 0.17 \text{ (stat)} \pm 0.09 \text{ (syst)})\% .$$

In an update to this paper in 2013, they included an extra term to their expression of a_{sl}^b , which is a contribution from the average lifetime Γ_d and the lifetime difference $\Delta\Gamma_d$ [24]. Now, a_{sl}^b can be expressed as

$$a_{\text{sl}}^b = A_{\ell\ell}^{\text{D0}} = C_{\text{sl}}^s a_{\text{sl}}^s + C_{\text{sl}}^d a_{\text{sl}}^d + C_{\text{int}} \frac{\Delta\Gamma_d}{\Gamma_d} . \quad (1.82)$$

The updated measurement is still three to four standard deviations away from the SM prediction, depending on which values are used for $\Delta\Gamma_d/\Gamma_d$. When taking the SM predictions for $\Delta\Gamma_d/\Gamma_d$, the D0 dimuon measurement is three standard deviations away from the Standard Model.

Since measurements of $\Delta\Gamma_d/\Gamma_d$ are thus far not very precise, one could argue that New Physics can enter through this. Reference [25] investigates a potential source of new physics that could enhance a_{sl}^d as well as the decay width difference $\Delta\Gamma_d$. It introduces modifications of the transitions $b \rightarrow c\bar{c}d$ and $b \rightarrow d\tau^+\tau^-$, which are not well constrained by experiments and could thus explain the anomalous D0 dimuon measurement.

1. Theoretical introduction

A similar approach to introduce new physics in $b \rightarrow s\tau^+\tau^-$ transitions and thus shift the values of a_{sl}^s and $\Delta\Gamma_s$ is explored in Reference [26]. However, this is heavily constrained by LHCb's measurement of CP violation in $B_s^0 \rightarrow J/\psi \phi$ decays such that it cannot explain the D0 anomaly.

In addition to their tagged measurements, the D0 collaboration also performed untagged measurements of a_{sl}^s [27] and a_{sl}^d [28]. The a_{sl}^d measurement is performed in bins of flight distance, as a measure for the time-dependence. The a_{sl}^s measurement can be made time-integrated due to the fast B_s^0 oscillations. This assumption is explained in more detail in Section 5.1.1. These two measurements yield the following outcomes:

$$\begin{aligned} a_{\text{sl}}^s &= (-1.12 \pm 0.74 (\text{stat}) \pm 0.17 (\text{syst}))\%, \\ a_{\text{sl}}^d &= (0.68 \pm 0.45 (\text{stat}) \pm 0.14 (\text{syst}))\%, \end{aligned}$$

which are consistent with SM predictions.

Measurements of a_{sl} at LHCb

Finally, LHCb has published measurements of both a_{sl}^s and a_{sl}^d . The a_{sl}^s measurement [29] is performed on the data set collected in 2011, corresponding to an integrated luminosity of 1 fb^{-1} . The analysis is performed time-integrated and untagged. The analysis discussed in Chapter 5 is based on the same technique and supersedes the 1 fb^{-1} result. The following value was found:

$$a_{\text{sl}}^s = (-0.06 \pm 0.50 (\text{stat}) \pm 0.36 (\text{syst}))\%,$$

which is in agreement with the SM prediction for a_{sl}^s .

The measurement of a_{sl}^d is also untagged, but time-dependent. In this case, the measured asymmetry is a combination of detection asymmetries that are measured using control samples (information on detection asymmetries is given in Chapter 4), production asymmetries (described in Section 1.3) and a_{sl}^d . The detection asymmetries are constant, the production asymmetry is time-dependent, and a_{sl}^d has both a constant and time-dependent component. Therefore, a time-dependent fit is performed, the results of which are shown in Figure 1.3. The resulting value of a_{sl}^d is

$$a_{\text{sl}}^d = (-0.02 \pm 0.19 (\text{stat}) \pm 0.30 (\text{syst}))\%.$$

This is measured using the dataset corresponding to an integrated luminosity of 3 fb^{-1} and agrees with the SM prediction.

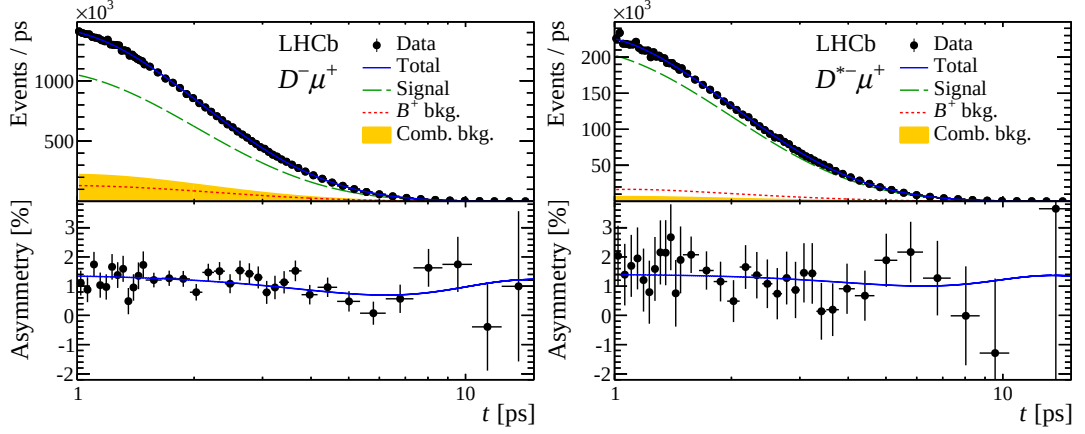


Figure 1.3: Time-dependent fits for the a_{sl}^d measurement of LHCb. The measurement is performed in two B^0 decay channels. On the left are the results from the $B^0 \rightarrow D^{*-}(\rightarrow \bar{D}^0(\rightarrow K^+\pi^-\pi^-)\mu^+\nu_\mu)X$ decay mode, and on the right from the $B^0 \rightarrow D^-(\rightarrow K^+\pi^-\pi^-)\mu^+\nu_\mu)X$ mode. These figures are taken from [29].

Overview of a_{sl} measurements

An overview of the past measurements of a_{sl}^s and a_{sl}^d is shown in Figure 1.4. This includes the measurements from the B -factories, D0 and LHCb. An average of these measurements, prior to the measurement discussed in this thesis, is provided by the Heavy Flavor Averaging Group (HFLAV) [30]. The world averages of pure a_{sl} measurements, provided by HFLAV, as of summer 2015 are

$$\begin{aligned} a_{\text{sl}}^d &= (+0.01 \pm 0.20)\%, \\ a_{\text{sl}}^s &= (-0.48 \pm 0.48)\%. \end{aligned}$$

This average does not include the anomalous D0 dimuon asymmetry measurement. Chapter 5 presents an update of the LHCb measurement of a_{sl}^s , significantly improving the precision of the a_{sl}^s average.

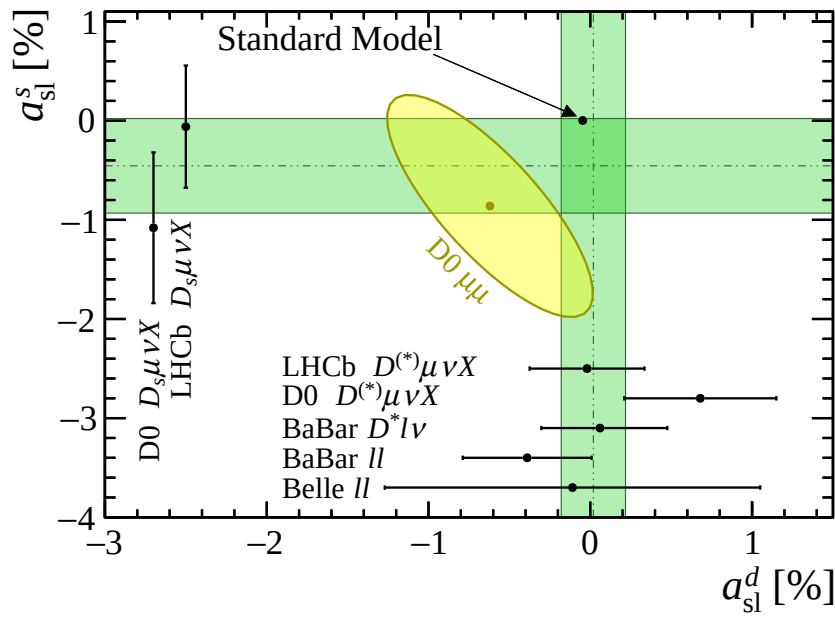


Figure 1.4: Overview of the a_{sl}^s and a_{sl}^d measurements as of Summer 2015. The yellow ellipse shows the result of the D0 dimuon measurement [31], while the points with error bars show the individual measurements of a_{sl}^s or a_{sl}^d from LHCb [29, 32], BaBar [21, 22], Belle [20], and D0 [27, 28]. The green bands are the averages of a_{sl}^s and a_{sl}^d , not including the D0 dimuon measurement.

1.3 Production asymmetries

The second physics analysis in this thesis concerns the measurement of the production asymmetry of D_s^+ mesons, which is reported in Chapter 6. This measures the difference in the cross-sections of $pp \rightarrow D_s^+$ and $pp \rightarrow D_s^-$, and is defined as

$$A_P(D_s^+) = \frac{\sigma(pp \rightarrow D_s^+) - \sigma(pp \rightarrow D_s^-)}{\sigma(pp \rightarrow D_s^+) + \sigma(pp \rightarrow D_s^-)}, \quad (1.83)$$

where $\sigma(D_s^+)$ is the inclusive prompt production cross-section of D_s^+ mesons.

Throughout this thesis, the D_s^+ production asymmetry is denoted as $A_P(D_s^+)$, as defined in Equation (1.83). This means that a surplus of c quarks compared to $\bar{c}$ quarks translates in a positive production asymmetry. The same holds for D^0 , D^+ and Λ_c^+ production asymmetries. B production asymmetries are indicated with B^- , $\bar{B}^0$, $\bar{B}^0$, and Λ_b^0 , similarly meaning that a surplus in b quarks compared to $\bar{b}$ quarks corresponds to a positive production asymmetry. Most available literature concerns D^+ and D^0 production asymmetries, which is the reason why most of this section does not discuss $A_P(D_s^+)$.

This section starts with a short description of perturbative QCD in Section 1.3.1, which does not predict any production asymmetries. Section 1.3.2 describes observations of charm production asymmetries and Sections 1.3.3 and 1.3.4 provide phenomenological models to describe these. A short summary of the centre-of-mass dependence from several models is given in Section 1.3.5. Heavy quark recombination reconciles QCD with observations of production asymmetries, which is explained in Section 1.3.6, and provides predictions of production asymmetries. The section concludes with a description of the previous $A_P(D_s^+)$ measurement in LHCb in Section 1.3.7 and B production asymmetries in LHCb in Section 1.3.8.

1.3.1 Perturbative QCD

Charm quarks are produced in pairs, through $q\bar{q} \rightarrow c\bar{c}$ and $gg \rightarrow c\bar{c}$, where the latter process is dominant at high energies, such as the LHC's. This does not introduce any asymmetry. This is explained through perturbative QCD, which has the following expression [33] at leading order in a $1/p_T$ expansion for the cross-section of $pp \rightarrow D + X$:

$$d\sigma[pp \rightarrow D + X] = \sum_{i,j} f_{i/p} \otimes f_{j/p} \otimes d\hat{\sigma}[ij \rightarrow c\bar{c} + X] \otimes D_{c \rightarrow D}. \quad (1.84)$$

1. Theoretical introduction

In this expression $f_{i/p}$ is the parton distribution function for parton i in the proton, $d\hat{\sigma}[ij \rightarrow c\bar{c}+X]$ is the partonic cross-section, and $D_{c \rightarrow D}$ the fragmentation function of a c quark into a D meson. Since charge conjugation is a good symmetry in QCD [33], $d\sigma[pp \rightarrow D+X] = d\sigma[pp \rightarrow \bar{D}+X]$, and no production asymmetry is predicted.

1.3.2 Observations of D meson production asymmetries

Although the charm quark production is symmetric, the hadronisation of these c quarks to mesons and baryons can introduce production asymmetries. The clearest case of this is in the production of D^+ mesons. Since these are partially made up from quarks that are valence quarks of protons, and the LHC collides only protons and no antiprotons, the hadronisation of D^- mesons is preferred over D^+ mesons.

The preference of a hadron to be formed with a valence quark from the hadronic beam is called the leading particle effect and has been observed by several experiments, which had pion, proton, kaon, and Σ^- baryon beams [34–39]. It explains why D^+ , D^0 and Λ_c^+ production asymmetries are expected to be larger than those from D_s^+ mesons. This effect has also been observed in charm mesons in the LHCb experiment, which measured $A_p(D^+)$ [40] using a sample of $D^+ \rightarrow K_s^0 \pi^+$ decays, and $A_p(D^0)$ [41], using samples of $D^0 \rightarrow K^+ K^-$, $D^0 \rightarrow \pi^+ \pi^-$, and $D^0 \rightarrow K^- \pi^+$ decays. The production asymmetries are measured to be

$$\begin{aligned} A_p(D^+) &= (-0.96 \pm 0.26 (\text{stat}) \pm 0.18 (\text{syst}))\%, \\ A_p(D^0) &= (-1.08 \pm 0.32 (\text{stat}) \pm 0.12 (\text{syst}))\%, \end{aligned}$$

at a centre-of-mass energy of $\sqrt{s} = 7$ TeV.

1.3.3 Beam drag model

The Lund string fragmentation model [42], implemented in PYTHIA [43, 44], describes non-perturbative hadronisation that can give rise to heavy flavour production asymmetries. In this model, heavy quarks that are produced perturbatively are colour connected to the beam remnants. This colour connection is colour neutral. This gives rise to the so-called beam drag effect: since the produced heavy quarks are connected to the beam remnant, the leading particle gains momentum by picking up some from the beam.

The beam drag gives rise to production asymmetries. Naively, this can be explained as follows. Due to the quark contents of the proton beam, c quarks prefer to form a charm baryon with the beam remnants, while $\bar{c}$ quarks have a preference for forming a charm meson. For the proton's valence quarks, these are the only possibilities to form a charm hadron. The momentum of the beam remnant contributes to the momentum of the charm mesons and baryons and thus causes a production asymmetry as a function of kinematics, because those mesons and baryons containing quarks from the beam are produced in the direction of the beam.

This is implemented in the beam drag model, as illustrated in Figure 1.5. On the left, a D^- meson is created, with a colour-connection from the $\bar{c}$ quark to the u or d quark of the beam remnant [45], to form a neutral colour connection. On the right, a D^+ meson has a colour-connection from the c to a ud or uu pair of the beam remnant. On average the ud pair has a higher momentum than the single u quark, the D^+ meson can pick up more of the beam's momentum than the D^- meson, causing an asymmetry as a function of momentum. Since the beam remnant propagates close to the beam line, at high rapidity, and small transverse momentum, the production asymmetry is also dependent on rapidity.

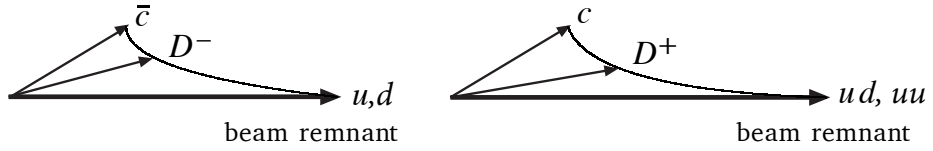


Figure 1.5: Illustration of the beam drag effect. On the left is a $\bar{c}$ quark that forms a D^- meson and has a colour connection to the beam remnant, changing its momentum. On the right a D^+ meson is formed from a c quark with a colour connection to the ud or uu diquark in the beam remnant, which has on average a larger momentum than the single u or d quark. This figure is adapted from [45].

Another mechanism to create a production asymmetry is called cluster collapse [46]. When the cluster, the colour string between the beam remnant and the heavy quark, has a small invariant mass, it can collapse and thus form a hadron with the heavy quark and one of the beam remnant valence quarks. This process is also dependent on the kinematics of the system, and the asymmetry arising from this has the opposite effect compared to the beam drag mechanism.

The combination of both mechanisms predicts production asymmetries that are dependent on rapidity and transverse momentum. These also arise in symmetric initial states where the net production asymmetry is zero. For example, in proton-

1. Theoretical introduction

antiproton collisions at the Tevatron, production asymmetries exist and are most extreme in very forward and backward regions [46].

At the LHC, the centre-of-mass energies are large, such that strings are massive and rarely collapse [46]. Any production asymmetries are created by the beam drag at high rapidities, as can be seen for B^0 production in Figure 1.6 for different p_T requirements. These predictions are dependent on different beam remnant and fragmentation models. Drag effects dominate at low transverse momentum, in the very forward region, whereas for higher transverse momentum, the cluster collapse is the dominating contribution to production asymmetries, except at very high rapidity [46].

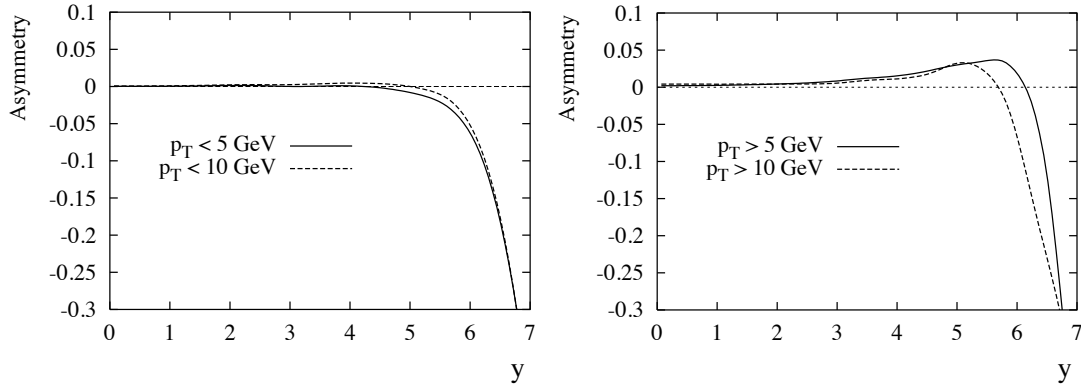


Figure 1.6: Production asymmetries for B^0 mesons from proton-proton collisions at the LHC, as predicted by beam remnant drag models implemented in PYTHIA. These figures are taken from [46]. Small differences are visible for different transverse momentum requirements applied to the B^0 meson.

1.3.4 Meson cloud model

Another approach to modelling charm production asymmetries comes from the meson cloud model (MCM) [47]. This model assumes that protons, or other beam particles, can fluctuate into a charm meson-baryon pair. To explain this, the proton can be decomposed in a series of so-called Fock states, which contains states such as $|p\rangle = |uudc\bar{c}\rangle$. In MCM, these Fock states are expressed as hadronic states, for example $|p\rangle = |\Sigma_c^{++} D^- \rangle$.

The proton can thus be described as a combination of multiple hadronic Fock states:

$$|p\rangle = Z[|p_0\rangle + \dots + |MB\rangle + \dots + |\Lambda_c^+ \bar{D}^0\rangle + |\Sigma_c^{++} D^- \rangle]. \quad (1.85)$$

In this expression, Z is a normalisation constant, and $|p_0\rangle$ is the bare proton, which is responsible for the majority of charm meson production including the perturbative QCD contribution. The production asymmetries are caused by the meson (M)-baryon (B) states. This is illustrated in Figure 1.7. It shows the scenarios in which the meson interacts with the other proton and forms a D^+ meson (left), where the baryon interacts and forms a D^+ meson (middle), and where the baryon interacts while the D^+ meson comes directly from the meson cloud (right). The first and second mechanisms are indirect D^+ production, while the latter is referred to as direct D^+ production and is most responsible for introducing asymmetries.

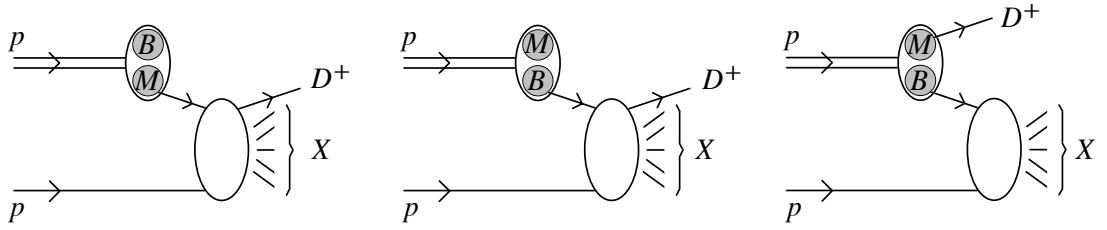


Figure 1.7: Illustration of D^+ meson production in the meson cloud model. The left and middle image show indirect D^+ production in which respectively the internal meson and baryon interact with the other proton. The right shows direct D^+ production where an internal D^+ meson escapes from the proton. The figure is adapted from [48].

1.3.5 Energy dependence

Perturbative processes are expected to grow faster with higher centre-of-mass energies than non-perturbative processes [47]. Consequently, production asymmetries decrease when collision energies increase. The meson cloud model predicts an asymmetry [49]:

$$A_p \propto \frac{\sigma_{hp}(s)}{\sigma_{c\bar{c}}(s)}, \quad (1.86)$$

where σ_{hp} is the hadron-proton cross-section, σ_{pp} at the LHC, and $\sigma_{c\bar{c}}$ the production cross-section of the $c\bar{c}$ pair. Other models predict production asymmetries to remain nearly constant with increasing energy [47]. The LHC provides an opportunity to test fragmentation models at much higher energies than before and probe the energy dependence.

1.3.6 Heavy quark recombination mechanism

While the beam drag and meson cloud models describe production asymmetries phenomenologically, it is difficult to unify them with QCD models [33]. To reconcile the observations of production asymmetry with QCD, it must be noted that Equation (1.84) has corrections that scale as powers of Λ_{QCD}/m_c and Λ_{QCD}/p_T [33]. These corrections are implemented in the heavy-quark recombination mechanism, which describes the interaction of light quarks in the proton to heavy quarks. They are probed by charm production asymmetries, which makes them interesting to study [50].

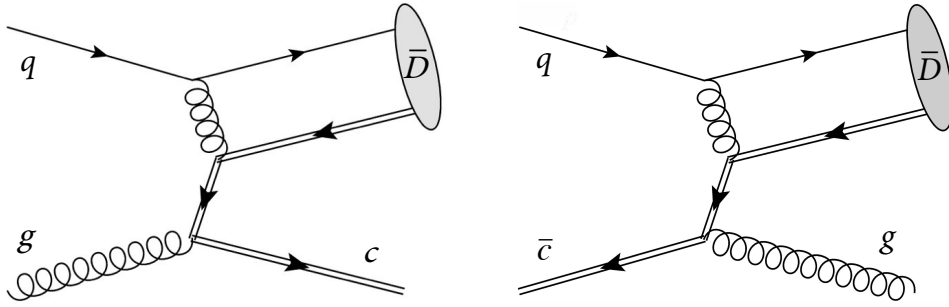


Figure 1.8: Diagrams illustrating the heavy-quark recombination mechanism for creating a $\bar{D}$ meson. The single lines represent light quarks q , while the double lines represent the heavy c quark. On the left is the diagram for $qg \rightarrow (\bar{c}q)^n + c$, on the right $q\bar{c} \rightarrow (\bar{c}q)^n + g$. This figure is adapted from [33].

The recombination mechanism gives a correction to Equation (1.84), which is given by

$$d\hat{\sigma}[\bar{D}] = d\hat{\sigma}[qg \rightarrow (\bar{c}q)^n + c]\rho[(\bar{c}q)^n \rightarrow \bar{D}]. \quad (1.87)$$

In this equation, the production of the $\bar{D}$ meson is expressed in a perturbative cross-section for a quark-gluon pair to a $\bar{c}q$ pair, where the quark q is a light quark with a momentum of Λ_{QCD} in the $\bar{c}$ rest frame. The $\bar{c}q$ pair is produced in state n , which indicates the colour and angular momentum quantum numbers. This process is illustrated in Figure 1.8 (left). The second part of Equation (1.87) is the non-perturbative factor $\rho[(\bar{c}q)^n \rightarrow \bar{D}]$ describing the probability of this $\bar{c}q$ pair to hadronise into a charm meson $\bar{D}$.

Similar expressions exist for the production of $\bar{D}$ mesons, starting from a light quark q and $\bar{c}$ quark in Equation (1.88), shown in Figure 1.8 (right), and from a light antiquark $\bar{q}$ and gluon in Equation (1.89):

$$d\hat{\sigma}[\bar{D}] = d\hat{\sigma}[q\bar{c} \rightarrow (\bar{c}q)^n + g]\rho[(\bar{c}q)^n \rightarrow \bar{D}], \quad (1.88)$$

$$d\hat{\sigma}[\bar{D}] = d\hat{\sigma}[\bar{q}g \rightarrow (c\bar{q})^n + \bar{c}]\rho[(c\bar{q})^n \rightarrow H] \otimes D_{\bar{c} \rightarrow \bar{D}}. \quad (1.89)$$

In the latter case, the c forms any hadron H , while the $\bar{c}$ fragments into a $\bar{D}$ meson. The perturbative part of Equations (1.87) to (1.89) is calculated, while the non-perturbative contributions are extracted [50, 51] from data from the E687 [52], E691 [53] and E791 [54] experiments.

The heavy-quark recombination mechanism gives descriptions of the D^+ production asymmetry [33], as a function of pseudorapidity and transverse momentum, as shown Figure 1.9. These are in good agreement with the production asymmetry measured by LHCb [40], as shown in Figure 1.9. Unfortunately, no such predictions exist for measurements of the D_s^+ production asymmetry.

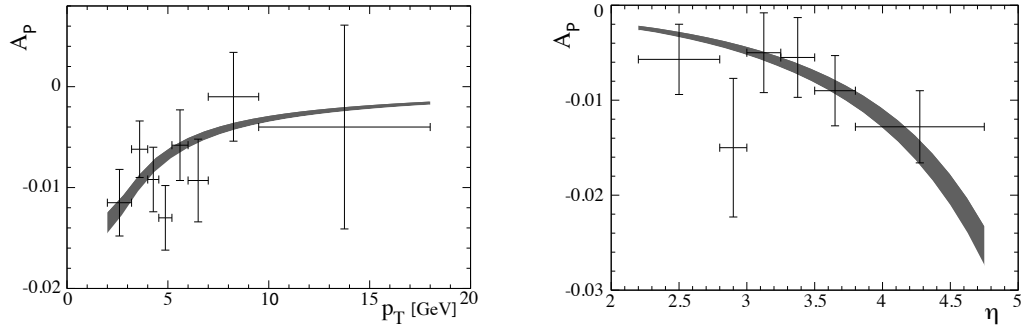


Figure 1.9: Comparison between the D^+ production asymmetry from the heavy-quark recombination mechanism and data from LHCb. On the left is A_p as a function of p_T and on the right as a function of η . This figure is adapted from [33].

1.3.7 Previous measurements of the D_s^+ production asymmetry

A measurement of $A_p(D_s^+)$ has been made by LHCb using the dataset recorded in 2011 [55]. It covers the kinematic range $2.0 < p_T < 25.0$ GeV and $2.0 < y < 4.5$. Here, y is the rapidity, which is defined as

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad (1.90)$$

throughout this thesis.

1. Theoretical introduction

A value of

$$A_P(D_s^+) = (-0.33 \pm 0.22 (\text{stat}) \pm 0.10 (\text{syst}))\%$$

was measured, where the first uncertainty is statistical and the second is systematic. This value is consistent with no production asymmetry and is performed in bins of transverse momentum, p_T , and rapidity, y . An overview of the measurement in LHCb's two magnet polarity modes, up and down, in these bins is shown in Figure 1.10. It indicates an upward trend in y and a downward one in p_T , although all values are consistent with zero.

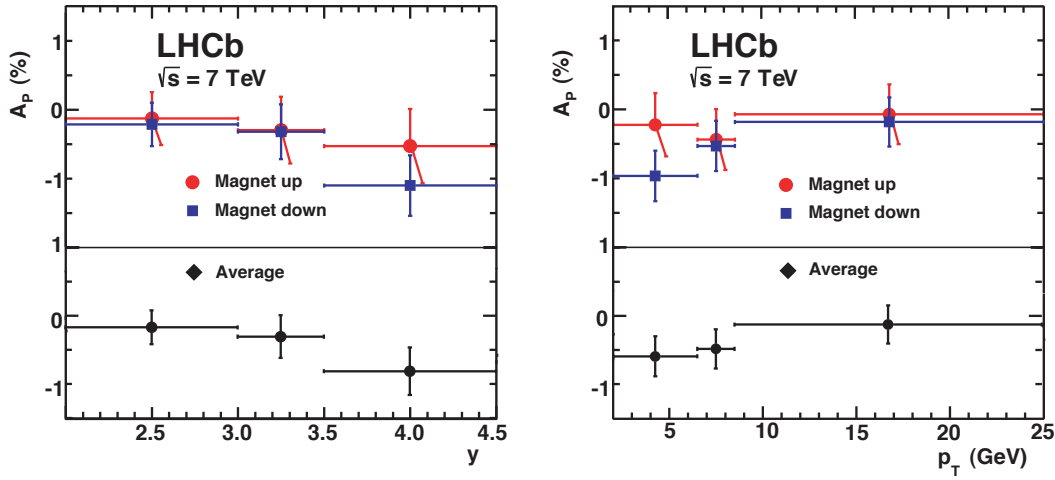


Figure 1.10: Measured values of $A_P(D_s^+)$ from the 2011 measurement in bins of p_T and y [55]. The uncertainties shown are statistical only and the red error bars are skewed to avoid overlapping with the blue ones.

The measurement of $A_P(D_s^+)$ described in this thesis aims to improve the statistical and systematic uncertainties of the previous measurement. It uses both the dataset measured in 2011 and in 2012, and measures the production asymmetry in similar bins of p_T and y . A comparison between the previous and current analysis is made in Section 6.7.7.

1.3.8 B production asymmetry measurements at LHCb

Mesons other than those containing charm can also have a production asymmetry. The same processes as described above also give rise to production asymmetries in beauty mesons and baryons. Due to the larger mass of the b quark, in the beam drag model B hadron production asymmetries are expected to be approximately two to three times smaller than D hadron production asymmetries [46].

Multiple measurements of B production asymmetries in LHCb exist, measured at centre-of-mass energies of $\sqrt{s} = 7$ and $\sqrt{s} = 8$ TeV. They are used to determine the asymmetries of the backgrounds of both measurements presented in this thesis, and are listed here in chronological order. The first measurement listed here is one of both the $\bar{B}^0$ and $\bar{B}_s^0$ production asymmetry [56], which measured

$$\begin{aligned} A_P(\bar{B}^0) &= (-0.35 \pm 0.76 (\text{stat}) \pm 0.28 (\text{syst}))\% \quad \text{at } \sqrt{s} = 7 \text{ TeV}, \\ A_P(\bar{B}_s^0) &= (1.09 \pm 2.61 (\text{stat}) \pm 0.66 (\text{syst}))\% \quad \text{at } \sqrt{s} = 7 \text{ TeV}, \end{aligned}$$

In addition, a measurement of the $\bar{B}^0$ production asymmetry [32] was performed when measuring the semileptonic asymmetry a_{sl}^d . It found values of

$$\begin{aligned} A_P(\bar{B}^0) &= (-0.66 \pm 0.26 (\text{stat}) \pm 0.22 (\text{syst}))\% \quad \text{at } \sqrt{s} = 7 \text{ TeV}, \\ A_P(\bar{B}^0) &= (-0.48 \pm 0.15 (\text{stat}) \pm 0.17 (\text{syst}))\% \quad \text{at } \sqrt{s} = 8 \text{ TeV}. \end{aligned}$$

Reference [57] measures the B^- production asymmetry, yielding

$$\begin{aligned} A_P(B^-) &= (-0.41 \pm 0.49 (\text{stat}) \pm 0.10 (\text{syst}))\% \quad \text{at } \sqrt{s} = 7 \text{ TeV}, \\ A_P(B^-) &= (-0.53 \pm 0.31 (\text{stat}) \pm 0.10 (\text{syst}))\% \quad \text{at } \sqrt{s} = 8 \text{ TeV}. \end{aligned}$$

The last paper [58] contains production asymmetry measurements of B^- , $\bar{B}^0$, and $\bar{B}_s^0$. In addition, it contains a derivation of the Λ_b^0 production asymmetry. This is not measured directly, but by using the fact that b and $\bar{b}$ quarks are predominantly pair-produced. This means that the sum of all B production asymmetries must be zero. Contributions from B_c^+ and b baryons other than Λ_b^0 can be neglected because of their small hadronisation fractions, and the following expression for the Λ_b^0 production asymmetry can be found:

$$A_P(\Lambda_b^0) \simeq - \left[\frac{f_u}{f_{\Lambda_b^0}} A_P(B^-) + \frac{f_d}{f_{\Lambda_b^0}} A_P(\bar{B}^0) + \frac{f_s}{f_{\Lambda_b^0}} A_P(\bar{B}_s^0) \right], \quad (1.91)$$

where f_u , f_d , f_s , and $f_{\Lambda_b^0}$ indicate the probability that a b quark hadronises to a B^- , $\bar{B}^0$, $\bar{B}_s^0$ meson, and Λ_b^0 baryon respectively. These are called fragmentation fractions.

1. Theoretical introduction

The following production asymmetries are reported:

$$\begin{aligned} A_P(B^-) &= (-0.23 \pm 0.24 (\text{stat}) \pm 0.37 (\text{syst}))\% \quad \text{at} \quad \sqrt{s} = 7 \text{ TeV} , \\ A_P(B^-) &= (-0.74 \pm 0.15 (\text{stat}) \pm 0.32 (\text{syst}))\% \quad \text{at} \quad \sqrt{s} = 8 \text{ TeV} , \\ A_P(\bar{B}^0) &= (0.44 \pm 0.88 (\text{stat}) \pm 0.11 (\text{syst}))\% \quad \text{at} \quad \sqrt{s} = 7 \text{ TeV} , \\ A_P(\bar{B}^0) &= (-1.40 \pm 0.55 (\text{stat}) \pm 0.10 (\text{syst}))\% \quad \text{at} \quad \sqrt{s} = 8 \text{ TeV} , \\ A_P(\bar{B}_s^0) &= (-0.65 \pm 2.88 (\text{stat}) \pm 0.59 (\text{syst}))\% \quad \text{at} \quad \sqrt{s} = 7 \text{ TeV} , \\ A_P(\bar{B}_s^0) &= (1.98 \pm 1.90 (\text{stat}) \pm 0.59 (\text{syst}))\% \quad \text{at} \quad \sqrt{s} = 8 \text{ TeV} , \\ A_P(\Lambda_b^0) &= (-0.11 \pm 2.53 (\text{stat}) \pm 1.08 (\text{syst}))\% \quad \text{at} \quad \sqrt{s} = 7 \text{ TeV} , \\ A_P(\Lambda_b^0) &= (3.44 \pm 1.61 (\text{stat}) \pm 0.76 (\text{syst}))\% \quad \text{at} \quad \sqrt{s} = 8 \text{ TeV} . \end{aligned}$$

All production asymmetry measurements in LHCb, with the exception of Reference [32], are performed in bins of the B or D meson's kinematics, in transverse momentum versus (pseudo)rapidity. None of the analyses has observed a significant kinematic dependence. However, since the uncertainties on most of the measurements are rather large compared to the value of the production asymmetries, especially when split in bins of kinematics, no firm conclusion can be made on the kinematic dependence.

2 The LHCb detector at the LHC

The LHCb detector is designed to make precision measurements of the decays of beauty and charm hadrons that are produced in proton-proton (pp) collisions at the LHC. The data analysed in this thesis were recorded in 2011 and 2012 (Run I), when the protons in the LHC were accelerated to a centre-of-mass ($\sqrt{s}$) energy of respectively 7 and 8 TeV. LHCb recorded an integrated luminosity of $\int \mathcal{L} = 1 \text{ fb}^{-1}$ in 2011 and $\int \mathcal{L} = 2 \text{ fb}^{-1}$ in 2012. In 2015, 2016, and 2017 the LHC accelerated protons to $\sqrt{s} = 13 \text{ TeV}$ and LHCb recorded $\int \mathcal{L} = 3 \text{ fb}^{-1}$ up to October 2017. This is the start of Run II, which will continue until 2018 and record a total of $\int \mathcal{L} = 5 \text{ fb}^{-1}$. This chapter gives a brief overview of the LHC in Section 2.1 and of the current LHCb detector in Section 2.2.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [59–61] is located at the Franco-Swiss border near Geneva. At the LHC, protons are accelerated to a speed close to the speed of light. These protons originate from a bottle of hydrogen. The hydrogen is stripped from electrons such that only protons are left. Before entering the LHC, they are accelerated through various accelerators; an overview of these accelerators is shown in Figure 2.1. Linac 2 is a linear accelerator, which accelerates the protons up to an energy of 50 MeV. The next step in the chain is the Proton Synchrotron Booster (PSB), which accelerates them to 1.4 GeV. After this comes the Proton Synchrotron (PS), pushing them to an energy of 25 GeV and grouping protons into bunches with 25 ns spacing. These bunches are then injected into the Super Proton Synchrotron (SPS), which has a circumference of 7 km and accelerates them to an energy of 450 GeV.

2. The LHCb detector at the LHC

Finally, the protons arrive in the LHC ring, in two beams that circulate in opposite directions and are kept on track by superconducting magnets. They are spaced into buckets and accelerated to an energy of 3.5 (4.0, 6.5) TeV through radio frequency cavities in 2011 (2012, 2015/2016). In Run I, the bunches were spaced at 50 ns, while in Run II, the spacing is at the design value of 25 ns. Steering and focusing magnets are responsible for causing bunches of protons to collide at four interaction points with energies of $\sqrt{s} = 7$ (8, 13) TeV. At one of these interaction points lies the LHCb detector.

The maximum luminosity that the LHC delivers is of the order of $5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ [62] and decreases over the time of a fill. The LHCb experiment requires a lower luminosity, to decrease the average number of visible interactions per bunch crossing (μ). Therefore, luminosity levelling is applied, which decreases the transversal beam overlap and keeps the luminosity constant¹ to a value of $3.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ in 2011 and $4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ in 2012. In Run II, the luminosity levelling was adapted to keep μ stable at 1.1.

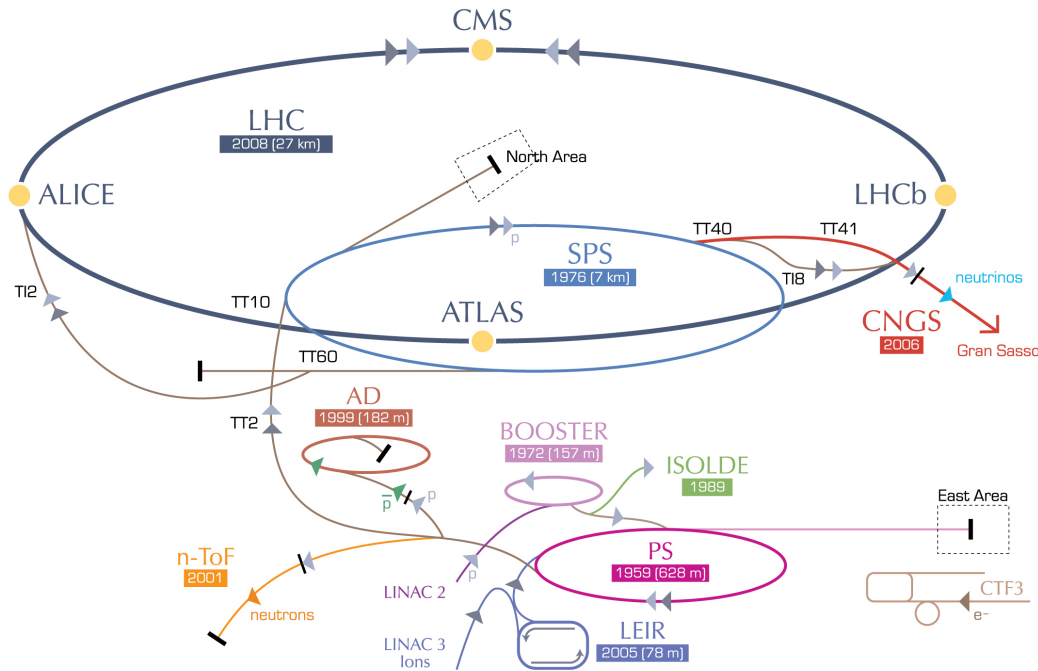


Figure 2.1: Schematic overview of the accelerator complex at CERN. This figure is reproduced from [63].

¹The instantaneous luminosity can be kept constant for up to 15 hours within a fill.

2.2 The LHCb detector

The LHC beauty (LHCb) experiment [64] is a single-arm forward spectrometer with a coverage in pseudorapidity of $2 < \eta < 5$, where η is defined as

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right], \quad (2.1)$$

and θ is the polar angle measured with respect to the beamline. LHCb is dedicated to precision measurements of beauty and charm hadron decays and aims to indirectly measure contributions of new physics in CP violation and rare decays. Beauty and charm hadrons are typically produced with a large boost in the forward and backward direction, which explains the geometry of the detector. This is because both $b\bar{b}$ and $c\bar{c}$ pairs at the LHC are produced mainly through gluon fusion where one of the gluons carries the vast majority of the energy. Unlike at the B -factories, the hadronisation of the $b\bar{b}$ and $c\bar{c}$ quark pairs happens incoherently. Hence, a $b\bar{b}$ pair can hadronise into a B^+ and $\bar{B}_s^0$ meson, for example.

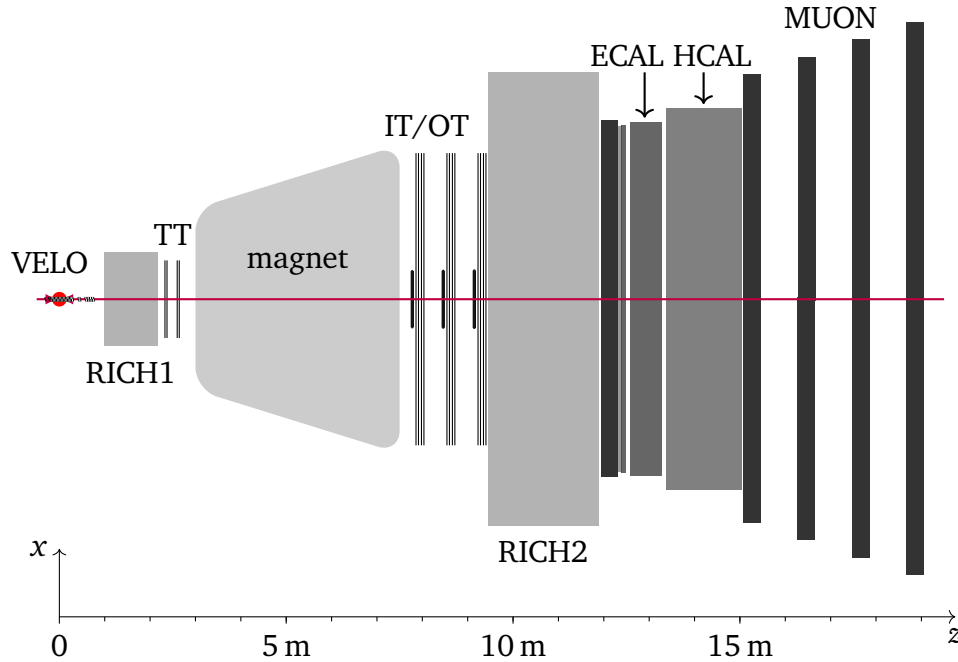


Figure 2.2: Schematic top view of the LHCb detector and its subdetectors. This figure is adapted from [65].

A schematic overview of the LHCb detector is given in Figure 2.2. The detector comprises a tracking system with a magnet in between and a particle identification system. The origin of the right-handed coordinate system in LHCb is at the interac-

2. The LHCb detector at the LHC

tion point, in the middle of the vertex locator. The region between the interaction point and the magnet is called the upstream region, while the downstream region refers to the part behind the magnet. The z -axis of the detector is parallel to the beam axis and points in the direction of the magnet, to the right side in Figure 2.2. The y -axis is vertical and points upwards, the x -axis points outside of the LHC ring.

The region where the protons collide is called the interaction region. The actual interaction point of two protons is called the primary vertex (PV) and its exact location can vary and is located using reconstructed tracks. When a B meson or another unstable particle is created in the PV, it flies a short distance before it decays at the secondary vertex (SV). This distance is the flight distance, which is also called vertex separation (VS). To determine whether a particle comes from the PV, or an SV, the impact parameter (IP), and the corresponding χ_{IP}^2 , can be studied. The IP is the smallest distance between the PV and a track. It is crucial to be able to reconstruct the tracks and their vertices with high precision in order to make the measurements performed in this thesis. The χ_{IP}^2 is the difference of the χ^2 of a vertex fit of a PV that is reconstructed with or without the track or candidate being considered.

Another variable used to study if a particle comes from the PV or not, is the direction angle (DIRA). This is the cosine of the angle between the particle's momentum, and the line between the particle's vertex and a specific point, in most cases this is the primary vertex (PV). Lastly, the distance of closest approach (DOCA) measures the minimum distance between two tracks.

2.2.1 The tracking system

The tracking system consists of the vertex locator (VELO) and the tracker turicensis (TT) in front of the dipole magnet, and three tracking stations (T1-T3) behind the magnet. The magnet has a bending power of 4 Tm and its polarity is reversible. The tracking stations behind the magnet use two different technologies: the inner tracker (IT) is located around the beampipe and is made of silicon. The outer tracker (OT) surrounds the IT and is made of gaseous straw tube detectors.

Together, the trackers can measure the displacement of secondary vertices and the momenta of particles. The tracking system provides a measurement of momentum of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV [62]. The tracking efficiency is better than 95% for tracks in the momentum region $5 \text{ GeV} < p < 200 \text{ GeV}$ [66].

Vertex locator

The VELO measures the track coordinates closest to the proton collision. The positioning of the VELO sensors at a distance of only 7 mm from the beam, with an active region at 8.2 mm from the beam, allows for precise measurements of the track coordinates near the interaction points. A VELO module consists of two types of silicon detectors, each of 300 μm thickness: an R -sensor to measure the radial coordinate, r , and Φ -sensor to measure the angular coordinate, ϕ . The sensors have a shape of half circles, with a hole in the middle to allow the beam to go through.

The VELO detector consists of two moveable halves, each with 21 modules that are arranged perpendicularly to the beam along a length of one metre. The two halves can be retracted to avoid damage while the beam is unstable. During the LHC fills, once the beams are stable, the two halves are inserted and the modules are closed to form a circle around the beam. A schematic layout of the sensors, when fully closed and when fully opened, is shown in Figure 2.3. This figure also shows the layout of the modules in the z direction.

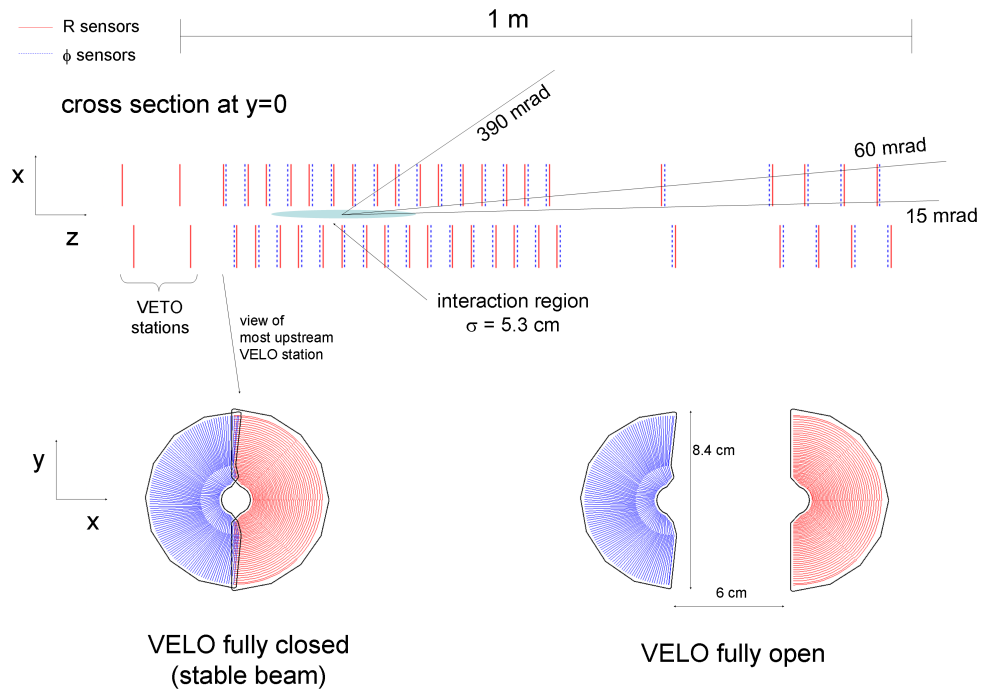


Figure 2.3: Schematic overview of the VELO detector. The top shows the lay-out of the VELO modules along the direction of the beam-axis, while the bottom shows the relative positions of the VELO sensors when the detector is fully closed, and fully opened. This image is taken from [64].

2. The LHCb detector at the LHC

The R -sensors have strips in concentric semi-circles and each of these strips is divided into four 45° regions to minimise the occupancy [64]. The pitch at the innermost radius is $40\text{ }\mu\text{m}$ and increases linearly to $101.6\text{ }\mu\text{m}$ at the outer radius of 41.9 mm . The Φ -sensors are split in an inner and outer region, at a radius of 17.25 mm . The inner region have a pitch ranging from $35.5\text{ }\mu\text{m}$ at a radius of 8.2 mm , to $78\text{ }\mu\text{m}$ at the boundary. In the outer region, the pitch ranges from $39\text{ }\mu\text{m}$ to $97\text{ }\mu\text{m}$.

The VELO is contained in a vacuum, which is surrounded by the so-called RF-foil. This foil not only protects the detector against the electromagnetic effects induced by the beam, but also suppresses the beam's wake field, and separates the VELO vacuum from the LHC vacuum.

The VELO performance is studied in Reference [67] and reports a typical decay time resolution of 50 fs . The primary vertex resolution for a vertex with 25 tracks is $13\text{ }\mu\text{m}$ in the transverse plane and $71\text{ }\mu\text{m}$ along the beam axis. Lastly, the IP resolution measured along the x - and y -axis behaves linearly in $1/p_T$. At high p_T , the IP resolution tends to $12\text{ }\mu\text{m}$, while for tracks with $p_T > 1\text{ GeV}$, the performance remains excellent with a resolution $< 35\text{ }\mu\text{m}$.

Tracker turicensis and inner tracker

The TT is located between the VELO and the magnet and is used both to improve the momentum resolution, but also to reconstruct long-lived neutral particles, such as K_s^0 and Λ^0 . Both the IT and TT are silicon trackers and consist of four layers per station of silicon strip detectors. The first and last layer are oriented vertically, while the other two layers are rotated by an angle of -5° and $+5^\circ$. There is one TT station and three IT stations. Each of the IT stations only covers a region 120 cm in width and 40 cm in height around the beam pipe.

The TT sensors are $9.64\text{ cm} \times 9.44\text{ cm}$ and have a thickness of $500\text{ }\mu\text{m}$. They have 512 strips with a pitch of $183\text{ }\mu\text{m}$. The IT sensors are $310\text{ }\mu\text{m}$ or $410\text{ }\mu\text{m}$ thick and have a size of $7.6\text{ cm} \times 11\text{ cm}$. Each of the IT sensors has 384 strips with a pitch of $198\text{ }\mu\text{m}$. The overall hit efficiency of the TT and IT is greater than 99.7% and 99.8% respectively [62], while the hit resolution of the TT is $50\text{ }\mu\text{m}$ and $60\text{ }\mu\text{m}$ for the IT.

Outer tracker

The outer tracker covers the outer region of the tracking stations T1, T2 and T3. It contains four modules and the two middle modules are rotated by an angle of -5° and $+5^\circ$ with respect to the other vertical ones. A module consists of two layers of straw tubes. These straws have a diameter of 4.9 mm, a length of 2.4 m and are filled with a mixture of Argon (70%), CO_2 (28.5%) and O_2 (1.5%). The hit resolution of the OT is measured to be $205\ \mu\text{m}$ [68].

Track types

The analyses in this thesis distinguish between the different track types that are present in LHCb. These are related to the various parts of the detector in which they are reconstructed and the design of the pattern recognition algorithms that use these, see Figure 2.4. VELO tracks are tracks that have only been detected by the VELO and are not linked to hits in the other detectors. Upstream tracks are detected both in the VELO and the TT, after which they are bent out of the experiment by the magnet. Downstream tracks are measured in both tracking stations, but not in the VELO, while T tracks are only reconstructed in the tracking stations after the magnet. Lastly, Long tracks are reconstructed in the VELO and the tracking stations after the magnet and may also have hits in the TT.

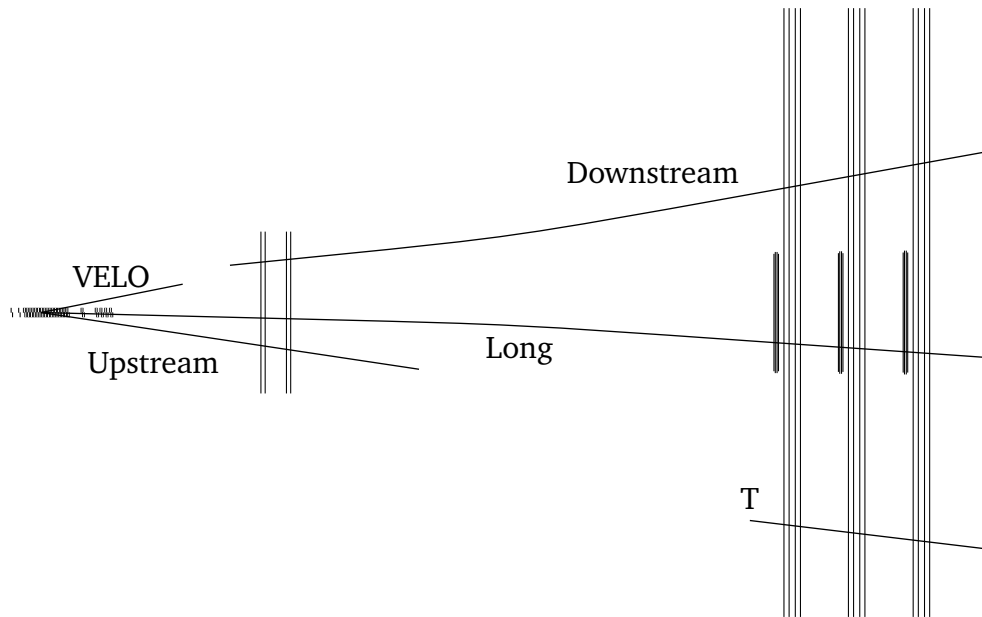


Figure 2.4: Overview of the different track types in LHCb: VELO, Long, Downstream, Upstream and T Tracks overlaid on the tracking system. This figure is reproduced from [65].

2.2.2 RICH detectors

The Ring Imaging Cherenkov (RICH) detectors are part of the particle identification system. LHCb has two RICH detectors: RICH1, which is located before the magnet, and RICH2, placed behind the magnet. The RICH detectors measure Cherenkov radiation, which is emitted in a cone by a charged particle travelling through a dielectric medium at a speed greater than the velocity of light in that medium. The angle θ_c of this cone depends on the velocity of the particle:

$$\cos \theta_c = \frac{1}{n\beta}, \quad (2.2)$$

where $\beta = v/c$, and n is the refractive index of the material.

The RICH1 detector has a C_4F_{10} radiator to measure tracks with low momenta, $1 < p < 60$ GeV and has a resolution of 1.6 mrad on θ_c [69]. The RICH2 detector operates in the high momentum range, $15 < p < 100$ GeV using a CF_4 radiator and has a resolution of 0.7 mrad. The Cherenkov light is reflected out of the acceptance using spherical and plane mirrors onto an array of Hybrid Photon Detectors (HPD).

Together with the momentum information of the tracking system, the RICH detectors enable LHCb to distinguish pions, kaons and protons. This is illustrated in Figure 2.5, where the reconstructed Cherenkov angle is shown as a function of the particle momentum. Also the different mass hypotheses are indicated and clearly distinguishable.

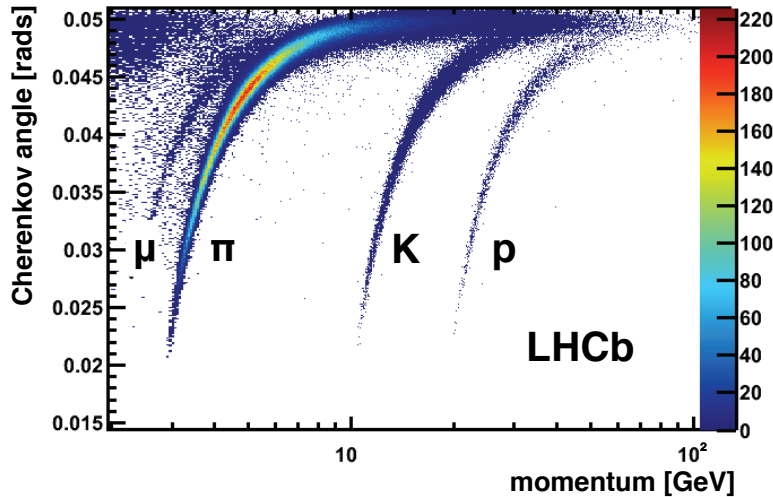


Figure 2.5: Reconstructed Cherenkov angle in the RICH1 detector as a function of the track momentum. Overlaid are the labels for the mass hypotheses of muons, pions, kaons and protons. This figure is taken from [69].

2.2.3 Calorimeters

The calorimeters in LHCb consist of three parts and serve to further identify particles, their energy, and position. Right after RICH2 is the scintillator pad detector (SPD) that discriminates between electrons ionising the scintillators, and photons which do not leave a signal. After the SPD follows the preshower (PS) that separates electrons from charged pions by making use of the different interaction lengths of pions and electrons. The electromagnetic calorimeter (ECAL) is made up of alternating layers of lead and scintillators, and measures the energy deposit of electromagnetic showers. Finally, the hadronic calorimeter (HCAL) comprises thick layers of iron and scintillators in which hadrons decay and their decay products are measured.

The calorimeters measure the transverse energy, E_T , that is deposited in 2×2 cell clusters using

$$E_T = \sum_{i=1}^4 E_i \sin \theta_i, \quad (2.3)$$

where E_i is the energy deposited in the i -th cell, and θ_i the angle of the cell with respect to the beam. The energy resolution of the calorimeters is determined as $\sigma_E/E = a/\sqrt{E} \oplus b \oplus c/E$, where E is measured in GeV, and a , b , and c represent respectively the stochastic, constant, and noise terms. The energy resolution of the ECAL is $\sigma_E/E = (8.2 \pm 0.4)\%/\sqrt{E} \oplus (0.87 \pm 0.07)\%$ for the inner modules and $\sigma_E/E = (9.4 \pm 0.2)\%/\sqrt{E} \oplus (0.83 \pm 0.02)\%$ for the outer modules [70]. For the HCAL, the energy resolution is $\sigma_E/E = (69 \pm 5)\%/\sqrt{E} \oplus (9 \pm 2)\%$ [71]. The noise term c is negligible for both calorimeters.

2.2.4 Muon detectors

The muon detector of LHCb is composed of five stations. The first of these stations is placed in front of the calorimeters and is used for high transverse momentum measurements in the trigger. The other four are placed behind the calorimeters. Between these four stations there are 80 cm thick iron walls to absorb particles other than the muons. The first muon chamber uses gas electron multipliers (GEMs) in its inner region, which are filled with a mixture of Argon (45%), CO₂ (15%), and CF₄ (40%). The outer region of M1 and the other four stations use multi-wire proportional chambers filled with a mixture of Argon (40%), CO₂ (55%), CF₄ (5%). The muon detection efficiency is well above 99% in all five stations [72].

2.2.5 Particle identification

To identify a particle, a mass is assigned to a track using the information from the RICH detectors. Initially, each of the tracks are assumed to have the mass of a pion since this is the most abundant particle observed. Then expected Cherenkov rings corresponding to the track's momenta and pion mass are projected onto the RICH detectors [73]. Per track, the likelihood of the track being a pion (L_π) is calculated by comparing the number of observed photon hits within each detector to those that are observed. Subsequently, for each track in turn, the mass hypothesis is changed to a kaon, a muon, a proton, an electron and the likelihood is calculated again.

The change in mass hypothesis that gives the largest increase in log-likelihood is determined and the new mass hypothesis of the respective track is set. For the other tracks, the mass hypotheses are then varied again and this procedure is repeated until the log-likelihood no longer increases. For each track, particle identification (PID) variables are stored. These are delta log-likelihood (DLL) variables for the kaon, muon, proton, and electron mass hypotheses, which are all calculated with respect to the pion mass hypothesis: $DLL_{K\pi}$, $DLL_{\mu\pi}$, $DLL_{p\pi}$, and $DLL_{e\pi}$. For example, $DLL_{K\pi}$ is defined as

$$DLL_{K\pi} = \ln(L_K) - \ln(L_\pi) . \quad (2.4)$$

The pion DLL value is zero by definition.

The misidentification efficiency is dependent on the momenta of the particle [69]. Figure 2.6 (left) shows the kaon identification efficiency, as well as the efficiency of pions that are misidentified as kaons. Both are shown as a function of kaon momentum. The open markers show the same variables, but after a tighter requirement on the $DLL_{K\pi}$ has been applied, which reduces the misidentification rate, but also the identification efficiency. A similar plot is shown in Figure 2.6 (right), for the proton identification efficiency and the rate of kaons misidentified as protons. All are measured from data.

Other PID variables use an artificial neural network combining tracking and PID information from the RICH detectors and the calorimeters. These networks are trained on MC samples and the outputs, which are normalised, and are called the PROBNN variables.

An extra requirement that can be applied to identify muons, is called IsMUON [74]. This variable extrapolates tracks through the muon stations and computes how many hits there are in these stations within a field of interest. De-

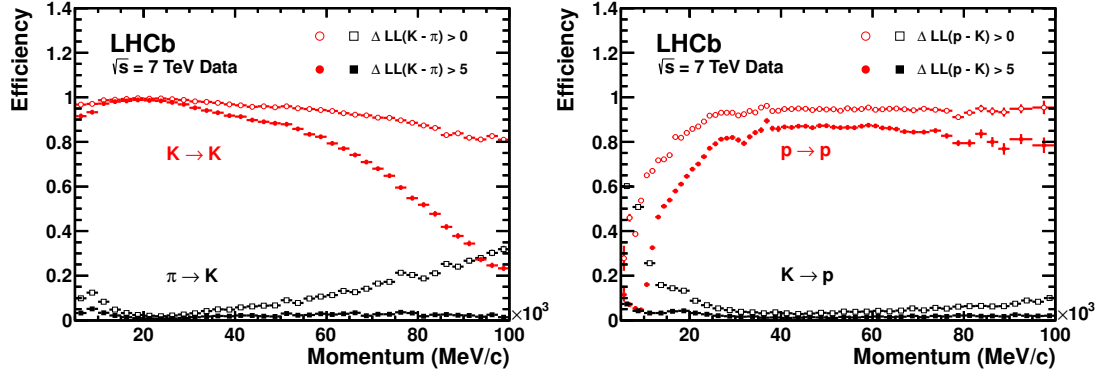


Figure 2.6: On the left: kaon identification efficiency and the rate of kaons misidentified as pions for two different requirements on $\Delta LL_{K\pi}$. On the right: proton identification efficiency and kaon misidentification rate. Both figures are taken from [69].

pending on the track momentum, a minimum number of hits is defined to pass the IsMUON requirement. The muon identification efficiency is dependent on its momentum. On average, while attaining a pion and kaon misidentification rate below 1%, the muon identification efficiency is above 98% [74].

2.2.6 The trigger system

The bunch crossing rate at LHCb in Run I was typically between 10 and 15 MHz, depending of the filling scheme of the LHC. The complete detector, however, can only be read out at a rate of 1 MHz. The LHCb trigger therefore reduces the rate and comprises three stages [75]. The first is a hardware Level-0 (L0) trigger, followed by two high-level software triggers: HLT1 and HLT2. A set of trigger requirements is combined in a trigger line. The combination of the exact selection in all trigger lines is stored in a trigger configuration key (TCK). Trigger lines do not change, although new ones can be created. The TCK, on the other hand, has changed as frequently as every couple of weeks during Run I.

The L0 trigger

The L0 trigger reduces the data rate to about 1 MHz. There are three independent L0 trigger streams: the L0-Calorimeter trigger, the L0-Muon trigger and the L0-PileUp trigger. The latter is only used for luminosity studies, and is not described in more detail here. All other L0 triggers make use of the fact that both beauty and charm mesons have a high mass and therefore decay into particles with relatively high transverse momentum and energy.

2. The LHCb detector at the LHC

The L0-muon trigger uses the information from the five muon stations (M1-M5), which are divided into quadrants. Each of these quadrants identifies the two muon tracks with highest and second-highest transverse momentum, and when these are defined, FPGAs are used to look for a straight track through the five stations that points towards the interaction point. Once such a track is found and it passes a p_T threshold, the event is triggered by the L0Muon trigger. When the product of the p_T of the tracks with the highest and second-highest p_T pass a threshold, the event is triggered by a L0DiMuon line.

The L0-calorimeter triggers use the information coming from the SPD, PS, ECAL and HCAL. Transverse energies are calculated in cell clusters as described in Section 2.2.3. From these clusters, three different candidates are built, according to the penetration power of the different particles:

- hadron (L0Hadron) candidates are built from the highest E_T HCAL cluster and combined with the highest E_T ECAL cluster if that is positioned in front of the HCAL cluster.
- photon (L0Photon) candidates are built from the highest E_T ECAL cluster, with one or two hits in the PS clusters in front, but no hits in the corresponding SPD cells.
- electron (L0Electron) candidates have the same requirements as L0Photon, but require at least one SPD cell hit in front of the PS cells.

To remove events that are too busy and thus may take too much CPU time to reconstruct, a maximum number of hits in the SPD detector of 600 is required for most trigger lines, except for the L0Dimuon line, which has a maximum of 900 SPD hits. The L0 has an output rate of approximately 1 MHz.

The HLT triggers

Unlike the L0 trigger, the High Level Triggers are software triggers, which may use information from the full detector. The HLT triggers have access to the full event information. Reconstructing full events takes too long to happen during the trigger, so they are still only partially reconstructed.

HLT1

At the beginning of an LHC fill, the mean PV position is determined. This position only changes within a few micrometers during a fill. In HLT1, all VELO tracks are reconstructed and vertices with at least five tracks, that are within 300 μm of the mean PV position, are called PVs.

For events that were triggered by the L0-muon triggers, a muon reconstruction algorithm is run. This searches for hits in M3 around tracks that are extrapolated from the VELO. If a hit is found within the search window, it is combined with the VELO track and the algorithm looks for hits in M2, M4 and M5. If at least one more hit is found, and the track is of good quality, the event is passed by `Hlt1TrackMuon`.

Events containing tracks with a high IP with respect to the PV and can be selected by, for example, `Hlt1TrackAll0`. Only VELO tracks with a good quality are selected, and those are extrapolated to the OT and IT for momentum reconstruction, which is called forward tracking. The output rate of HLT1 was 43 kHz in 2011 and 80 kHz in 2012.

HLT2

In HLT2, most of the VELO tracks with a sufficiently large p or p_T , can be extrapolated to the IT and OT. There exist 130 different HLT2 lines, which can be divided into two classes: the exclusive lines, which reconstruct all tracks in a specific final state, and inclusive lines, which trigger for example on a decay with two charged tracks and a displaced vertex (a typical B decay). The HLT2 reduced the trigger rate to 3 kHz in 2011, and 5 kHz in 2012.

The HLT2 lines can also trigger on partially reconstructed decays, which is crucial for the a_{sl}^s analysis. These lines are called the topological lines and use the corrected mass (m_{corr}) variable [76]. This is the minimum mass of the partially reconstructed particle, assuming that all its unreconstructed momentum is transverse, and is associated to a massless particle. It is defined as

$$m_{\text{corr}} = \sqrt{m_{\text{vis}}^2 + p_{\text{T,miss}}^2} + p_{\text{T,miss}} ; \quad (2.5)$$

where m_{vis} is the visible mass of the decay, and $p_{\text{T,miss}}$ the transverse momentum of the non-reconstructed tracks, in this case the neutrino. Since transverse momentum is conserved, $p_{\text{T,miss}} = p_{\text{T,vis}}$, which is illustrated in Figure 2.7.

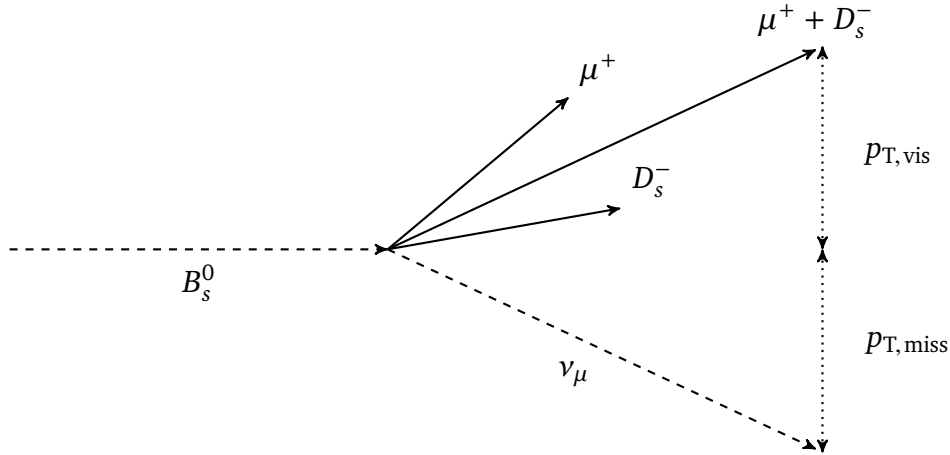


Figure 2.7: Illustration of the visible and missing transverse momenta, $p_{T,\text{vis}}$ and $p_{T,\text{miss}}$, in the decay $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu X$.

Trigger categories

Since many particles are created during a pp collision, a specific trigger line may have fired on a particle that is not part of the event selection. Therefore, various trigger categories have been defined and the analyses in this thesis use two of these:

- triggered independent of signal (TIS): either a different set of tracks, or a random combination of detector hits has fired the trigger,
- triggered on signal (TOS): the offline candidate alone was sufficient to trigger this event.

The definition of TOS depends on the trigger line. In case of a track-trigger this means that more than 70% of the hits of the trigger track are used in the offline track. For a composite particle it means that the offline reconstructed tracks contain the tracks of the trigger candidate. For example in the decay $D_s^+ \rightarrow K^+ K^- \pi^+$, the `Hlt1TrackAllL0` can be required, which reconstructs just one track and can be triggered by either three of the D_s^+ decay products. If at least one of the three kaon and pion tracks meet the trigger criteria, the D_s^+ candidate is TOS.

It should be noted that a candidate can be both TIS and TOS, which is called TISTOS. This simply means that the offline candidate meets the trigger criteria, and that the rest of the event, without the signal candidate, also meets them.

2.2.7 Offline reconstruction and software

LHCb's software is based on the GAUDI framework [77] and the HLT lines are written in the MOORE application [78]. The events that have passed the triggers are stored to disk. From there they are further reconstructed and selected. The reconstruction is CPU intensive and is performed by the Worldwide LHC Computing Grid (WLCG).

The first step in the offline computing uses the BRUNEL software [79], which reconstructs the tracks and uses the PID information to assign mass hypotheses to these tracks to create particle objects. Then the events are further analysed using the DAVINCI software [80], which can combine them into composite particles and create vertices.

Simulated events are generated by event generators, such as PYTHIA [43, 44], with an LHCb-specific tuning [81]. The decays of beauty and charm hadrons are simulated using EVTGEN [82], which also simulates mixing and interference effects. From here, events are passed on to GEANT4 [83] to simulate hadronic and electromagnetic interactions with the LHCb detector. Lastly, the detector response is simulated using BOOLE [84]. From here, the simulated events can go through the same reconstruction software as detected events.

2. The LHCb detector at the LHC

3 Adhesives for the VELO upgrade

After Run II, the LHCb detector will be upgraded [85] to allow operation at higher luminosity and to improve the trigger strategy. The detector systems need to cope with higher occupancy and a higher readout rate. When Run III starts in 2021, $\int \mathcal{L} = 5 \text{ fb}^{-1}$ will be collected per year at $\sqrt{s} = 14 \text{ TeV}$. The upgraded detector will continue to operate through Run IV and a total integrated luminosity of $\int \mathcal{L} = 50 \text{ fb}^{-1}$ is expected at the end of it. Recently, plans have been made for a further upgraded experiment [86], phase II, to collect $\int \mathcal{L} = 300 \text{ fb}^{-1}$ in Run V of the LHC. This will be complemented by consolidation of the experiment to be performed in the shutdown between Run II and III.

The VELO sensors need to be cooled and therefore attached to a cooling system. The cooling of the VELO sensors is done by conduction because the VELO is operated in a vacuum. Therefore, the adhesives with which the sensors are attached are crucial for the cooling process. To decide which adhesive fulfils best the requirements for the VELO upgrade, three were tested.

This chapter describes the major features of the LHCb upgrade in Section 3.1 and in particular of the VELO upgrade in Section 3.2. It then continues to discuss the studies that were performed to test adhesives for the VELO upgrade. The adhesives that have been tested are detailed in Section 3.4.

A shear test apparatus was designed to measure the shear stress that the attached samples can undergo before they either break or move. The apparatus and test results are described in Section 3.5. Thermal conductivity measurements were performed on the samples and are described in Section 3.6. A conclusion and outlook are given in Section 3.5.5 and Section 3.6.3.

3.1 The LHCb upgrade

After the upgrade, during the Long Shutdown 2 (LS2) which is scheduled during 2019 and 2020, the LHC will operate with a luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at a centre-of-mass energy of 14 TeV. The bunch spacing will be 25 ns and at LHCb the instantaneous luminosity will be an order of magnitude above the design luminosity of the current experiment at $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. The average number of visible pp interactions per bunch crossing, μ , increases from 1.5 in the current setup to 5.2. The entire system will be read out at a rate of 40 MHz, which corresponds to once every bunch crossing. This provides much improved flexibility in the trigger, leading to significantly higher selection efficiencies in many modes.

Many elements of the current system are limited by its readout rate of 1.1 MHz [87], hence to accomplish a readout at 40 MHz, a large part of the LHCb detector will be replaced or adapted. Moreover, the upgraded detector is designed to cope with a higher occupancy and increased radiation, since the expected integrated luminosity will be increased to 5 fb^{-1} per year. Over a period of data taking of 10 years, a total integrated luminosity of 50 fb^{-1} is expected. An overview of the upgraded detector is shown in Figure 3.1 and major changes are described in the following paragraphs. Further consolidation of the upgrade experiment during LS3 in 2024-2026 is currently being discussed, including the replacement of the inner regions of the ECAL that are expected to be radiation damaged by that time [86].

Currently, the L0 trigger uses only the muon chambers and calorimeters, and performs excellently for decays with a muon in the final state. Its performance is less effective for triggering on fully hadronic final states. Typically, the efficiency for a muonic channel is a factor of two higher than for a fully hadronic channel. Improving the trigger efficiency for hadronic decays requires the readout of the full detector at 40 MHz and the removal of the current L0 hardware trigger. The entire trigger system will be software based [89]. The selections in the trigger will be as similar as possible to those applied in offline analyses to trigger more efficiently on interesting events.

A key element of this triggering is the use of displaced vertices using the VELO. To comply with the readout at 40 MHz, all electronics and sensors of the VELO need to be replaced [90]. The current silicon strip VELO sensors will be replaced by pixel sensors and the first sensitive pixel is placed at a distance of 5.1 mm from the beam. The cooling of the sensors is provided by CO₂ microchannel cooling. The VELO upgrade is described in more detail in Section 3.2.

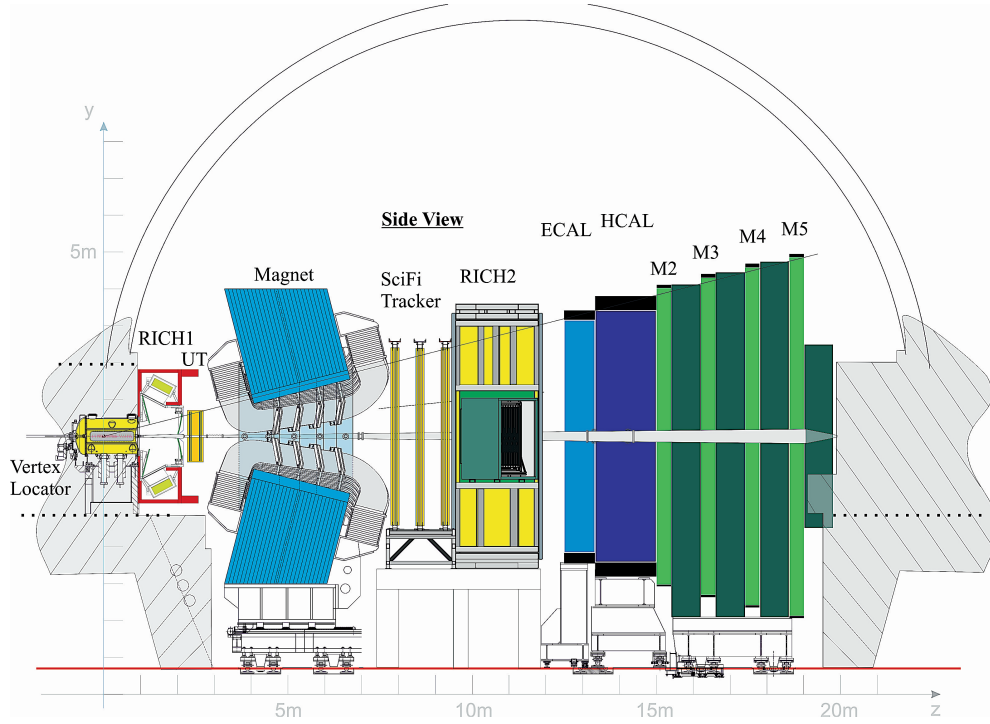


Figure 3.1: Schematic overview of the upgraded LHCb detector and its subdetectors. This figure is taken from [88].

The tracker station before the magnet (TT) will be replaced by the Upstream Tracker (UT) [88], which consists of silicon micro-strip planes. The UT will have a larger acceptance than the current TT. The T1, T2 and T3 tracking stations will be replaced by a Scintillating Fibre Tracker (SciFi), which comprises 2.5 m long fibres with silicon photo-multipliers. Rather than using different technologies for the inner and outer tracker, the SciFi exploits the same technology everywhere.

The RICH detectors in the upgrade will still have two stations. RICH1 will be largely new, and more similar to RICH2, by using the same mirror arrangement. RICH2 reuses its mechanical structure. For both RICH detectors, the photon tubes, mirrors and readout electronics will be replaced to provide the 40 MHz readout [91].

For the calorimeters, relatively little needs to change since they are already equipped to run at a high rate [91]. The major change is the replacement of the front-end and back-end electronics to comply with the 40 MHz readout to the software trigger. Moreover, the SPD and PS will be removed, as they no longer will be used in the trigger. This leads to loss of particle identification at low transverse momentum, but also improves the resolution of the ECAL and simplifies the calorimeter calibration.

3. Adhesives for the VELO upgrade

The increased particle rate coming from the increased LHC luminosity is too high for the muon station M1 [91], which is located before the calorimeters and the least shielded of the muon stations. Therefore, this station will be removed during the upgrade. In addition, extra shielding material will be installed around the beam pipe to protect M2. The readout of the muon stations at 40 MHz is already possible and only new off-detector readout electronics will be installed.

3.2 VELO upgrade

The main task of the VELO is to identify the characteristic displaced vertices from heavy-flavoured particles. The complete detector modules have to be replaced because they have integrated front-end electronics [90]. While maintaining or improving its physics performance, the VELO upgrade must be able to deal with the increased occupancy and radiation. To accomplish this, the VELO upgrade consists of hybrid pixel detectors rather than silicon strips. The layout of the pixels improve both the pattern recognition and track reconstruction speed.

The choice of pixels changes the shape of the sensors, which will no longer be circular, but rectangular. For the VELO upgrade, both the tank and retractable stand, as described in Section 2.2.1 are reused. The number of modules is increased to 26, and the layout in z is very similar to the current design. When the VELO upgrade is fully closed, there is a slight overlap between two modules and the first sensitive element is only 5.1 mm away from the beam. Figure 3.2 (left) shows the layout of the sensors when the VELO upgrade is fully closed, overlaid with the corresponding expected rate, which is clearly non-uniform. The occupancy in the VELO upgrade varies from 0.13% for the pixels closest to the beamline, to 0.01% at 20 mm from the beam.

As for the current VELO, the LHC vacuum will be separated from the VELO vacuum with the RF foil. Due to the different shapes of the upgrade sensors, this RF foil is redesigned. To keep the amount of material as small as possible, the upgrade RF foil is planned to be around 250 μm .

The upgraded VELO is expected to have an improved tracking efficiency, despite the higher track multiplicity. Not only is the efficiency higher than that of the current VELO, it is also more uniform throughout the detector. On top of that, the impact parameter resolution is expected to improve significantly, which is displayed in Figure 3.2 (right). Here the IP resolution is shown as a function of inverse transverse momentum for the current and the upgraded VELO.

An overview of the current design of an upgrade module is shown in Figure 3.3

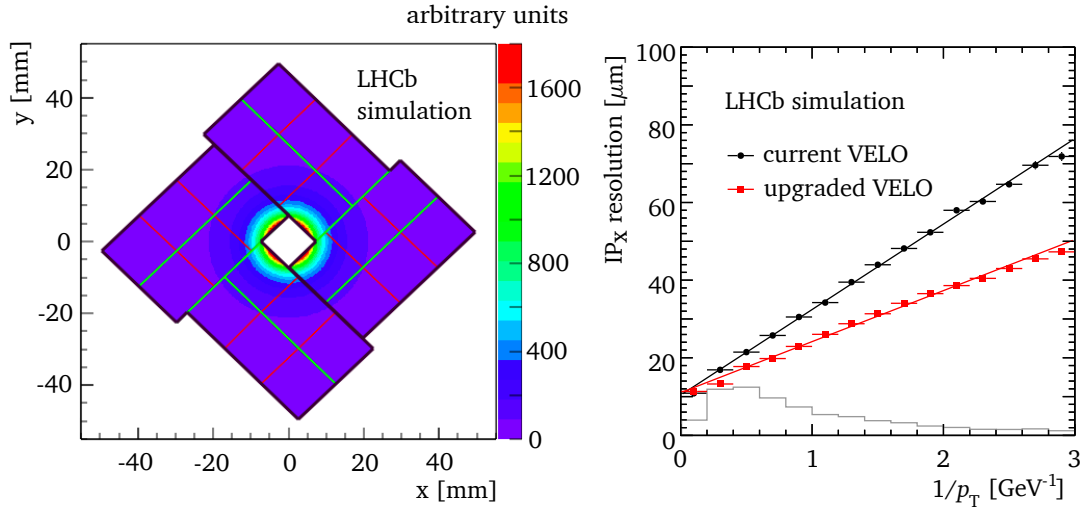


Figure 3.2: On the left: occupancy of the VELO upgrade module, in arbitrary units on a linear scale. This figure is adapted from [92]. On the right: IP resolution of the current and upgraded VELO as a function of inverse transverse momentum. The grey distribution indicates the population in the $1/p_T$ bins. The figure is adapted from [90].

and described in the coming paragraphs. Each detector module has four silicon sensors (red), two on either side. These are read out by 3×1 arrays of application-specific integrated circuits, ASICs, (orange). For the upgrade, new ASICs are developed, which are called VeloPix [93] and are based on the MediPix family of ASICs. The VeloPix ASICs each have a sensitive area of $14.08 \times 14.08 \text{ mm}^2$ and three of them together are bump-bonded onto a silicon sensor to form a tile.

The electronic support and bias voltage for the ASICs is provided by hybrids (light blue) made from copper and kapton. A GigaBit transmitter, GBTx, (orange square) receives the signal from the ASICs and serialises this for transmission through the data tapes. From there, the data travel via vacuum feedthroughs to optical and power boards, after which they are sent through optical fibres to the processing board known as TELL40. This is based on field programmable gate arrays (FPGAs), which are integrated circuits than can be programmed after they have been manufactured. The TELL40 digitises and processes the signal after which it is sent to the CPU trigger farm.

The ASICs produce heat, which can be as much as 3 W for the ASICs closest to the interaction point. In addition, the sensors and support electronics, such as the GBTx, dissipate heat. At the same time, the sensors should be operated at temperatures of -30°C to limit radiation damage. In the baseline design, the cooling of the VELO upgrade therefore must be capable of dealing with up to 40 W per module, while keeping a low material budget.

3. Adhesives for the VELO upgrade

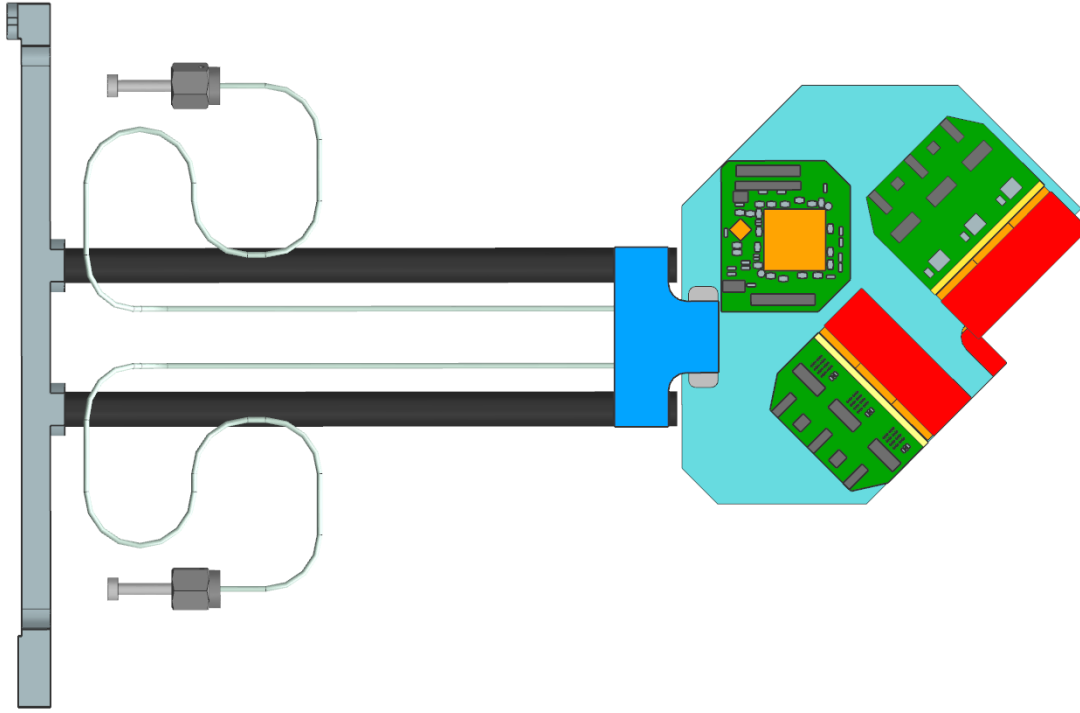


Figure 3.3: Layout of the VELO upgrade module, on the connector side. The figure shows the sensors (red), VeloPix ASICs (orange), the hybrid (light blue), microchannel substrate (blue), GBTx (orange square), cooling connector, legs (black) and module foot (grey) [94].

The cooling is provided by microchannel cooling [95], which is a novel technique of etching $120 \times 200 \mu\text{m}^2$ channels into a $400 \mu\text{m}$ thin silicon substrate (light blue). The substrate forms the backbone of the VELO modules. The channels circulate evaporative CO_2 which is provided by the current successful CO_2 cooling system. Additional advantages of the microchannel cooling are a perfect thermal expansion match with the silicon ASICs and a reduced material budget.

The CO_2 from the cooling system goes through the capillary routing shown in yellow on Figure 3.3. It is then connected with a cooling connector to the microchannels. On the left of Figure 3.3 the cooling connector is visible, since this is the connector-side (C-side). The black bars represent the carbon fibre legs that support the modules and connect them to the aluminium module feet (grey). A midplate of carbon fibre or glass (blue) links the carbon fibre tubes.

3.3 Requirements for VELO upgrade adhesives

A cross-section of the VELO upgrade module design is shown in Figure 3.4, indicating which of the components need to be glued. The requirements that must be fulfilled by the adhesive are the following. Firstly, since the VELO modules are positioned in a vacuum, the adhesives provide the only interface between the sources of heat and the cooling plates. Therefore, the adhesive must be sufficiently thermally conductive.

Secondly, the detector will operate in a radiation environment. The dose that the inner regions of the sensors will receive during their operation of ten years is $8 \times 10^{15} \text{ MeV n}_{\text{eq}}/\text{cm}^2$, where n_{eq} stands for the equivalent dose of a 1 MeV neutron. Hence, the adhesive must be radiation-hard.

Finally, the precision on the positioning of the sensor tiles is required to be better than 10 μm . This not only means that the tiles must be positioned precisely during the assembly, but also that their movement during the detector operation must be minimal. This displacement could be caused by shear stress due to gravity. For the attachment of the Kapton readout hybrid circuit, the positioning precision is relaxed.

These requirements lead to the necessity to identify adhesives with good mechanical and thermal properties for operation in vacuum, elevated radiation levels and working temperatures down to -30°C . Three adhesives were studied using tests on the shear stress and thermal conductivity, which are described in an LHCb Public Note [1], co-written by the author, and summarised in this chapter.

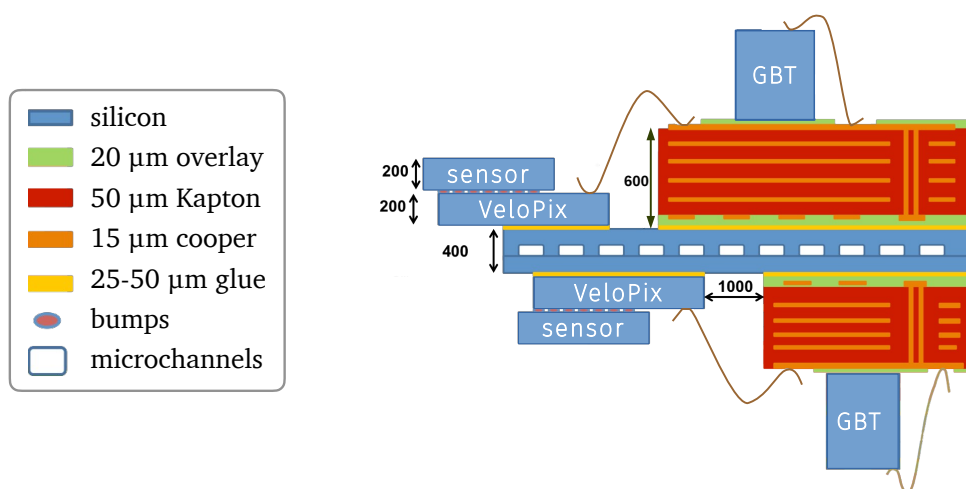


Figure 3.4: Cross-section of the VELO upgrade module design. The sensors and VeloPix ASICs will be glued to the microchannel substrate. The Kapton hybrid must also be attached to the substrate. This figure is adapted from [96].

3.4 Adhesives under study

The following adhesives have been considered for using in the VELO upgrade: Araldite 2011, Stycast 2850FT and 3M 9461P. The first two are liquid glues that can be dispensed using a glue dispenser robot, while the last is a double-sided adhesive tape. Their relevant properties, according to the manufacturers, are summarised in Table 3.1.

Liquid glues have the advantage that the positioning can be corrected before the glue cures, while this is not the case for tape. The 3M tape, on the other hand, has a thickness of 30 μm , which is thinner than the typical 60 μm thick glue layer of liquid glues.

As the sensors are operated in a vacuum, one must make sure no air bubbles are trapped in the adhesives. These would expand in the vacuum environment and could compromise the integrity of the joint. For the liquid glues, the deposition pattern needs to be optimised such that no air is trapped, but at the same time the area covered is maximised to improve the thermal performance. For the tape, the entire surface can be covered, though air bubbles may be trapped there as well. Preliminary attempts to remove air trapped in tape by placing samples under vacuum for several hours were unsuccessful.

Table 3.1: Summary of the properties of the adhesives studied relevant for their preparation and handling.

adhesive	mixing ratio	curing schedule	pot life	shelf life
Araldite 2011 [97]	100:100 by volume	10 h @ 23°C	100 mins	36 months
Stycast 2850 FT [98]	100:3.5 by mass	24 h @ 25°C	45 mins	12 months
3M 9461P 30 μm [99]	N/A	N/A	N/A	18 months

3.5 Shear test

To measure the mechanical properties of the different adhesives, a shear test setup was built. The samples were subjected to shear forces while the displacement between the two glued layers was measured with micron precision. The device used to measure the forces and displacement is described in Section 3.5.1, and the sample preparation in Section 3.5.2. Finally the results are presented in Section 3.5.4.

3.5.1 Apparatus

A specially designed shear testing apparatus was built for the tests, fitted with force and distance sensors for data recording. A schematic diagram of this device can be seen in Figure 3.5, in which the main components of the device are labelled. The diagrams show the relative positioning of the sensors, the test sample compartment and the direction in which the force is applied. The tested sample is attached to aluminium carrier plates to which shear stress is applied via the load spring. The spring module can be detached and weights can be hung over the pulley to act as a load, which is used for the calibration of the force measuring load-cell and can also be used to apply larger forces. The position of the carrier plate is measured using a Linear Variable Differential Transducer (LVDT), which is a device based on electromagnetic induction that accurately measures distances. The load cell is a mechanical to electrical transducer that is based on a strain gauge, which measures the force applied to the cell.

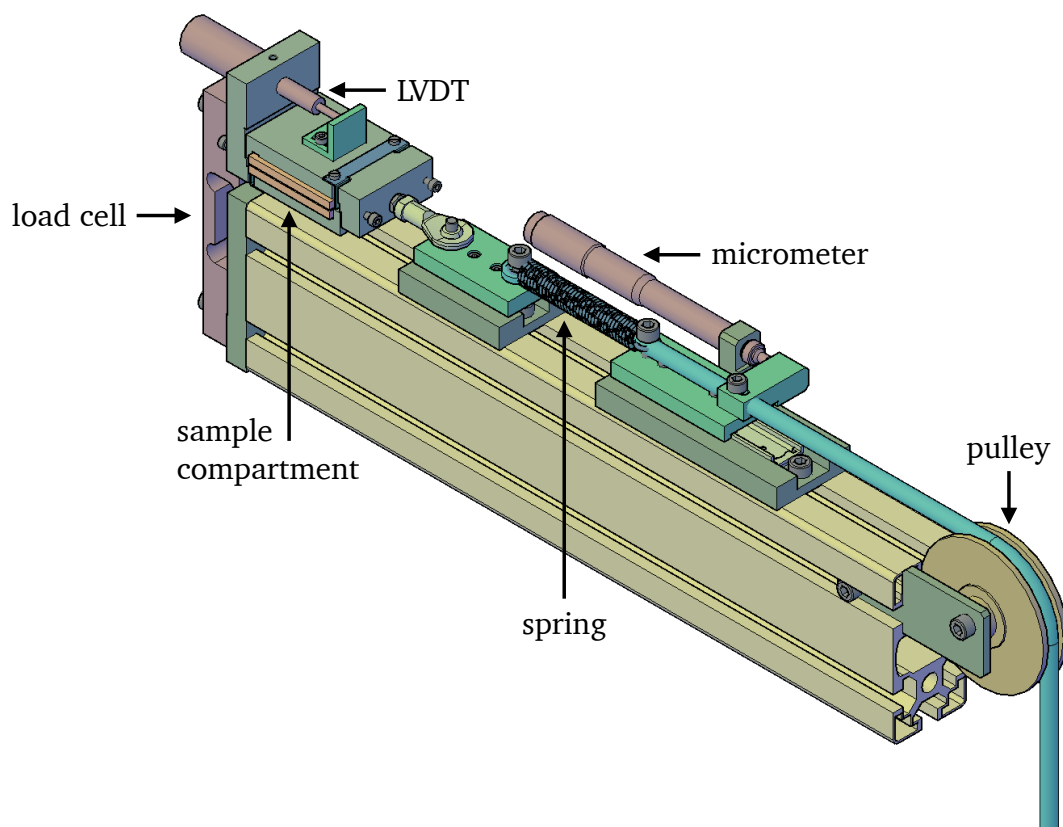


Figure 3.5: Schematic diagram of the shear testing apparatus with the main components labelled. The tested sample is attached to aluminium carrier plates to which shear stress is applied via the load spring or a weight hung over the pulley to act as a load.

3. Adhesives for the VELO upgrade

To hold the test samples in place and ensure that the shear load is applied uniformly, they are sandwiched between two larger aluminium plates before being placed in the sample compartment. The plates have the size of the compartment and allow for the secure positioning within the compartment via screws at both top and bottom plates of the compartment. The shear stress is applied to the sample by pulling tangentially on the carrier plates. The plates are positioned lying flat where the bottom one is held in place and the top one is allowed to move under the influence of an external force.

To control the extension of the spring, a micrometer is provided that can precisely push the spring. The forces applied to the test samples are exerted by either a spring of force 0.1 N or 1.0 N, or a weight of 975 g, which roughly corresponds to 10 N. In addition, the LVDT contains a spring to push its metal rod against the setup in the same direction as the shear force is applied. This was determined to be of the order of 0.5 N, such that the total forces exerted on the samples were approximately 0.5, 1.5, and 10 N.

3.5.2 Sample preparation

Ten samples made of silicon were prepared for each of the three adhesives, of which five were irradiated. All of the adhesives are expected to be radiation-hard: for the glues this was specified by their manufacturers, while the 3M tape has been tested by the NA62 experiment. To measure any effects of radiation, the samples were irradiated at the proton cyclotron at the University of Birmingham. They have been irradiated up to a fluence between 6 and $8 \times 10^{15} \text{ MeV n}_{\text{eq}}/\text{cm}^2$. This is similar to the maximum expected fluence for the VeloPix sensors: $8 \times 10^{15} \text{ MeV n}_{\text{eq}}/\text{cm}^2$ [90].

The sample sizes were chosen to be $15 \times 16 \text{ mm}^2$, which is close to the size of the VeloPix ASICs. Each of the produced samples was given a unique ID to track the details of the assembly procedure and shear tests. The non-irradiated samples were used to test the procedures and practice using the apparatus; the following results are from the irradiated samples only.

Adhesive deposition

Araldite and Stycast are epoxy-based two-component solutions. To mix them and achieve optimal bond strength, care must be taken to keep the glues free from air bubbles. Therefore, a mixing robot was used to mix these glues, which also ensures consistency in the preparation throughout the tests.

An automated glue dispenser robot was used to deposit the glue on the silicon samples. It was programmed to release glue in a rectangular pattern using a 5×5 grid of dots; an image of this pattern is shown in Figure 3.6 (left). The distance between the dispenser and the sample, as well as the time spent releasing the glue at each point, were kept constant.

During the prototyping stage of the measurement, various glue patterns were tested on glass tiles with similar thickness as the silicon tiles. This allows to study the effect of sandwiching the glue between two tiles to ensure that the pattern does not trap any air bubbles.

The 3M tape does not need any preparation before attaching the two silicon tiles. This tape never cures and for optimal performance the manufacturer recommends that it is thermally cycled before maximum adhesive strength is achieved. The manufacturer's recommendations were followed and the samples cycled four times in a climate chamber through 4 hours at 70°C , 4 hours at -29°C , and 16 hours at 25°C .

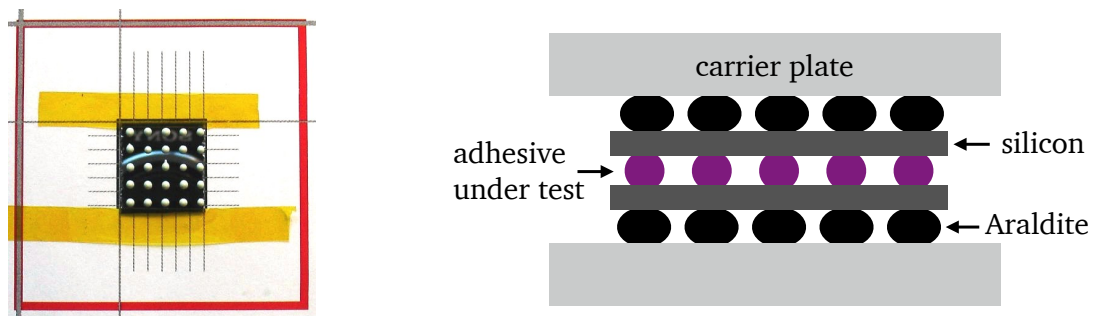


Figure 3.6: On the left: picture of a $15 \times 16 \text{ mm}^2$ silicon sample tile attached onto the glue deposition pattern. On the right: schematic overview of the attachment of the carrier plates to the silicon-glue sandwich.

Carrier plates attachment

To test samples with the shear testing apparatus, the glued sample tiles must be attached to larger aluminium carrier plates. This was done using the Araldite 2011 adhesive as it was identified as the strongest available. Glue was applied on both carrier plates using the dispenser robot and the same deposition grid as before. The only difference was a slightly larger deposition of glue, since this is only used for the shear test and does not need to mimic the eventual behaviour in a vacuum setup.

3. Adhesives for the VELO upgrade

The carrier plates are then attached to the outside of the silicon tiles, while care was taken to position the two plates perpendicular to one another. A misalignment between the carrier plates can cause a force to be exerted when positioning them in the shear test apparatus. A schematic of the attachment of silicon samples, carrier plates and glue is shown in Figure 3.6 (right).

3.5.3 Temperature correction

The temperature in the lab varies between 17.5 and 22.5°C over a period of 24 hours. This causes the aluminium carrier plates to expand a measurable amount and a correction for this is applied. The distance between the back edge of the top plate and the left-most side of the sample is approximately 4 cm and changes due to the laboratory temperature. Based on the thermal expansion coefficient of aluminium ($22.2 \times 10^{-6} \text{ m}/(\text{m}\cdot\text{K})$), an extension of the apparatus of $\sim 0.8 \text{ }\mu\text{m}/^\circ\text{C}$ is expected.

To measure the thermal coefficient of the shear test apparatus, a solid aluminium block was placed in the sample compartment. This block has the same thickness of the usual sample sandwich including the carrier plates. Data are taken over a period of two days. Before calibrating, data taken in periods where the temperature changes rapidly ($\sim 4^\circ\text{C}$ in an hour) are removed. A linear least squares fit was performed, see Figure 3.7, yielding a temperature correction of: $0.801 \pm 0.002 \text{ }\mu\text{m}/^\circ\text{C}$. This is the same as the expectation of $0.8 \text{ }\mu\text{m}/^\circ\text{C}$.

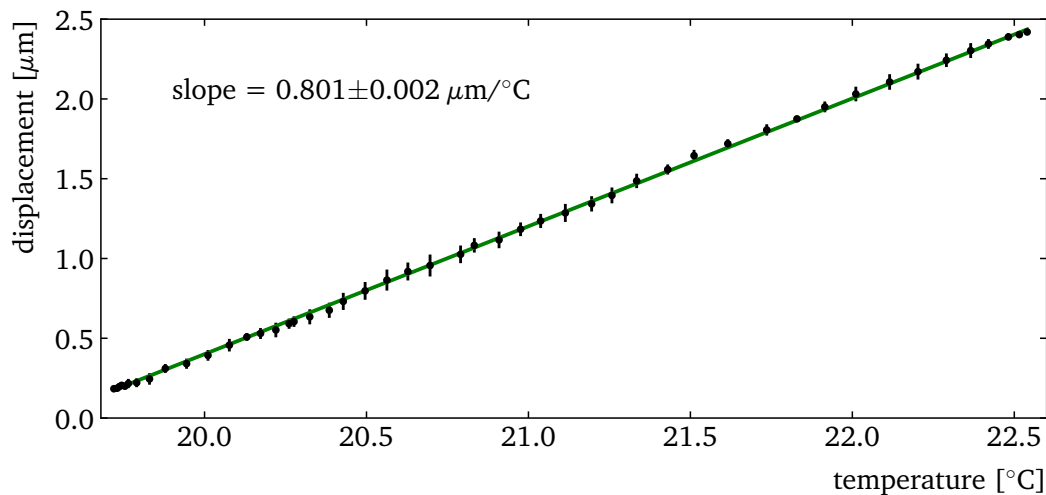


Figure 3.7: Displacement as a function of temperature using a solid aluminium block, fit by a straight line with a slope of $0.801 \text{ }\mu\text{m}/^\circ\text{C}$.

When the temperature fluctuates rapidly, the temperature correction for the displacement does not work sufficiently and leaves spikes in otherwise flat graphs. Therefore, when the temperature fluctuates by more than 0.2°C in two hours, the data is removed from this analysis. This explains the gaps in the data shown below. On one of the days, when sample S8 was tested, the temperature in the lab fluctuated rapidly, and for that day data was only removed when the temperature fluctuated more than 0.5°C in two hours.

3.5.4 Results

Of the five irradiated samples of each adhesive, three were dedicated to undergo shear tests, while the others were reserved for thermal studies. The first of the three samples was to undergo all three tests, while the other two were dedicated for either the 10 N test, or repeating others if deemed necessary. For Stycast, one additional sample was used because the previous three gave inconclusive results. The tested samples and the forces applied are listed in Table 3.2, while the outcomes of the tests are described per adhesive in the following paragraphs.

Table 3.2: Shear test samples and the forces applied during the tests.

Adhesive	Label	Force [N]
Araldite 2011	A2	10
Araldite 2011	A6	10
Araldite 2011	A10	0.5; 1.5; 10
Stycast 2850FT	S2	10
Stycast 2850FT	S4	0.5
Stycast 2850FT	S7	0.5
Stycast 2850FT	S8	10
3M 9461P	3M2	0.5; 1.5; 10
3M 9461P	3M4	0.5
3M 9461P	3M6	0.5; 1.5; 10

Araldite

The Araldite samples show little to no displacement under any weight applied. Therefore, only the 10 N tests are shown. This was expected and justifies assembling the carrier plates using Araldite. An overview of the displacement as a function of time for three samples under a shear force of 10 N is shown in Figure 3.8.

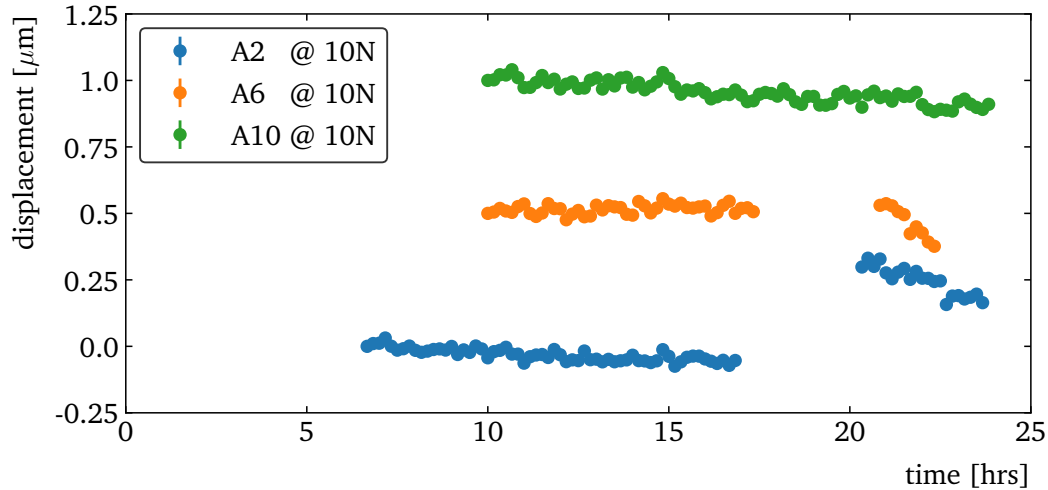


Figure 3.8: Displacement over time for the three Araldite samples tested at 10 N. The gaps occur at rapid temperature fluctuation, when the correction function did not suffice.

Stycast

The Stycast samples proved to be rather fragile. Samples S4 and S7 were tested using 0.5 N and broke. Both of them broke after ~20 hours of testing, which is shown in Figure 3.9. When Stycast samples break, usually all the glue residue is deposited on one side, while the other silicon tile is clean. The samples that broke during the shear tests seemed to break during or after a rapid change of temperature. However, there is not enough data to confirm this.

Two more Stycast samples (S2 and S8) were tested afterwards at 10 N. These samples both stayed intact and showed no displacement. A plot of the displacement versus time at 10 N is shown in Figure 3.9. The large fluctuations in sample S8 can be explained by many rapid fluctuations of 0.5°C in the temperature of the lab. The usual removal of data with large temperature fluctuations could not be applied as almost all the data would have been removed.

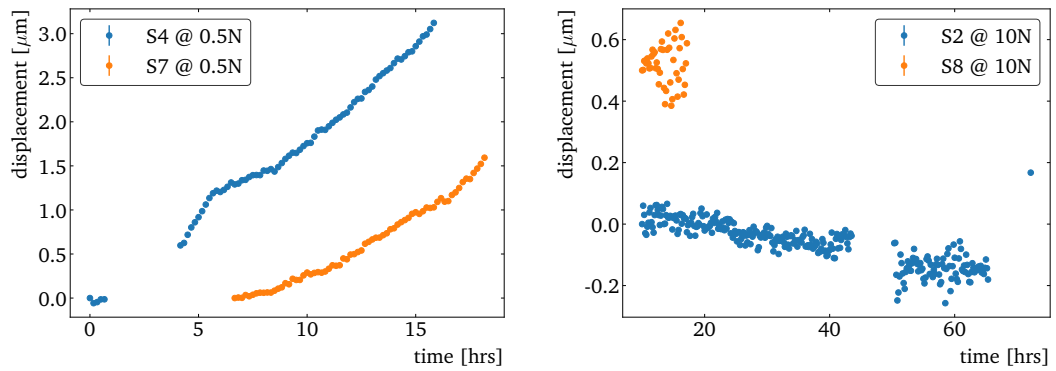


Figure 3.9: Displacement as a function of time for the Stycast samples. On the left: the samples that broke at a test of 0.5 N. On the right: the samples with a force of 10 N applied that show no displacement. The large fluctuation in sample S8 can be explained by the continuous rapid temperature change in the lab.

3M tape

One of the 3M samples (3M4) broke after removing it from the compartment holder after the 0.5 N test. The other two (3M2 and 3M6) have been tested over the full range and show minor displacement over time. Figure 3.10 shows the results for the different forces applied. As some samples showed increasing displacement over time, a longer test of 10 N over 35 days was performed using sample 3M6. The results of this are shown in Figure 3.10 and show that the sample moves during the first week, before it stabilises and remains at a constant position.

3.5.5 Conclusions

This study has evaluated the mechanical performance of three adhesives. Irradiated samples of all three adhesives, Stycast 2850FT, Araldite 2011 and 3M 9461P have shown no displacement under a shear force of 10 N, which is more than sufficient for the VELO upgrade.

During the process of conducting different steps in the study, potential factors for improvement have been identified. If Stycast is utilised, the fragility of the prototype modules should be studied in more detail. For the 3M tape, leaving the samples under vacuum for several hours did not remove the tiny air bubbles that were trapped under the tape. Hence, a different method to remove those needs to be studied if this is to be used.

3. Adhesives for the VELO upgrade

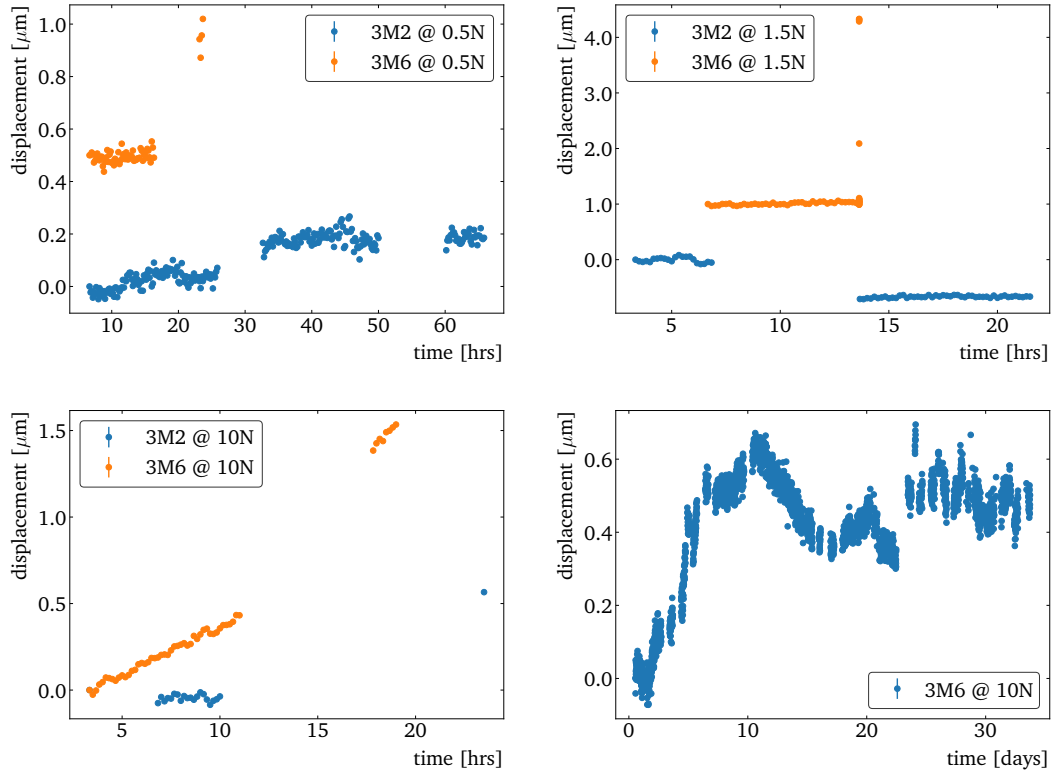


Figure 3.10: Results of the shear test for the 3M samples. On the top left: no displacement at 0.5 N. On the top right: probably no displacement at 1.5 N, as the jump for the 3M2 sample seems to be explained by an imperfect temperature correction. On the bottom left: increasing displacement for one of the samples at 10 N. On the bottom right: initial displacement, followed by stabilisation after a week for sample 3M6 tested at 10 N.

3.6 Thermal studies

Direct measurements of the thermal conductivity using an infrared camera were attempted. However, these proved to be difficult since silicon is transparent to infrared, hence the temperature measured was not that of the silicon. Covering the samples in non-reflective black paint did not solve this problem since the paint was less thermally conductive than the glues and distorted the measurement.

Therefore, to check the manufacturers specifications of the three different adhesives, their relative thermal conductivities were measured and compared to the specifications. This was done by connecting two aluminium blocks by the adhesive under test, applying a heat source on one side, and waiting until the temperature of both blocks stabilised.

Applying heat perpendicularly to the adhesive area, Fourier's law, relating heat transfer to the temperature gradient, can be used:

$$\frac{\Delta Q}{\Delta t} = -A \sigma \frac{\Delta T}{\Delta x}. \quad (3.1)$$

Here, $\Delta Q/\Delta t$ is the heat flow through a uniform material, A is the area covered by the adhesive, Δx is the adhesive's thickness, σ is the adhesive's thermal conductivity, and ΔT is the temperature difference between the two blocks.

By equalising the heat flow through the various samples, ratios of thermal conductivities can be obtained:

$$\frac{\sigma_1}{\sigma_2} = \frac{A_2}{A_1} \frac{\Delta x_1}{\Delta x_2} \frac{\Delta T_2}{\Delta T_1}. \quad (3.2)$$

This is achieved by applying the same heating source to each sample and waiting for a constant temperature difference between both blocks. Determining the thickness and area of the glue joint, and measuring the temperature difference, allows a calculation of the ratio of thermal conductivities between the glues.

3.6.1 Test setup

The test samples to perform these measurements consist of two small aluminium blocks, each of size $\sim 25 \times 9 \times 9 \text{ mm}^3$, as it is shown in Figure 3.11. The aluminium blocks are attached to one another with the adhesive under test. For the sample attached with 3M tape, a single layer ($30 \pm 5 \mu\text{m}$ thick) is placed between the blocks and pressure is applied briefly to produce a secure joint. For the Araldite and Stycast samples, two strips of Kapton are attached to opposite edges of the gluing area to act as a $60 \pm 5 \mu\text{m}$ spacer. The adhesive area is measured before the samples are assembled and left to cure.

Two PT100 temperature sensors are glued on the two free ends of the aluminium blocks to measure the temperature gradient, while a small resistive heater with a constant 0.75 W power is attached to one the aluminium blocks. The setup lies on a table while the tests are performed and is left for approximately one hour to reach a constant temperature. The temperature on either side of the aluminium blocks is shown in Figure 3.12 for all three samples; the figures indicate the temperature difference after an hour. The uncertainty on each point is the standard deviation of the readings in a minute, which were taken every second.

3. Adhesives for the VELO upgrade

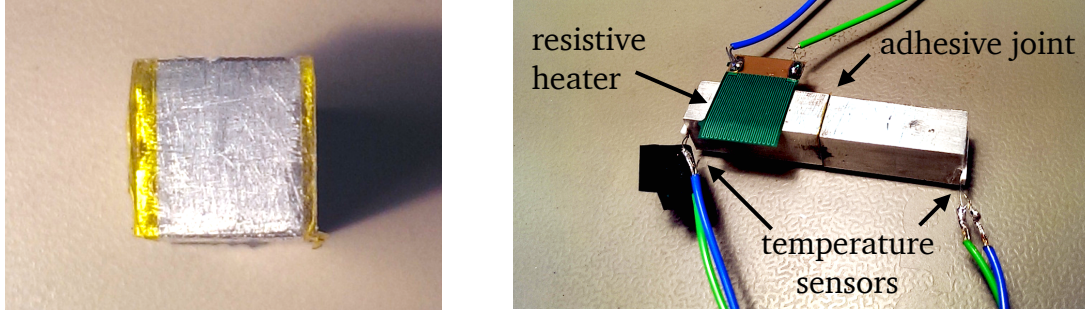


Figure 3.11: On the left: picture of the aluminium block viewed from the surface where the glue will be deposited, with two narrow Kapton strips attached on the edges of the aluminium block. On the right: picture of the two aluminium blocks glued together, with a heater attached to one block and temperature sensors glued on the side of each block.

3.6.2 Results

Since the Kapton spacer has lower thermal conductivity than the glues, a virtual area A' is calculated as follows:

$$A' = A_{\text{Kapton}} \times \frac{\sigma_{\text{Kapton}}}{\sigma_{\text{glue}}}. \quad (3.3)$$

This area corresponds to the area covered by the adhesive under study that would have the same conductivity as the area of Kapton has. A' , is added to the area that is covered by the glue, A_{adh} , to be the effective area A_{eff} , defined as

$$A_{\text{eff}} = A_{\text{adh}} + A'. \quad (3.4)$$

For the purposes of this correction, the thermal conductivities (σ) of Araldite, Stycast and Kapton are taken from the manufacturers' data sheets [97, 98, 100]. Consequently, if the final results of the study are not in agreement with these values, an additional correction would be required.

A summary of the relative thermal conductivities and the comparisons with manufacturer specifications can be seen in Table 3.3. This table shows the fraction of the area covered by glue ($A_{\text{adh}}/A_{3\text{M}}$), the manufacturers thermal conductivity (σ_{spec}), the effective areas for the glues ($A_{\text{eff}}/A_{3\text{M}}$), adhesive thickness (Δx), temperature difference after an hour (ΔT), the relative measured thermal conductivity ($\sigma/\sigma_{3\text{M}}$) and the relative thermal conductivities as specified by the manufacturer ($(\sigma/\sigma_{3\text{M}})_{\text{spec}}$). All results have been calculated relative to the 3M samples, which thus has a ratio of 1.00.

Table 3.3: Summary of the thermal conductivity of the three glues, as specified by their manufacturers, and the outcome of the measured relative thermal conductivities.

Adhesive	$A_{\text{adh}}/A_{3\text{M}}$	σ_{spec} [W/m·K]	$A_{\text{eff}}/A_{3\text{M}}$	Δx [μm]	ΔT [$^{\circ}\text{C}$]	$\sigma/\sigma_{3\text{M}}$	$(\sigma/\sigma_{3\text{M}})_{\text{spec}}$
3M	1.00 ± 0.02	0.18 [99]	1.00 ± 0.02	30 ± 5	1.70 ± 0.06	1.00 ± 0.24	1.00
Stycast	0.76 ± 0.02	1.12 [98]	0.79 ± 0.02	60 ± 5	0.85 ± 0.07	5.09 ± 1.07	6.22
Araldite	0.80 ± 0.02	0.22 [97]	0.91 ± 0.02	60 ± 5	2.09 ± 0.10	1.79 ± 0.35	1.22
Kapton	–	0.12 [100]	–	60 ± 5	–	–	–

The results in Table 3.3 confirm that Stycast is the best thermal conductor of the three adhesives, and its relative conductivity to 3M is in line with the suggested values from the manufacturer. Moreover, Araldite appears to be a substantially better thermal conductor than the 3M tape, and possibly better than the manufacturer claimed. Finally, the results are close enough in agreement to justify the corrections that are made using the manufacturers specifications.

3.6.3 Conclusion

The thermal conductivities of the three adhesives are compatible with the specifications of their manufacturers. Stycast is approximately five times more conductive as the 3M tape, and Araldite is approximately twice as conductive as the 3M tape. The area that can be covered by the adhesives will be largest using the 3M tape, since that can cover the full area of the sensors. The areas of the glues can be studied only after the design of the glue pattern has been finalised and optimised such that no air bubbles will be trapped by the glue. It is estimated that the glues will cover approximately half the area of the 3M tape. This means that Stycast is still the most conductive of the three, while Araldite and 3M tape become comparable, if they have the same thickness.

In combination with the outcome of the shear studies in Section 3.5.5, the following is concluded. To exploit the thermal conductivity of Stycast, and the robustness of Araldite, it is proposed to utilise Stycast with drops of Araldite in the corners.

3. Adhesives for the VELO upgrade

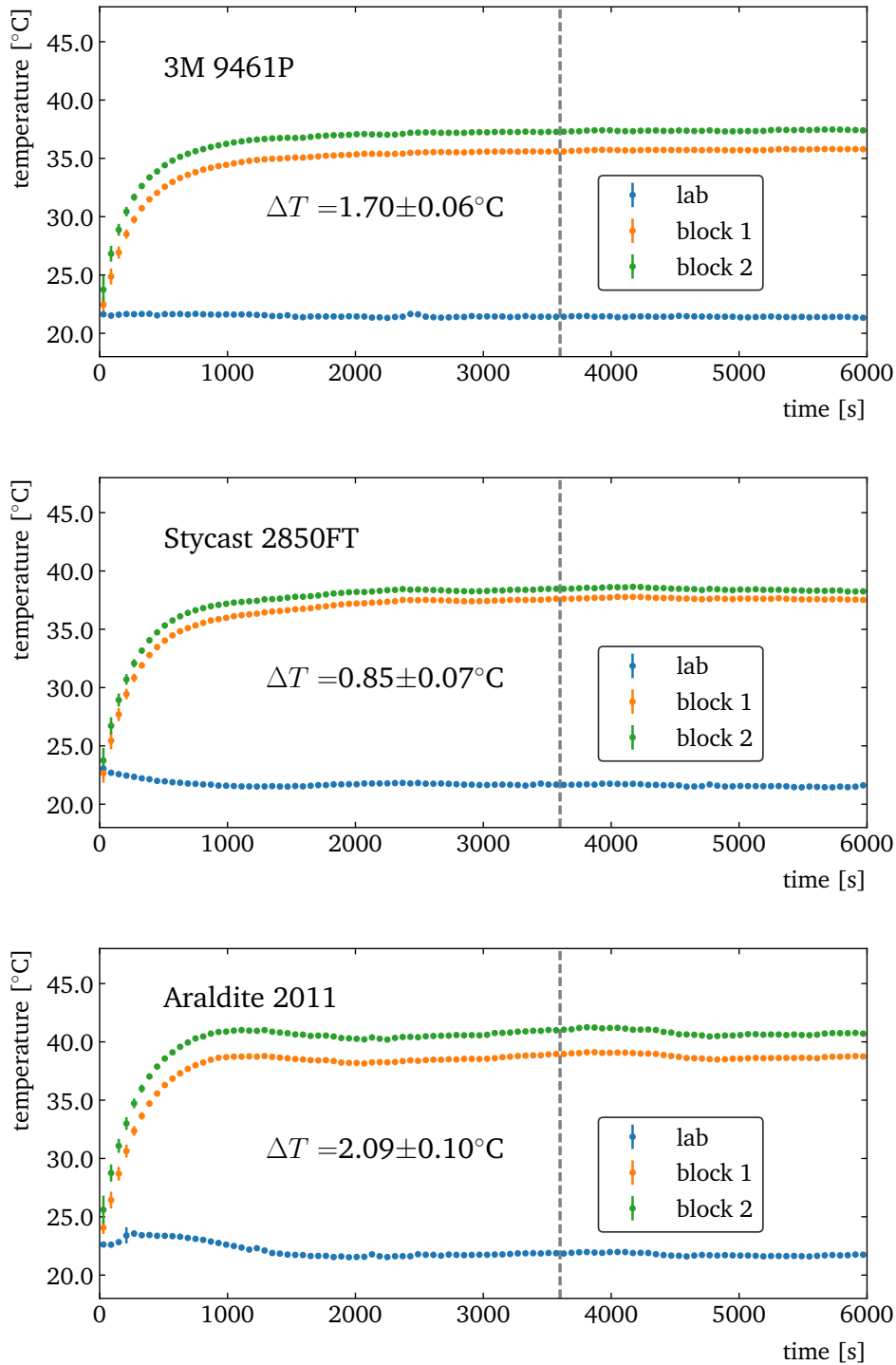


Figure 3.12: Temperature as a function of time of the three different adhesive samples. Lab is the temperature of the air in the lab; block 1 denotes the temperature of the block without the heater, and block 2 the temperature of the block with the heater attached. The temperature difference is measured after an hour, when the setup reached a stable temperature, indicated by the grey line.

4 Detection asymmetries

The main challenge for both analyses in this thesis is to determine the detection asymmetries. These arise from a difference in reconstruction of matter and antimatter particles, which here is usually a difference between positively and negatively charged particles, $h^\pm$. The efficiency to reconstruct a particle can depend on its kinematics and is defined as

$$\varepsilon(h^\pm, \vec{p}) = \frac{N_{\text{reco}}(h^\pm, \vec{p})}{N_{\text{total}}(h^\pm, \vec{p})}, \quad (4.1)$$

where, $N_{\text{reco}}(h^\pm, \vec{p})$ is the number of reconstructed particles, while $N_{\text{total}}(h^\pm, \vec{p})$ is the total number of particles. This total number can be the number of created particles, or reconstructible particles, depending on the efficiency to be determined.

Similar to the efficiencies, the detection asymmetries, $a_D(\vec{p})$, can be dependent on kinematics and originate from different sources. The detection asymmetry is defined as

$$a_D(\vec{p}) = \frac{\varepsilon(h^+, \vec{p}) - \varepsilon(h^-, \vec{p})}{\varepsilon(h^+, \vec{p}) + \varepsilon(h^-, \vec{p})}, \quad (4.2)$$

while the asymmetry integrated over kinematics is denoted as A_D :

$$A_D = \frac{\varepsilon(h^+) - \varepsilon(h^-)}{\varepsilon(h^+) + \varepsilon(h^-)}. \quad (4.3)$$

The uncertainties on the detection asymmetries $\delta(A_D)$ are determined as

$$\delta(A_D) = 2\sqrt{\frac{\varepsilon^2(h^+)\delta^2(\varepsilon(h^-)) + \varepsilon^2(h^-)\delta^2(\varepsilon(h^+))}{(\varepsilon(h^+) + \varepsilon(h^-))^4}}, \quad (4.4)$$

which is obtained from uncertainty propagation, where $\delta(\varepsilon(h^\pm))$ is the uncertainty on $\varepsilon(h^\pm)$.

4. Detection asymmetries

Several processes contribute to detection asymmetries. One source of detection asymmetry is the difference between the nuclear interactions of particles and antiparticles with the detector. The COMPAS group [7] compiled data and a fit for the cross-sections of positively and negatively charged kaons on fixed proton or deuterium targets, which is shown in Figure 4.1 (left). For positively and negatively charged pions, the difference is negligible for momenta higher than 2 GeV, as can be seen in Figure 4.1 (right).

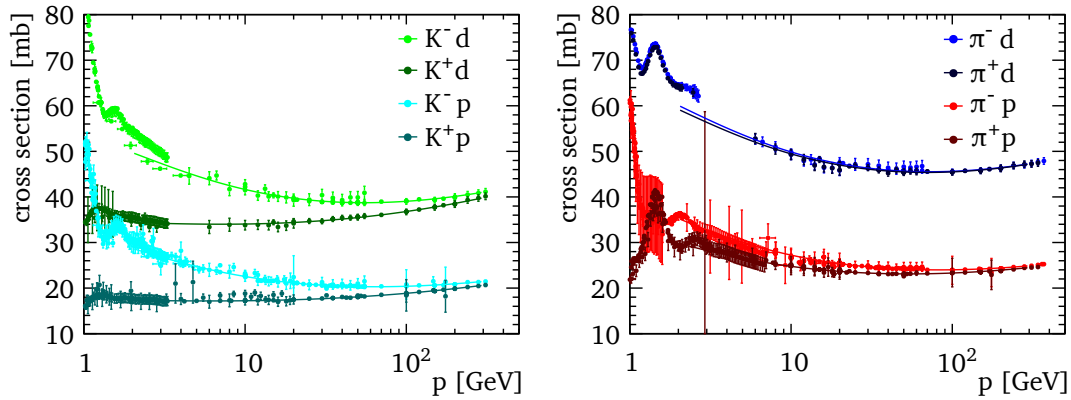


Figure 4.1: Kaon (left) and pion (right) cross-sections on deuterium and proton targets, measured as a function of momentum. This figure is taken from [101].

These asymmetries can qualitatively be explained by the presence of valence u and d quarks in protons and deuterons, which can interact strongly with $\bar{u}$ and $\bar{d}$ quarks in pions and kaons. A K^- meson contains an $\bar{u}$ quark, whereas a K^+ does not, hence this results in a larger cross-section for the K^- meson than for the K^+ meson. For pions, the difference is more subtle, since they contain a $\bar{u}$ and d or vice versa. Therefore, only a small difference is visible for protons, which have more u than d valence quarks, so they interact more with the π^- than the π^+ meson. Finally, deuterium has an equal number of u and d quarks, such that no interaction asymmetry for charged pions is visible in this figure.

A second origin of detection asymmetries comes from the fact that the LHCb detector is not perfectly left-right symmetric. This can be due to variations in detector efficiency between the left and right sides of the detector or misalignments, but also is partially inherent in the design due, for example, to cabling that is present only on one side of the detector.

The combination of these effects leads to detection asymmetries in the trigger, both on the hardware and software level, in track reconstruction, in particle identification, and in material interaction. The latter is the combination of nuclear

interaction asymmetries and asymmetries in the amount of material that particles encounter while traversing the LHCb detector.

Multiple detection asymmetries can be combined into a total detection asymmetry by taking the product of the efficiencies, or, by adding up the asymmetries. The latter is equivalent to the former for small asymmetries, which is shown as follows. Two detection asymmetries, A_{D1} and A_{D2} , have corresponding reconstruction efficiencies $\varepsilon_1(h^\pm)$ and $\varepsilon_2(h^\pm)$. Combining the two into a single detection asymmetry A_D is done using

$$\begin{aligned}
A_D &= \frac{\varepsilon_1(h^+)\varepsilon_2(h^+) - \varepsilon_1(h^-)\varepsilon_2(h^-)}{\varepsilon_1(h^+)\varepsilon_2(h^+) + \varepsilon_1(h^-)\varepsilon_2(h^-)} \\
&= \frac{\bar{\varepsilon}_1(1 + A_{D1})\bar{\varepsilon}_2(1 + A_{D2}) - \bar{\varepsilon}_1(1 - A_{D1})\bar{\varepsilon}_2(1 - A_{D2})}{\bar{\varepsilon}_1(1 + A_{D1})\bar{\varepsilon}_2(1 + A_{D2}) + \bar{\varepsilon}_1(1 - A_{D1})\bar{\varepsilon}_2(1 - A_{D2})} \\
&= \frac{A_{D1} + A_{D2}}{1 + A_{D1}A_{D2}} \\
&\approx A_{D1} + A_{D2} + \mathcal{O}(A_D^3).
\end{aligned} \tag{4.5}$$

Here, it is used that $\varepsilon(h^\pm) = \bar{\varepsilon}(1 \pm A)$, where $\bar{\varepsilon}$ is the mean efficiency. For the asymmetries considered in this thesis, $A_D \sim 10^{-2}$, and $\mathcal{O}(A_D^3)$ is negligible compared to the precision of the measurements of a_{sl}^s and $A_p(D_s^+)$.

Possible variations of the detector performance on either the left or right side of the detector introduce left-right asymmetries. This could cause either positively or negatively charged particles to be detected less efficiently. This effect is cancelled to first order in LHCb by using data samples taken with both magnet polarities, thus reversing the direction in which positively and negatively charged are deflected [102]. The magnet polarity is reversed every few weeks, to ensure that any gradual drifts in performance with time are also largely cancelled. In 2011 and 2012 the magnet polarity was reversed approximately twice per month, as is illustrated in Figure 4.2.

4. Detection asymmetries

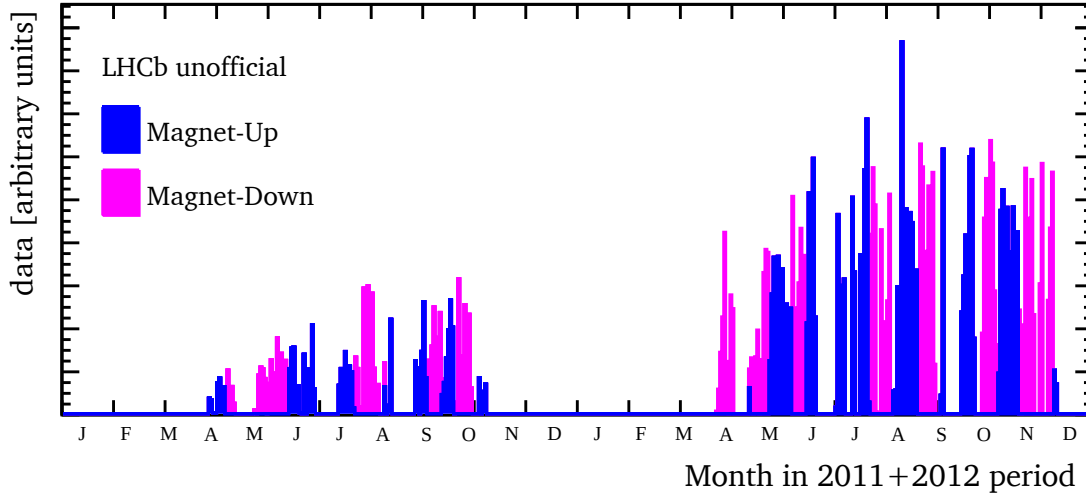


Figure 4.2: Distribution of the amount of data recorded per magnet polarity in 2011 and 2012. This figure is taken from [102].

Reversing the magnet polarity cancels detection asymmetries only if data is recorded for both polarities under the same detector and operating conditions. While this is aimed for, residual biases may remain. To make measurements with a precision of $O(10^{-3})$, these must be measured using data-driven methods. This cannot be done using simulations, which are not precise enough to capture the exact data-taking conditions which are necessary to measure the detection asymmetries to the required precision.

Several techniques are used to determine detection asymmetries for the a_{sl}^s and $A_{\text{P}}(D_s^+)$ measurements. The following sections discuss all methods that are used and the type of detection asymmetries that can be measured. Section 4.1 describes some techniques common to multiple methods: making charge-neutral pairs of tracks, using event reweighting to equalise kinematic distributions, and assigning signal weights.

The most common method for determining detection asymmetries is the tag-and-probe method which is explained in Section 4.2. This is used to quantify tracking, trigger, and particle identification asymmetries. Tracking asymmetries can also be measured using partially reconstructed charm decays, which is described in Section 4.3. A comparison of these methods is made in Section 4.4. Lastly, by taking the ratios of two decays, combined tracking and particle identification asymmetries are measured, which is explained in Section 4.5.

4.1 Common techniques for detection asymmetries

This section lists several techniques that are used for almost all detection asymmetry measurements. To avoid repetition, they are explained here.

4.1.1 Charge-neutral pairs

A useful technique for different types of detection asymmetries is to group particles with opposite charge and similar kinematics into a charge-neutral pair to cancel detection asymmetries. Often, the asymmetry of a pair of tracks can be determined with better precision than of one track alone.

As an example, a muon and pion with opposite charge and the same kinematics cancel out one another's tracking asymmetries. This can be performed also on kinematic distributions of two oppositely charged particles, as is illustrated in Figure 4.3. Here, the transverse momentum and pseudorapidity distributions of the muon and pion in the a_{sl}^s signal sample are shown. The overlapping region is white, and does not contribute to the tracking asymmetry measurements, while the non-overlapping regions are indicated in blue and red. When determining the tracking asymmetries, this is only done for these blue and red regions, which reduces the systematic uncertainties.

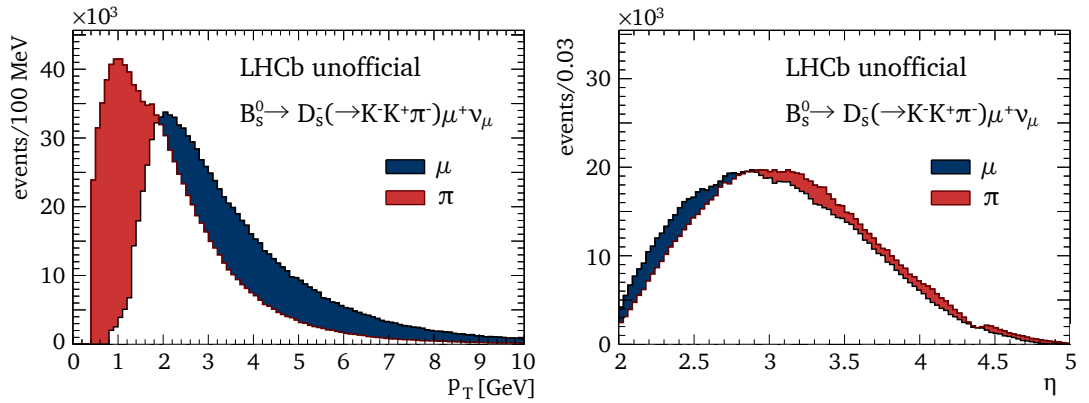


Figure 4.3: Transverse momentum (left) and pseudorapidity (right) distributions of the muons and pions in the a_{sl}^s analysis. The overlapping region is indicated in white and does not contribute to the tracking asymmetries. The non-overlapping regions are indicated in red and blue. These figures are adapted from [103].

4.1.2 Event reweighting

Since detection asymmetries can be dependent on kinematics, many of the methods to determine them use event reweighting to match the kinematic distributions

4. Detection asymmetries

of the control samples to one another, or to the signal sample. This technique gives a weight to every event such that the kinematic distributions overlap. An example is shown in Figure 4.4 (left), which shows the p_T distributions of a pion in two different decay modes: $D^0 \rightarrow K^- \pi^+$ and $B_s^0 \rightarrow D_s^- (\rightarrow K^- K^+ \pi^-) \mu^+ \nu_\mu$. Especially at low p_T , the overlap is poor. To match the distributions, the events of the $D^0 \rightarrow K^- \pi^+$ sample are each given a weight: a higher weight for the low p_T events, and a lower weight for the high p_T events, such that the p_T distributions overlap after reweighting, as shown in Figure 4.4 (right). These plots contain data from LHCb with a selection that is described in Section 4.5.2.

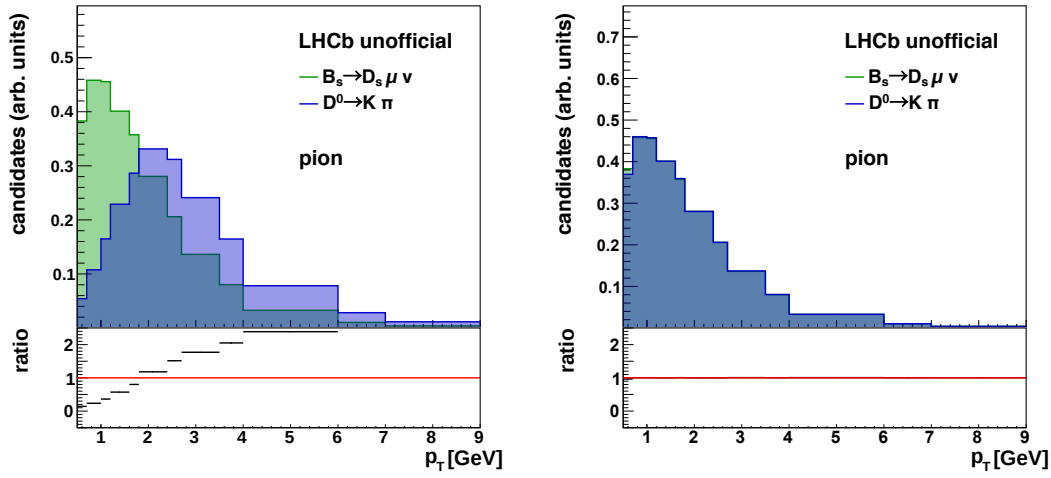


Figure 4.4: Pion transverse momentum distributions of $D^0 \rightarrow K^- \pi^+$ and $B_s^0 \rightarrow D_s^- (\rightarrow K^- K^+ \pi^-) \mu^+ \nu_\mu$ decays, before (left) and after (right) applying event reweighting.

When defining the original distribution as f_{original} , the target distribution as f_{target} , the weight in bin i can be calculated as

$$w(x_i) = \frac{f_{\text{target}}(x_i)}{f_{\text{original}}(x_i)}, \quad (4.6)$$

where x is the variable to reweight in, in the example x is p_T . These weights can have a value larger than one, and must be normalised, as the statistical power of the sample cannot increase if no additional information is added.

Before reweighting, the statistical power of a sample of size N is $1/\sqrt{N}$, while after reweighting the sample size becomes

$$N' = \sum_{i=1}^N w_i, \quad (4.7)$$

4.1. Common techniques for detection asymmetries

with a variance of

$$\delta^2(N') = \sum_{i=1}^N w_i^2. \quad (4.8)$$

The effective sample size N_{eff} is defined, which is the size that a sample would have if it had the same variance as the reweighted sample:

$$\frac{N_{\text{eff}}}{\delta(N_{\text{eff}})} = \frac{\sum_{i=1}^N w_i}{\sqrt{\sum_{i=1}^N w_i^2}}. \quad (4.9)$$

Now, the effective number of entries, N_{eff} in the reweighted sample is

$$N_{\text{eff}} = \frac{(\sum_{i=1}^N w_i)^2}{\sum_{i=1}^N w_i^2}. \quad (4.10)$$

If all weights w_i are equal to one, this equation yields $N_{\text{eff}} = N$, as expected. The above expression also explains that if there is only one event with a much larger or much smaller weight than the rest, the effective statistical power of the sample is strongly reduced. This can be avoided by truncating weights, as is done for some of the methods described in the next sections. In the example of the pion reweighting in Figure 4.4, this is visible at the lowest p_T bin. Here, there is a large discrepancy between the two samples, which is manageable when reweighting in one dimension. The reweighting in this example, however, is done both in p_T and η and yielded large weights in a scarcely populated region of phase space. By truncating these large weights, the effective statistical power is maintained to a reasonable number. However, truncation may reduce the accuracy of reweighting and is thus a tradeoff between accuracy and precision. In this case the overlap between both distributions is good enough, even after truncating.

The balance between finding the optimal binning schemes to reweight distributions and maximise the overlap while maintaining a large statistical power, is quite complex. When increasing the overlap in one variable, the overlap in another variable may be worsened. In addition, the more dimensions the reweighting schemes have, the harder it becomes to find a good binning scheme. Recently, reweighting methods have been developed using multivariate analysis (MVA) techniques [104]. This approach helps dealing with multiple dimensions to reweight in, but its results may be inaccurate in regions with large differences between the kinematic distributions of the original and target sample. This is because MVA methods are developed to distinguish signal from background, and therefore focus

4. Detection asymmetries

on regions in which this is hard to do, not on those with large differences. When reweighting distribution to resemble one another, these are exactly the regions that need attention.

To overcome this problem, gradient boosted decision trees (GBDTs) based on the ADABOOST algorithm [105] are used to reweight events [106]. This uses trees that split the sample into different regions by trying to maximise the difference between the original and target variables in these regions. Hence it identifies those regions that need most reweighting. Event weights are then defined using the kinematic regions chosen by the GBDTs. These are defined as the ratio of the target distribution over the ratio of the original distribution, as in Equation (4.6). The difference between the methods comes only from the way that the reweighting regions are defined. The results of both reweighting methods used for determining a muon-pion detection asymmetry is discussed in Section 4.5.2.

4.1.3 Discriminating signal from background using sWeights

In both analyses in this thesis, combinatorial background must be subtracted when determining detection asymmetries. This is done with another weighting method, which defines weights to discriminate between signal and background. This is used to apply the detection asymmetries to the kinematic distributions of the signal. Since it is hard to tell whether a track with certain kinematics comes from signal or background, a signal weight (sWeight) is assigned to every event on the basis of a discriminating variable.

In the case of the analyses discussed in this thesis, the discriminating variable is the invariant mass of the D_s^+ meson. A maximum likelihood fit is performed to the invariant mass after which sWeights are determined using the sPlot [107] formalism. In fact, sWeights are a sophisticated way to perform background subtraction.

In principle, several classes of events can be classified using this formalism, but in these analyses the sWeights distinguish only between two classes, signal and background. They are normalised and can have values between -1 and 1. By weighting each event with these sWeights, an approximation is made of the signal's kinematic distributions. This can only be used if the variables to which the sWeights are applied are independent of the discriminating variable, the invariant mass in this case.

4.2 Tag-and-probe

The most commonly used method for assessing detection asymmetries is called the tag-and-probe method. This exploits the fact that there is enough redundancy in the reconstruction and selection such that particles can be reconstructed without using all available information. This method is well illustrated by the example of the $J/\psi \rightarrow \mu^- \mu^+$ tracking asymmetry measurement, which is described in Section 4.2.1 and reconstructs tracks without using the information from all subdetectors. Similarly, asymmetries on the HLT1 trigger are extracted in Section 4.2.2. Those arising from the L0 hardware trigger are discussed in Section 4.2.3. Lastly, hadron identification asymmetries are determined using the method discussed in Section 4.2.4.

4.2.1 Tracking asymmetries

Tracking efficiencies and corresponding asymmetries can be measured precisely using clean samples of $J/\psi \rightarrow \mu^- \mu^+$ decays, in which the J/ψ is required to come from a B hadron decay. This is described in more detail in an LHCb internal note [103] and summarised in this section. This particular method is used to determine tracking asymmetries, as described in Sections 5.5.4 and 6.6.4, but very similar ones, using nearly the same dataset, are used also to determine the muon trigger efficiencies, both for Level-0 in Section 5.5.1 and HLT1 in Section 5.5.2.

One of the muons in the J/ψ decay is defined as the tag track, the other as the probe. For the tag track, the muon is fully reconstructed, meaning that it leaves hits in all tracking stations and, in addition, has been identified as a muon.

For the probe track, the subdetector that is being probed is excluded from the track reconstruction algorithm. Nevertheless, the probe track must carry enough information on the momentum to reconstruct the J/ψ invariant mass. Figure 4.5 shows an example of the $J/\psi \rightarrow \mu^- \mu^+$ tag-and-probe method, in which the T stations are probed by requiring hits in the VELO and muon stations. Similarly, the VELO stations can be probed by tracks with hits in the T and muon stations.

4. Detection asymmetries

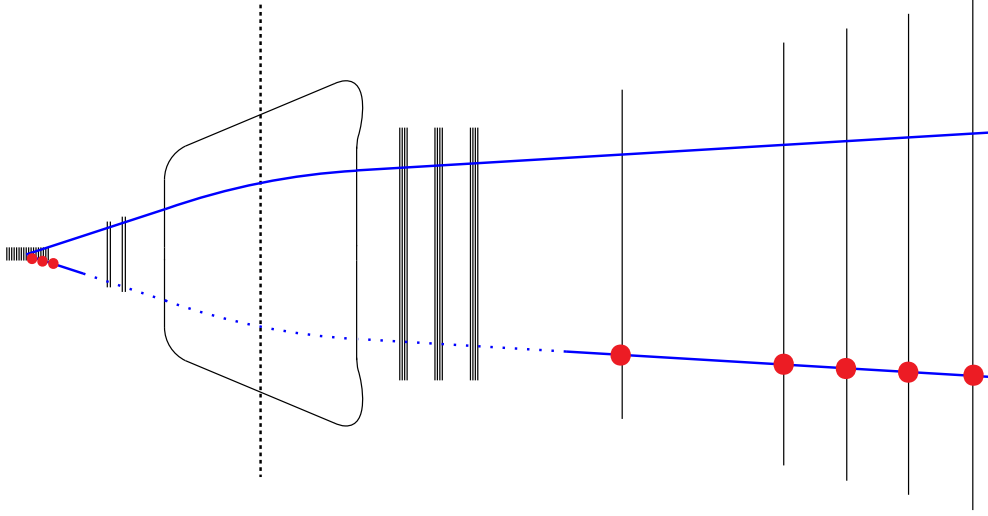


Figure 4.5: Illustration of the $J/\psi \rightarrow \mu^- \mu^+$ tag-and-probe method, probing the T stations. The track on top is the tag track, the one on the bottom the probe. From left to right, the VELO, the two TT layers, the magnet, the three T stations, and the five muon stations are shown. The red dots indicate where hits from the probe track are required. This figure is reproduced from [108].

A check is performed to see if the probe track shares hits with a fully reconstructed track. If this is the case, the track is said to be matched, and finally the efficiency is determined by

$$\varepsilon = \frac{N_{\text{matched}}(J/\psi \rightarrow \mu^- \mu^+)}{N_{\text{total}}(J/\psi \rightarrow \mu^- \mu^+)} . \quad (4.11)$$

The efficiencies for positively and negatively charged probe tracks are computed by fitting the J/ψ yields of samples in which the probe track is matched to determine the numerator of Equation (4.11), and for the samples in which the track is not matched to be combined to $N_{\text{total}}(J/\psi \rightarrow \mu^+ \mu^-)$. This is done separately for positively and negatively charged probe tracks such that using Equation (4.3) a value for A_{track} can be determined.

Most tracks used in LHCb analyses are long tracks, which require hits both in the VELO and T stations. The corresponding tracking asymmetry $A_{\text{track}}^{\text{long}}$ is constructed by adding those of the VELO tracking asymmetry, $A_{\text{track}}^{\text{VELO}}$, and the T station asymmetry, $A_{\text{track}}^{\text{T station}}$. Therefore, this measurement is performed in bins of p_T and η . An example of the outcome as a function of p_T is shown in Figure 4.6. A study on the systematic uncertainties is performed by changing the binning schemes, including variations using bins of momentum, p .

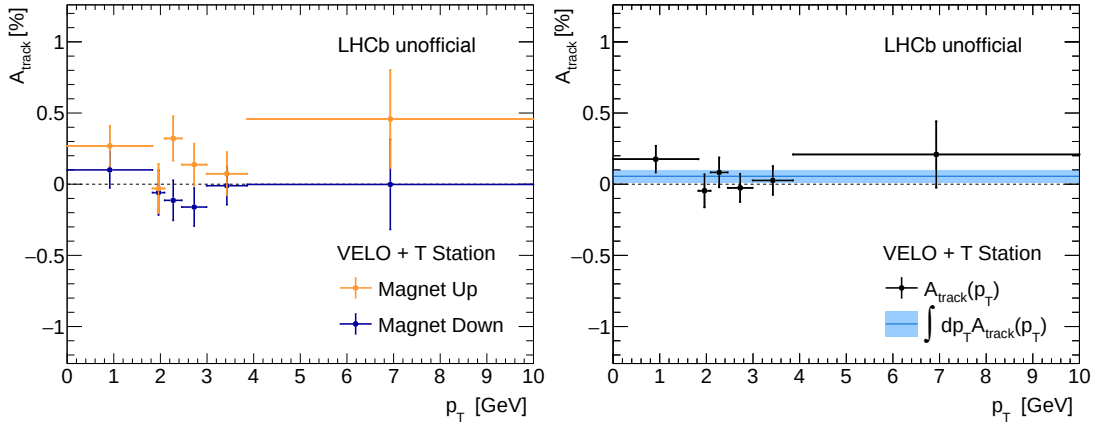


Figure 4.6: Combined VELO and T station tracking asymmetries as a function of p_T . On the left, the data is split between the two magnet polarities. On the right, the average is shown, as well as an integrated asymmetry. These figures are taken from [103].

4.2.2 Software trigger asymmetries

To control biases coming from the HLT1 trigger, two different methods are used. The first one was used for those tracks triggered by the muon, `Hlt1TrackMuon` trigger and is described in Section 4.2.1. The second one is described in this section and considers all tracks that were triggered using the `Hlt1TrackAllL0` trigger, which is used in Sections 5.5.2 and 6.6.2.

For both analyses, the HLT1 requirement is TOS (see Section 2.2.6), meaning that the trigger has fired as a result of using information from the candidate's final state tracks arising from the B or D decay that is being studied. The corresponding asymmetry between the particle and antiparticle samples is known as the TOS asymmetry. To determine the TOS asymmetry, the TOS sample efficiency is determined per track in bins of pseudorapidity and either momentum or transverse momentum for both particle and antiparticle samples. The corresponding per-track asymmetry is used to determine the per-event asymmetries.

Per-track HLT1 TOS asymmetry

The per-track asymmetry is determined using the $D_s^+ \rightarrow K^+ K^- \pi^+$ sample which is the signal sample used for the $A_P(D_s^+)$ measurement. To reduce the background and simplify the measurement, only the $D_s^+ \rightarrow \phi \pi^+$ resonant region is selected (the Dalitz plot regions are discussed in Chapter 6). The exact selection is described in Section 6.3. However, this does not include the requirement that the HLT1 trigger must be fired on the charge-neutral combination of tracks, as was done in Section 6.3 to reduce the HLT1 asymmetry. The online transverse momentum and

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impact parameter variables that are used in the trigger are not the same as the offline variables onto which the selection is applied. This occurs as the reconstruction in the trigger makes approximations to reduce the CPU time consumed. Due to the approximations made, the offline reconstructed p_T does not show a sharp cut-off, and the same is true for the impact parameter. Consequently, to better align the online and offline selection, the online requirements are reapplied offline.

In each of the events, at least one of the $D_s^\pm$ daughters satisfies the Hlt1TrackAllL0 trigger requirements, since this is the definition of the TOS sample. Determining the Hlt1TrackAllL0 TOS efficiency is done by labelling two of the $D_s^\pm$ daughters as a tag, while the third is the probe. When one or both of the tag particles are TOS, the probe track can be used to determine the TOS efficiency. If the probe track is also TOS, the track is flagged as pass, if not, as fail. This method can only be applied if the p_T of the probe track is high enough that it could have fired the trigger.¹ Histograms of the reconstructed D_s^+ mass in the events are produced, splitting between whether the probe track passed (is TOS) or failed (is not TOS). The TOS efficiency can be calculated as follows:

$$\varepsilon_{\text{HLT1}} = \frac{N(D_s^+ \rightarrow K^+ K^- \pi^+)_{\text{pass}}}{N(D_s^+ \rightarrow K^+ K^- \pi^+)_{\text{total}}} . \quad (4.12)$$

The efficiency is determined for both positively and negatively charge probe tracks separately. $N(D_s^+ \rightarrow K^+ K^- \pi^+)$ is found by performing a fit to the D_s^+ mass distributions, discriminating signal and background. For this, the same fit strategy as described in Section 6.5 is used. This uses a Hypatia function [109] with all tail parameters fixed for the signal, combined with an exponential to describe the background. The Hypatia function is similar to a Crystal Ball function, and is described in more detail in Section 5.4. The sample is split between probe pions and kaons, in bins of momentum, transverse momentum, or pseudorapidity, and the outcome is shown in Figure 4.7.

One noticeable feature in these plots is the large asymmetry at $\eta < 3$ in the kaon η plot. Since there is a tight requirement on the track quality (χ^2/ndf) in the HLT1 line, this could possibly introduce these asymmetries. To study that, a requirement of $\chi^2/\text{ndf} < 1.5$ has been applied to the probe tracks, shown in Figure 4.8. This removes the discrepancy between the magnet polarities at kaon $\eta < 3.0$. It does however introduce a new feature for both the pion and kaon in the bin $3.0 < \eta < 3.25$.

¹The probe p_T requirement is $p_T > 1.7$ GeV in 2011 and $p_T > 1.6$ GeV in 2012.

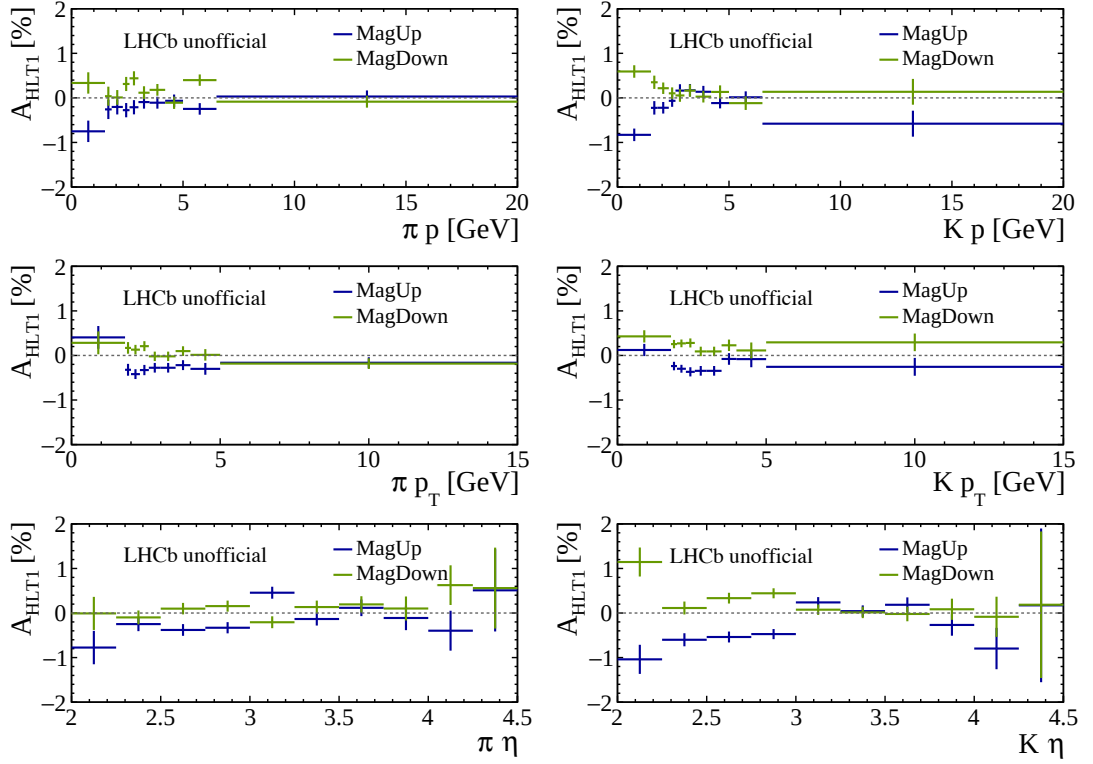


Figure 4.7: HLT1 detection asymmetries as a function of momentum, transverse momentum, and pseudorapidity for the 2012 data-taking year. On the left are the asymmetries for pions, on the right for kaons.

To confirm that the track χ^2/ndf is the cause of the discrepancy, another check is performed by applying the reverse requirement: $\chi^2/\text{ndf} > 1.5$, for which the result is shown in Figure 4.9. There is a clear discrepancy between the distributions recorded with the magnet polarity up and down at $\eta < 3.0$. To further investigate whether the difference between the polarities comes from this track χ^2/ndf selection, one should study the online χ^2/ndf variable rather than the different offline variable used here. However, this variable was not readily available. Hence, it is concluded that this is the most likely source of this feature but it was not definitively demonstrated. For the purpose of this analysis, since the final result is averaged over the data taken with both polarities, this effect is considered to have a negligible contribution to the HLT asymmetries, with the determination of the systematic uncertainties discussed below.

Systematic uncertainties

To probe the systematic uncertainties related to the method, several inputs are varied. In the default measurement, a two-dimensional binning scheme in p_T

4. Detection asymmetries

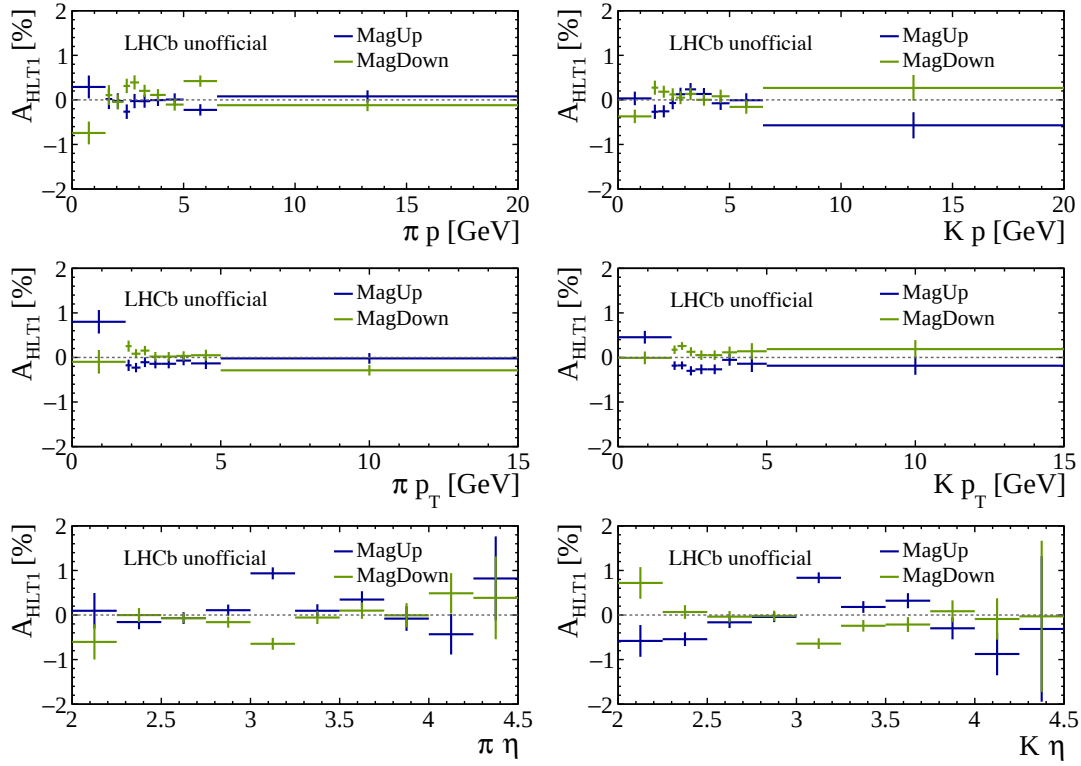


Figure 4.8: TOS efficiency asymmetries as a function of momentum, transverse momentum, and pseudorapidity, after applying an additional requirement on the track quality ($\chi^2/\text{ndf} < 1.5$) of the probe tracks. On the left are the asymmetries for pions, on the right for kaons.

versus η is used. To capture the systematic uncertainties of the variables that are used for binning, an alternative binning method was used in p versus η .

Moreover, the HLT1 asymmetries are split between kaons and pions. However, the track reconstruction in the HLT1 trigger is the same for kaons and pions, and no difference is expected. Therefore, another systematic check is to combine the kaon and pion probe samples into one by averaging them. Lastly, the offline p_T requirement that is used in the analyses is not the same as the online one in the trigger. This means that in the offline p_T spectrum, a smooth turn-on is visible rather than a hard requirement. To capture the importance of this effect, the p_T requirement used to select probe tracks is loosened.² The systematic uncertainties assigned are the maximum difference between the default method and any of the variations.

²The probe p_T requirement is loosened to $p_T > 1.65$ GeV in 2011 and $p_T > 1.55$ GeV in 2012.

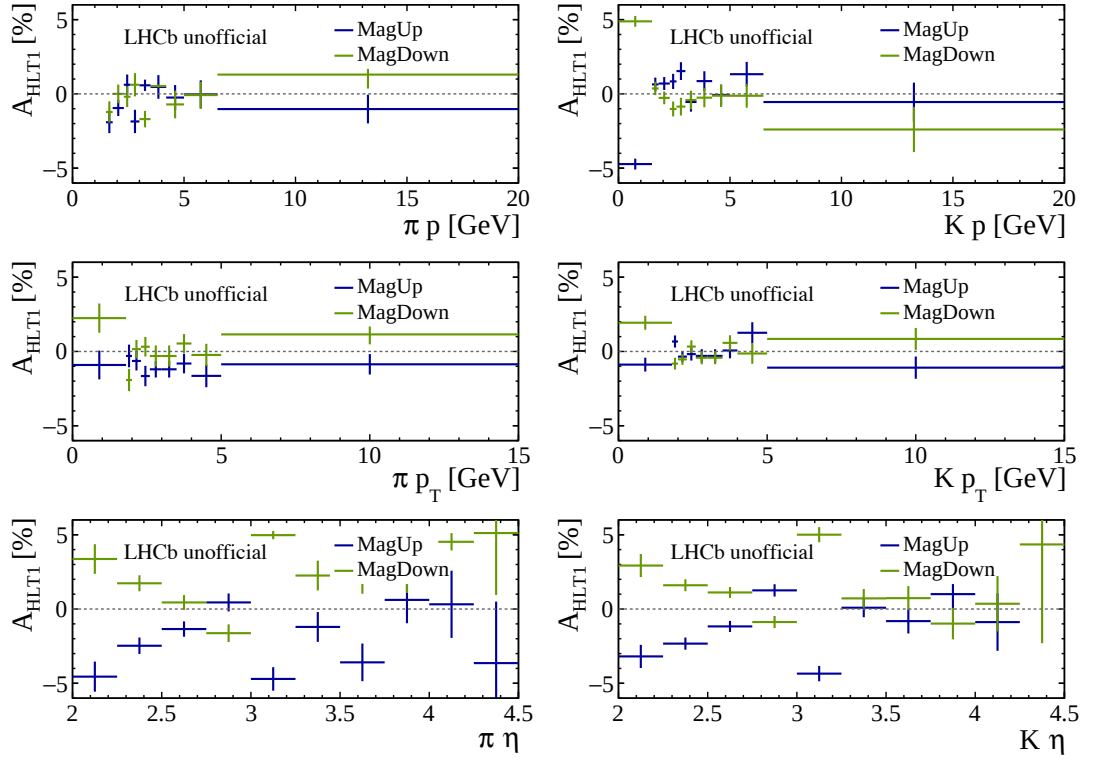


Figure 4.9: TOS efficiency asymmetries as a function of momentum, transverse momentum, and pseudorapidity, after applying an additional requirement on the track quality of the probe tracks ($\chi^2/\text{ndf} > 1.5$, the opposite of the requirement applied in Figure 4.8). On the left are the asymmetries for pions, on the right for kaons.

4.2.3 Hardware trigger asymmetries

This section describes the asymmetries coming from the hardware trigger. These are the so-called L0 TIS (Trigger Independent of Signal) asymmetries, relevant for the $A_P(D_s^+)$ analysis, and further detailed in Section 6.6.1. By dividing events in TIS, TOS (Trigger On Signal) and TISTOS (events that pass the trigger due to signal, TOS, and non-signal tracks, TIS), trigger efficiencies can be determined.

The TIS efficiency, ε_{TIS} is defined as

$$\varepsilon_{\text{TIS}} = \frac{N_{\text{TIS}}}{N_{\text{acceptance}}} . \quad (4.13)$$

Here N_{TIS} is the number of events triggered by the L0 TIS trigger, and $N_{\text{acceptance}}$ the total number of events in the LHCb acceptance. Since events are not recorded if they do not fire the trigger, $N_{\text{acceptance}}$ is unknown. Therefore, only the efficiency

4. Detection asymmetries

of TIS with respect to TOS, $\varepsilon_{\text{TIS}|\text{TOS}}$ can be determined, which is defined as

$$\varepsilon_{\text{TIS}|\text{TOS}} = \frac{N_{\text{TISTOS}}}{N_{\text{TOS}}}, \quad (4.14)$$

where N_{TISTOS} is the number of candidate decays that are both TIS and TOS, and N_{TOS} the events that are TOS. If the TIS decision is independent of the TOS decision, the following assumption can be made:

$$\varepsilon_{\text{TIS}} \simeq \varepsilon_{\text{TIS}|\text{TOS}}. \quad (4.15)$$

Using this assumption, the L0 TIS asymmetries can be determined.

The TIS and TOS trigger decisions are independent for track triggers, which use finely segmented tracking detectors that can discriminate between tracks from different particles. The calorimeter trigger, on the other hand, uses the coarse calorimeters in which clusters arising from different particles often overlap. This makes it hard to measure trigger efficiencies. For example, in a sample of $D^+ \rightarrow K^- \pi^+ \pi^+$ the efficiencies of the pions are higher than those of the kaons, simply because having the same charge, they end up in the same region of the calorimeter [110]. Therefore, the L0Hadron efficiencies do not factorise to allow the efficiency of multiple particles to be combined for a candidate event. Moreover, the efficiencies differ between decay channels.

Unfortunately, it is also difficult to determine the L0Hadron efficiencies using simulations, and no reliable Monte Carlo simulations exist. Measuring the L0-Calorimeter efficiencies must therefore be done using the same decay as the rest of an analysis, in this case a sample of prompt $D_s^+ \rightarrow K^+ K^- \pi^+$. The D_s^+ signal sample selection is described in Section 6.3, but for this study, only the $\phi\pi$ resonant region is used, which has a 97% signal purity. Section 6.3 also includes a requirement on a charge-neutral combination for the HLT1 trigger, which was removed for the L0 TIS study.

The TIS requirement of the sample is L0Global, which is a combination of all the physics triggers: L0Muon, L0DiMuon, L0Photon, L0Electron, L0Hadron. To determine the L0Global TIS efficiency, also the TOS requirement is L0Global, but because all tracks coming from the D_s^+ candidate are hadrons, this requirement is equivalent to L0Hadron.

The sample is split up in bins of transverse momentum or rapidity and within each of these bins, the TIS efficiency was determined using Equation (4.14), after which the TIS asymmetry was calculated. The results are shown in Figure 4.10. No

clear dependence is found on the transverse momentum, as shown in Figure 4.10 (left).

Also as a function of D_s^+ rapidity, no clear dependence is seen as shown in Figure 4.10 (right). However there is a cross-over between the asymmetries measured using the datasets from the two magnet polarities in the 2012 sample around $y = 3$. This is thought to be dependent on the L0Muon TOS asymmetry which is studied in more detail in a Λ_b^0 production asymmetry measurement [111]. For the measurement of the D_s^+ production asymmetry, the L0 TIS asymmetry is determined in bins of rapidity and transverse momentum, as was done for the measurement. The results are given in Section 6.6.7.

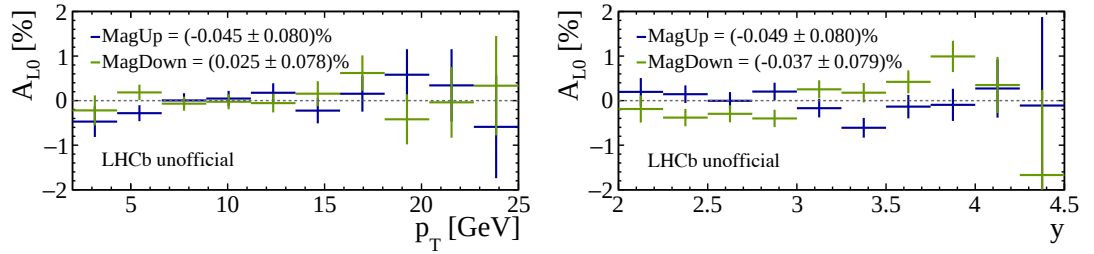


Figure 4.10: L0 TIS asymmetries as a function of D_s^+ transverse momentum (left) and of D_s^+ rapidity (right), determined on the dataset recorded in 2012.

Systematic uncertainties

To determine the systematic uncertainty, a clean sample of $D^+ \rightarrow K^- \pi^+ \pi^+$ is used, which has a much higher signal yield than the $D_s^+ \rightarrow K^+ K^- \pi^+$ sample. Two studies are performed using this sample. The first concerns the validity of Equation (4.15). The second studies the dependence of the L0 TIS asymmetries on different regions in the Dalitz phase space.

The L0Hadron trigger objects are formed as follows. An offline signal track is extrapolated to the calorimeter and the intersecting cells, together with the eight neighbours surrounding the cells, are called the signal cells. Calorimeter trigger objects consist of 2×2 cells, and if any of the signal cells overlap with a calorimeter object, the trigger decision is called TOS. These L0 objects cannot be used for a TIS decision, even though the trigger object may be created by several particles. Hence, the TIS decisions are biased by the signal, and not truly independent.

To probe how much the TIS asymmetry depends on the TOS candidate, the TIS asymmetry of the D^+ sample was determined using different TOS requirements. They were TOS on either the D^+ , the kaon or one of the pions. It is found that there is a significant difference between the asymmetries from the various TOS

4. Detection asymmetries

requirements, as is shown in more detail for the $A_P(D_s^+)$ analysis in Figure 6.11. The asymmetry with the TOS requirement on the pions have a very similar behaviour, which is expected since they have the same charge. A dependence on the magnet polarity is visible, which cancels in the measurement. Therefore, the systematic uncertainty is determined on the magnet averaged values and is taken as plus or minus half the maximum difference between the three L0 TIS asymmetries.

Another study was performed to check the dependence on the decay chain. The $D^+ \rightarrow K^- \pi^+ \pi^+$ Dalitz plot is shown in Figure 4.11, which displays $m^2(K\pi)$ vs $m^2(K\pi)$, where the horizontal axis is chosen as the combination of kaon and pion that gives the largest value of $m^2(K\pi)$. A K^* resonance is visible as a horizontal band around $m^2(K\pi) = 0.8 \text{ GeV}^2$ and a resonant region near the top of the plot arising from low mass $\pi\pi$ resonances. The resonance near the top is due to $\rho^0(770)$ and other light unflavoured mesons and is removed from this study.

The difference in the L0 TIS asymmetry is studied between the K^* - and non-resonant region. The K^* resonant region is selected by requiring the $m^2(K\pi)$ to be between 0.7 and 1.1 GeV^2 . The non-resonant region is divided into two parts, one between 0.5 and 0.7 GeV^2 , and one between 1.1 and 1.6 GeV^2 . A systematic uncertainty is assigned, as plus or minus half the difference between the two Dalitz regions, determined on the mean of the magnet polarities.

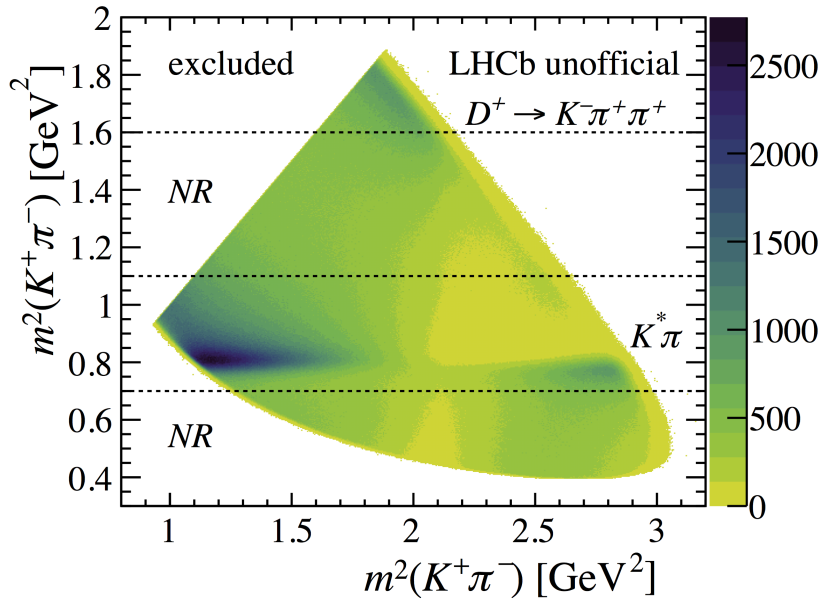


Figure 4.11: Dalitz plot for the decay $D^+ \rightarrow K^- \pi^+ \pi^+$, using data recorded in 2011 and 2012 combined, with both magnet polarities. The different resonant regions are indicated as $K^* \pi$, NR (non-resonant) and excluded. The excluded region includes a contribution from resonances of light unflavoured mesons, such as $\rho^0(770)$ along the diagonal.

4.2.4 Hadron identification asymmetries

In the signal selection, particle identification (PID) criteria are applied to correctly classify particles as for example kaons, pions, or muons. These PID variables on which the requirements are applied are based on input from the RICH1 and RICH2 detectors (the DLL variables), while others include also inputs from the track quality and calorimeters (the PROBNN variables). All of them are thus dependent on the performance of the RICH detectors and their alignment. A small misalignment or a malfunctioning HPD could cause PID asymmetries which are explained in more detail in Sections 5.5.6 and 6.6.6.

These asymmetries are determined using large samples of prompt charm decays. For the analyses in this thesis, the only hadron identification asymmetries are from kaons and pions. The calibration sample that is used to measure these is $D^0 \rightarrow K^- \pi^+$, of which the purity is improved by requiring the $D^{*+} \rightarrow D^0 \pi^+$ decay chain. A selection is applied to reduce the background, and maximum likelihood mass fits are performed on the mass difference between the D^{*+} and D^0 invariant mass. This is used to determine the sWeights on the full sample.

Since PID asymmetries may depend on the kinematics of the kaons and pions, the samples are split into kinematic bins. Then the PID efficiency of a specific PID requirement is determined by comparing the sum of the sWeights in a kinematic bin before, and after, applying the PID selection. The kaon PID efficiencies as a function of the kaon transverse momentum for two selection criteria used in the a_{sl}^s analysis are shown in Figure 4.12.

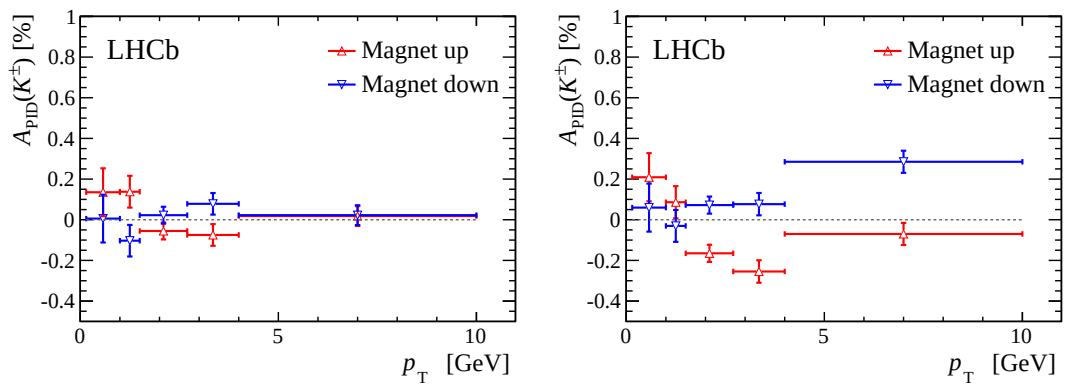


Figure 4.12: Kaon PID asymmetries as a function of transverse momentum. On the left is the asymmetry coming from the PID requirements $\text{DLL}_{K\pi} > -5$ and $\text{PROBNNK} > 0.1$, which is applied in the $\phi\pi$ region for the a_{sl}^s analysis. On the right are the PID asymmetries arising from the $\text{DLL}_{K\pi} > 4$ and $\text{PROBNNK} > 0.15$ requirements, corresponding to the selection in the K^*K and NR region of the a_{sl}^s analysis.

4. Detection asymmetries

An important systematic uncertainty in this method comes from determining the sWeights. This is performed on the overall sample, before it is split into kinematic bins. Since the shape of the invariant mass depends on the kinematics of the signal, the fit used to determine the sWeights may not be representative in a specific kinematic bin. This effect is assessed by first splitting the data in kinematic bins, before determining the sWeights and results in a difference of around 0.02% in the PID asymmetry.

4.3 Partially and fully reconstructed decays

This section discusses a method to determine detection asymmetries by comparing partially to fully reconstructed decays. This method probes the asymmetry of the reconstruction efficiency of the track that is or is not reconstructed, which in this analysis is applied to a pion.

4.3.1 Tracking asymmetries using charm decays

A second technique, in addition to that discussed in Section 4.2.1, used to determine tracking asymmetries compares partially to fully reconstructed charm decays. This was first used in the determination of the D_s^+ production asymmetry [55]. In this thesis, it is used to determine tracking asymmetries both for the a_{sl}^s analysis in Section 5.5.4 and the $A_{\text{P}}(D_s^+)$ analysis in Section 6.6.4. The decay that is studied is $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$, where one of the pions may be missing. The flavour of the D^0 is tagged by requiring it to come from $D^{*+} \rightarrow D^0 \pi^+$.

By assuming that the D^{*+} candidate originates from the primary vertex, the D^0 flight direction is known. Additionally, using energy and momentum conservation, the three-momentum of the missing pion can be inferred using the method described in Reference [112]. Consequently, in the sample of partially reconstructed decays, the missing pion is searched for. If it is found, the decay is also fully reconstructed and the reconstruction efficiency of the pion can be determined as

$$\varepsilon(\pi^\pm) = \frac{N_{\text{full}}(\pi^\pm)}{N_{\text{partial}}(\pi^\pm)}, \quad (4.16)$$

where $N_{\text{full}}(\pi^+)$ is the number of fully reconstructed decays and $N_{\text{partial}}(\pi^+)$ the number of partially reconstructed decays.

To determine $N_{\text{full}}(\pi^+)$ and $N_{\text{partial}}(\pi^+)$, a maximum likelihood mass fit is performed to the Δm distribution, which is defined as

$$\Delta m_{\text{partial}} = m(\pi^+ K^- \pi^+ \pi^-) - m(K^- \pi^+ \pi^-), \quad (4.17)$$

for the partially reconstructed decay, and as

$$\Delta m_{\text{full}} = m(\pi^+ K^- \pi^+ \pi^- \pi^+) - m(K^- \pi^+ \pi^- \pi^+), \quad (4.18)$$

for the fully reconstructed decay. The Δm distributions are shown in Figure 4.13 for the partially (left) and fully (right) reconstructed decays. From the width of the Δm peaks, it is clear that the mass resolution improves when the decay is fully reconstructed. The distributions of the combinatorial background are determined by fitting a so-called wrong-sign sample in which the kaon is required to have the same charge as the soft pion. In this wrong-sign fit, the contribution from the doubly-Cabibbo-suppressed D^0 decay is taken into account.

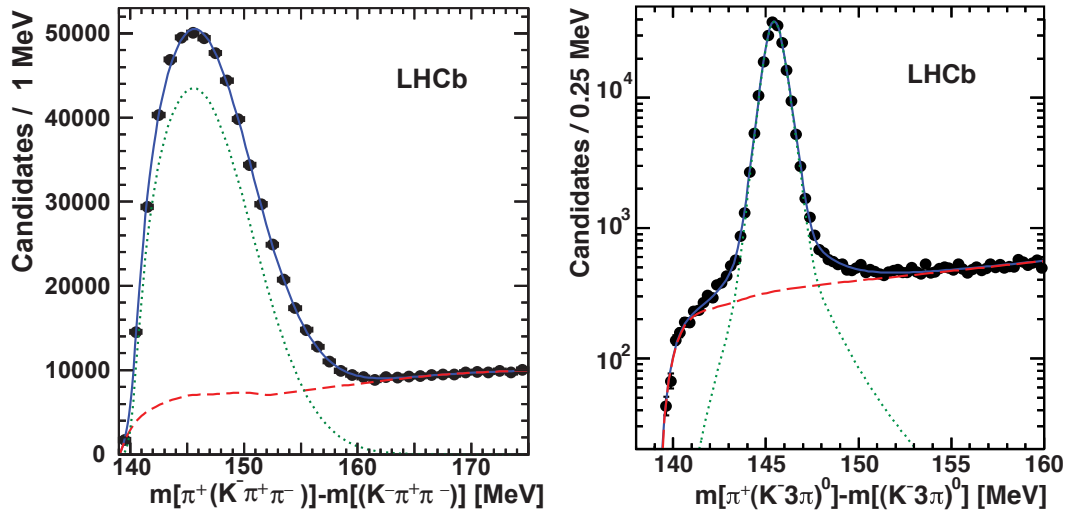


Figure 4.13: Δm fits for the partially (left) and fully (right) reconstructed $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ samples. The red dashed lines indicate the combinatorial backgrounds, for which the shapes are determined on the wrong-sign sample. The green dotted lines are the signal distributions, and the blue lines the sum of the signal and background. This figure is adapted from [55].

4. Detection asymmetries

The pion efficiency is determined in bins as a function of its momentum. However the momentum inferred from the partially reconstructed decay has a worse resolution than that of the measured momentum of the pion. Consequently tracks may not be associated with their correct momentum bin but may instead migrate into a neighbouring bin. In order to correct for this an unfolding procedure is applied as follows.

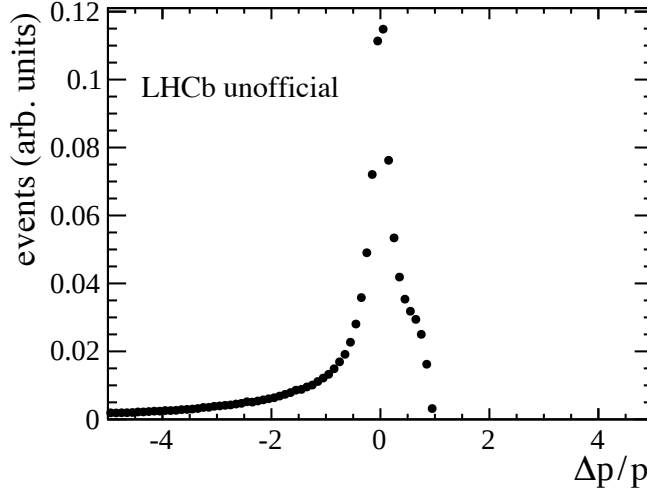


Figure 4.14: Inferred momentum resolution of the partially reconstructed D^* method.

The fully reconstructed sample is used to replicate the situation of a partially reconstructed decay. One of the pion tracks, in the fully reconstructed decay, with momentum p_{detected} , is removed and then its momentum is inferred in the same manner as is done for the partially reconstructed decay. Its inferred momentum can then be compared with its measured momentum. The inferred momentum resolution can be calculated using

$$\frac{\Delta p}{p} = \frac{p_{\text{detected}} - p_{\text{inferred}}}{p_{\text{detected}}} . \quad (4.19)$$

This yields the distribution that is shown in Figure 4.14.

Using the inferred and detected momentum, a response matrix, W_{ij} , is created that contains the probabilities that a pion with a detected momentum p_j has an inferred momentum p_i . This matrix is regularised using the Single Value Decomposition (SVD) method [113]. Different configurations of this method are used to assign a systematic uncertainty.

4.4. Comparing tracking asymmetry measurements

As a systematic check, the pion detection asymmetry is also determined as a function of the pion transverse momentum. The resulting pion asymmetries as a function of p and p_T are shown in Figure 4.15.

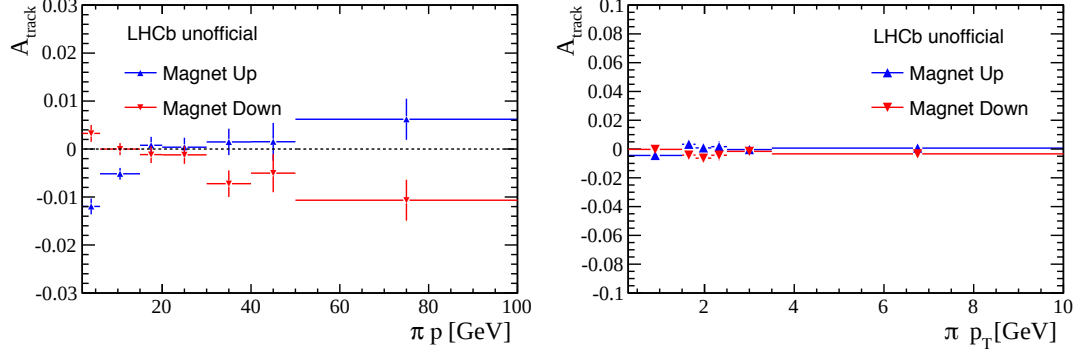


Figure 4.15: Pion detection asymmetry as a function of momentum (left) and transverse momentum (right), determined using the partially reconstructed D^{*+} method.

4.4 Comparing tracking asymmetry measurements

There are two methods to determine the tracking asymmetries for the muon-pion pair in the a_{sl}^s analysis, see Section 5.5.4, and for the pion in the $A_p(D_s^+)$ analysis, see Section 6.6.4: the J/ψ tag-and-probe discussed in Section 4.2.1, and the partially reconstructed D^{*+} method discussed in Section 4.3. While both methods measure a tracking asymmetry, they do not measure the exact same quantity. The first difference is the pion nuclear interaction asymmetry, as illustrated in Figure 4.1. This is needed for both analyses, and is measured by the partially reconstructed D^{*+} method which uses pions. The J/ψ tag-and-probe method, on the other hand, only uses muons, and thus does not measure this.

Another difference between the two methods concerns the probing of the acceptance asymmetry. This asymmetry is due to the combination of the beam crossing-angle and the shape of the detector. Although the detector is approximately symmetric in the (x, z) -plane, the beam crossing-angle moves the average position of the primary vertices away from the centre of the detector. Combined with the hole for the beam-pipe, and the outer edge of the detector, this introduces an acceptance asymmetry. While this asymmetry is captured by the partially reconstructed D^{*+} method, the J/ψ tag-and-probe method only measures the asymmetry of particles that are detected both before and after the magnet, and are therefore already in LHCb's acceptance.

4. Detection asymmetries

Both these effects can be determined using simulations which are described in Section 4.4.1. The J/ψ tag-and-probe method can then be corrected using the determined asymmetries. After applying these corrections, the methods are compared in Section 4.4.2.

4.4.1 Correcting tracking asymmetries using simulations

Nuclear interaction asymmetries cannot be studied using for example a tag-and-probe approach, because there is no redundant information. These are therefore determined using simulations, based on the candidates in the signal data sample. For every candidate that passed the selection, the position of the D_s^+ vertex and the pion's momentum are used to create two simulated pion tracks with opposite charge. Both these tracks are propagated through the detector, and the amount and type of material that the pions encounter while traversing the detector is recorded and combined with the corresponding nuclear interaction asymmetries from the Particle Data Group [7], which are shown in Figure 4.1 for deuterium and proton targets. To prevent double-counting the acceptance asymmetry, only those events where both pion tracks are in the acceptance are taken into account when calculating the interaction asymmetry.

It is found that not only is there a difference in the cross-sections of the positively and negatively charged pions, but also in the amount of material they traverse. This is mainly due to the cables behind the inner tracker that are only located in one half of the detector. As expected from the nuclear cross-sections, the asymmetry is largest at low momenta. No strong dependency on the magnet polarity is found.

For the geometric acceptance, a similar study is performed where two pions of opposite charge are propagated from the D_s^+ vertex through the LHCb detector. These tracks are said to be in the acceptance when they hit a minimum amount of detectors stations in the VELO and T-station. For this simulation, the LHCb alignment conditions database from a representative data-taking period in the 2011 and 2012 data-taking years is used. When the tracks are both reconstructed in the VELO and muon stations, or both in the TT- and T-stations, their asymmetry is probed by the J/ψ tag-and-probe method and these events are therefore neglected in this simulation study. The geometric acceptance asymmetry largely cancels when combining the data taken using both magnet polarities.

4.4.2 Comparing the corrected tracking asymmetries

Ideally the simulated acceptance and interaction asymmetries are used to correct the value obtained for the J/ψ tag-and-probe measurements. For the $A_P(D_s^+)$ measurement, this is done and the two tracking asymmetry measurements are in agreement, with a $\chi^2/\text{ndf} = 1.25$ over all 144 data samples that are used in this analysis, coming from 12 kinematic bins, 3 Dalitz plot regions, 2 data-taking years and 2 magnet polarities.

For the α_{sl}^s measurement, this is more complicated. Since this measurement combines the tracking asymmetries of a muon-pion pair, the partially reconstructed D^{*+} method must also be corrected for nuclear interaction asymmetries. This is because part of the contribution is cancelled when the kinematic distributions of the two tracks overlap, while the other non-overlapping region also contains a nuclear interaction component for muons. Instead, to compare the tracking asymmetries for that measurement, the simulated asymmetries are added as an additional systematic uncertainty. The nuclear interaction asymmetries are added to both methods, while the acceptance asymmetry is only added for the J/ψ method. After considering these systematic uncertainties, the results of both methods are in agreement within one standard deviation.

4.5 Ratio of decays

The last method discussed here to determine detection asymmetries uses the ratios of two similar decays. After ensuring that the kinematics of both decays are similar, many production and detection asymmetries cancel between the two decays and only a relevant asymmetry remains. This section describes how to use the ratio of prompt charm decays to determine the combined kaon-pion asymmetry in Section 4.5.1 and the combined muon-pion asymmetry in Section 4.5.2.

4.5.1 Combined kaon-pion tracking and PID asymmetries

To determine combined kaon and pion asymmetries, the ratio of two abundant charm decays, $D^- \rightarrow K^+ \pi^- \pi^-$ and $D^+ \rightarrow K_s^0 \pi^+$, is used. This method is documented in Reference [101] and has been used in various analyses. It measures the tracking and nuclear interaction asymmetry from kaons and pions, and is sensitive to PID asymmetries.

4. Detection asymmetries

The ratio that is measured is

$$\frac{\varepsilon(K^+\pi^-)}{\varepsilon(K^-\pi^+)} = \frac{N(D^- \rightarrow K^+\pi^-\pi^-)}{N(D^+ \rightarrow K^-\pi^+\pi^+)} \times \frac{N(D^+ \rightarrow K_s^0\pi^+)}{N(D^- \rightarrow K_s^0\pi^-)}, \quad (4.20)$$

where N is the number of signal candidates. The ratio of the $D^- \rightarrow K^+\pi^-\pi^-$ decays measures a kaon-pion-pion asymmetry, from which a pion asymmetry is subtracted using the ratio of the $D^+ \rightarrow K_s^0\pi^+$ decays. This works only after reweighting the D^+ and π^+ kinematic distributions of the $D^+ \rightarrow K_s^0\pi^+$ decays to those of the $D^- \rightarrow K^+\pi^-\pi^-$ decays, to cancel D^+ production and π^+ detection asymmetries.

The K_s^0 in the $D^+ \rightarrow K_s^0\pi^+$ decay are produced with a specific flavour, since the D^+ only decays into a $\bar{K}^0$, and thus introduces an additional asymmetry. The nuclear interaction cross-sections of the K^0 and $\bar{K}^0$ mesons are well-known and the effective asymmetry can be calculated using the LHCb material map.

For the a_{sl}^s and $A_P(D_s^+)$ analyses, see respectively Sections 5.5.5 and 6.6.5, not a kaon-pion, but a kaon-kaon asymmetry is necessary. In order to do this, the kaon-pion asymmetry described in this section is determined twice, once for a same-sign kaon, and once for a opposite-sign kaon, where the sign is defined with respect to the D_s^+ meson. After reweighting the kinematic distributions to match the signal kinematics of the kaon, these two asymmetries are combined to a kaon-kaon-pion-pion asymmetry in which the pion-pion asymmetry cancels, such that only the kaon-kaon asymmetry is left. In this approach, the K^0 asymmetry contributes twice with opposite sign and almost completely cancels. A systematic uncertainty is assigned to this assumption, based on the values for the kaon's nuclear interaction asymmetry that are found in Reference [114].

4.5.2 Combined muon-pion tracking and PID asymmetries

Another method concerns the detection asymmetries of a muon-pion pair, and is evaluated using charm decays. It was developed for the detection asymmetries of the a_{sl}^s analysis, see Section 5.5.4, since the combined muon-pion asymmetries of the previous a_{sl}^s analysis formed the dominating systematic uncertainty. However, the samples used in this method have a poor kinematic overlap with the a_{sl}^s signal sample and hence its application does not improve beyond the other methods discussed above (see Section 4.2.1 and Section 4.3) that are applied to the muon-pion detection asymmetry. Consequently, it is not used to assess the detection asymmetry in the a_{sl}^s analysis, but can provide a cross-check for the other two $\mu\pi$ asymmetry studies. It is presented here as it is a novel method.

The decays chains that are used are from D^0 mesons, which are abundant and can be flavour-tagged by requiring them to come from a $D^{*+} \rightarrow D^0 \pi^+$ decay. In the D^{*+} decay, the charge of the pion, called a slow pion, determines the flavour of the D^0 . Subsequently, the D^0 can decay into a $K^- \mu^+ \nu_\mu$ or $K^- \pi^+$ final state. The selection of both D^0 decays is kept as similar as possible, such that most production and detection asymmetries cancel out. The selection is split into trigger, stripping and fiducial selection, where the latter concerns aligning the selection criteria on both samples. The selection is described in detail later in this section.

Using these two decays, the ratio of the reconstruction efficiency of the $\mu^+ \pi^-$ pair, over the efficiency of the $\mu^- \pi^+$ pair can be determined:

$$\frac{\varepsilon(\mu^+ \pi^-)}{\varepsilon(\mu^- \pi^+)} = \frac{N(D^0 \rightarrow K^- \mu^+ \nu_\mu)}{N(\bar{D}^0 \rightarrow K^+ \mu^- \bar{\nu}_\mu)} \times \frac{N(\bar{D}^0 \rightarrow K^+ \pi^-)}{N(D^0 \rightarrow K^- \pi^+)}, \quad (4.21)$$

where N denotes the number of candidates of a specific decay. This works only if both the D^0 production asymmetry, and the kaon detection asymmetries cancel, which is true when the kinematics of the kaons and D^0 mesons are equal in both decays. Effectively, this is done by equalising the kinematic distributions of the D^{*+} 's, the kaons, and the soft pions, and is detailed later in this section.

Thereafter, to determine the efficiency ratio, mass fits are performed. These mass fits are complicated due to the missing momentum of the neutrino in the $D^0 \rightarrow K^- \mu^+ \nu_\mu$ decay. Finally, the $\mu\pi$ detection asymmetry, $A_{(\text{track})}^{\mu^+ \pi^-}$ can be calculated using

$$A_{(\text{track})}^{\mu^+ \pi^-} = \frac{\varepsilon(\mu^+ \pi^-)/\varepsilon(\mu^- \pi^+) - 1}{\varepsilon(\mu^+ \pi^-)/\varepsilon(\mu^- \pi^+) + 1}. \quad (4.22)$$

The advantage of this measurement is that this measures not only the tracking asymmetries, but also the PID, trigger and pion interaction asymmetries. The samples used in this study need to have been selected with the same trigger and PID requirements as for the main analyses for the asymmetry to be directly corresponding. Unlike the two other methods, this one uses a pion and a muon, which is exactly what is needed for the a_{sl}^s analysis, such that no corrections are necessary for the acceptance or interaction asymmetry. The outcome and shortcomings of this method are discussed at the end of this section.

Trigger selection

The trigger selection is the same for both decays, such that any bias coming from the trigger does not introduce an additional asymmetry. Wherever possible, this paragraph refers to sections in the later analysis chapters in which the trigger lines

4. Detection asymmetries

are explained in more detail.

The hardware trigger that is used triggers on the D^{*+} candidate. It uses a combination of all L0 physics triggers, called L0Global (for more detail, see Section 6.3.1). The muonic decay of the D^0 meson could pass the muon and hadron triggers, whereas the hadronic D^0 meson decay can only trigger the hadronic triggers. To minimise L0 trigger asymmetries to this measurement, the L0 selection is required to be independent of the signal (TIS).

The first level software trigger, HLT1, is a track trigger that is applied to the kaon track, Hlt1TrackAllL0, to prevent introducing HLT1 asymmetries. This trigger selects clean tracks with a minimum transverse momentum and is detailed in Section 5.2.2.

Lastly, the second level software trigger, HLT2, reconstructs D^0 meson decays to at least two hadrons, where the D^0 meson is required to come from a D^{*+} meson. This trigger line is called Hlt2CharmHadD02HHXDst_hhX and was introduced in 2012, such that this method only works for measuring detection asymmetries in dataset recorded in 2012 and thereafter. It selects good quality tracks that together form a candidate with a good quality vertex, which is a distance away from the primary vertex. In addition, to ensure the D^0 candidate does not come from the PV, a minimum value for the χ^2_{IP} is required on its decay products.

The soft pion has relaxed requirements on the p_T and p and, because the D^{*+} meson does not fly any measurable distance, it is required to come from a vertex very close to the primary vertex by selecting on the χ^2_{IP} . Finally, the D^{*+} candidate has a p_T selection, and a maximum distance between the D^0 meson and the soft pion. Since the D^0 meson may decay semileptonically and is then not fully reconstructed, there is a requirement on the mass difference between the reconstructed D^{*+} and D^0 candidate, which is less strict than a mass requirement on the D^{*+} meson. The full HLT2 selection is listed in Table 4.1.

Stripping selection

The first step of the offline reconstruction and selection is called the stripping selection, and is different for both decays. Both stripping lines are designed to reconstruct $D^{*+} \rightarrow D^0 \pi^+$ decays. The first discussed here reconstructs $D^0 \rightarrow K^- \mu^+ \nu_\mu$ decays and is called StrippingCharmForVub.³ The second reconstructs the decay $D^0 \rightarrow K^- \pi^+$ and is called StrippingDstarForPromptCharm.

³ This was designed to be used for the measurement of the quark coupling strength $|V_{ub}|$ [115].

Table 4.1: Requirements for the HLT2 trigger line: HLT2CharmHadD02HHXDst_hhX. DOCA refers to the distance of closest approach between two tracks, and DIRA to the direction angle, as defined in Section 2.2.

	variable	requirement
event	# tracks	< 180
D^0	track χ^2/ndf	< 2.25
	track χ^2_{IP}	> 36
	$\chi^2_{\text{vtx}}/\text{ndf}$	< 10
	χ^2_{VS}	> 100
	DIRA	> 0.99
	$m(D^0)$	< 2500 MeV
soft π	p_T	> 300 MeV
	p	> 3000 MeV
	track χ^2/ndf	< 2.25
	χ^2_{IP}	< 9
D^{*+}	DOCA	< 100 mm
	p_T	> 3750 MeV
	$m(D^{*+}) - m(D^0)$	$\in [0, 285]$ MeV

The selection for the $D^0 \rightarrow K^- \mu^+ \nu_\mu$ decay uses muons and kaons with a minimum p_T as input, and a PID requirement to reduce backgrounds. It combines muon and kaon tracks into D^0 candidates if they are not too far removed from one another. The D^0 candidate has requirements on the minimum mass and (transverse) momentum. Since the D^0 candidate flies before it decays, it is removed from the primary vertex, and travels in the forward direction. It is required to have a good quality vertex. Lastly, the corrected mass variable m_{corr} (described in Section 2.2.6) is used to select on the D^0 mass, due to the missing neutrino momentum.

Finally, after applying a PID requirement to the soft pion, this pion and the D^0 candidate are combined to form a D^{*+} if they are close enough to one another. This D^{*+} is required to have a minimum mass and good quality vertex. To suppress combinatorial background, a requirement is applied on the mass difference between the D^{*+} and D^0 . The full stripping selection for the $D^0 \rightarrow K^- \mu^+ \nu_\mu$ decay is listed in Table 4.2. Approximately four million $D^0 \rightarrow K^- \mu^+ \nu_\mu$ candidates are left after the stripping selection.

For the $D^0 \rightarrow K^- \pi^+$ decay, kaons and pions are combined to form a D^0

4. Detection asymmetries

candidate. The selection on these kaons and pions is nearly identical and selects clean tracks with a minimum p_T , a range in p and η , a good fit quality of the tracks and a minimum requirement on the impact parameter χ^2 to ensure the tracks originate from a secondary vertex.

False (ghost) tracks are removed by placing a requirement on the probability they are fake. This probability is given by an artificial neural network optimised to distinguish between real and fake tracks [116] and is based on the track quality. The PID requirements for the kaon and pion are different and reduce the misidentification probability. The D^0 candidate is required to have a mass close to its known value of 1865 MeV. In addition, a minimum requirement on its flight distance, vertex quality and p_T are applied.

Table 4.2: Stripping selection for the $D^0 \rightarrow K^- \mu^+ \nu_\mu$ decay, applied in the StrippingCharmForVub line. DOCA refers to the distance of closest approach between two tracks and the DLL variables are defined in Section 2.2.5. The corrected mass variable is explained in Section 2.2.6.

	variable	requirement
event	# PV	≥ 1
μ	p_T	$> 800 \text{ MeV}$
	$\text{DLL}_{\mu\pi}$	> 0
	IsMUON	true
K	p_T	$> 600 \text{ MeV}$
	$\text{DLL}_{K\pi}$	> 3.0
D^0	$m(D^0)$	$< 1950 \text{ MeV}$
	$\Sigma p_T(K^- \mu^+)$	$> 2800 \text{ MeV}$
	DOCA	$< 0.07 \text{ mm}$
	p	$> 20 \text{ GeV}$
	distance from PV	$> 4.0 \text{ mm}$
	m_{corr}	$\in [1400, 2700] \text{ MeV}$
	$z_{\text{vtx}}(D^0) - z_{\text{vtx}}(PV)$	$> 0.0 \text{ mm}$
	$\chi^2_{\text{vtx}}/\text{ndf}$	< 9.0
soft π	$\text{DLL}_{\mu\pi}$	< 1.0
D^{*+}	$m(D^{*+})$	$> 300 \text{ MeV}$
	DOCA	$< 0.4 \text{ mm}$
	$\chi^2_{\text{vtx}}/\text{ndf}$	< 9.0
	$m(D^{*+}) - m(D^0)$	$< 200 \text{ MeV}$

Lastly, a D^{*+} candidate is formed from the combination of the D^0 candidate with a soft pion. Also here, the combinatorial background is reduced by selecting on the D^{*+} and D^0 mass difference. The selection of the stripping line for the $D^0 \rightarrow K^- \pi^+$ decay is listed in Table 4.3. After the stripping selection is applied, there are approximately 11 million $D^0 \rightarrow K^- \pi^+$ candidates.

Table 4.3: Stripping selection for the $D^0 \rightarrow K^- \pi^+$ decay, applied in the StrippingDstarForPromptCharm line. The DLL variables are defined in Section 2.2.5

	variable	requirement
event	# PV	≥ 1
π	p_T	$> 250 \text{ MeV}$
	track χ^2/ndf	< 5
	track GhostProb	< 0.5
	η	$\in [2.0, 4.9]$
	p	$\in [3.2, 150] \text{ GeV}$
	PROBNN π	> 0.1
	χ_{IP}^2	> 9.0
	DLL $_{K\pi}$	< -2.0
K	p_T	$> 250 \text{ MeV}$
	track GhostProb	< 0.5
	η	$\in [2.0, 4.9]$
	p	$\in [3.2, 150] \text{ GeV}$
	PROBNNK	> 0.1
	χ_{IP}^2	> 9.0
	DLL $_{K\pi}$	> 2.0
D^0	$ m(D^0) - 1865 $	$< 75 \text{ MeV}$
	$\Sigma p_T(K^- \pi^+)$	$> 1900 \text{ MeV}$
	$\chi_{\text{vtx}}^2/\text{ndf}$	< 9.0
	p_T	$> 2000 \text{ MeV}$
	SV	$> 0.1 \text{ mm}$
D^{*+}	$m(D^{*+})$	$< 2.5 \text{ GeV}$
	$m(D^{*+}) - m(D^0)$	$< 155 \text{ MeV}$
	χ_{vtx}^2	< 64

Fiducial selection

The last stage of the selection equalises the requirements applied to both samples. The PID requirements in the two stripping lines are different, which introduces PID asymmetries. To avoid this as much as possible, additional PID requirements are applied on the kaon and soft pion on the $D^0 \rightarrow K^- \pi^+$ sample. These requirements are listed in Table 4.4.

As explained in the introduction, this measurement is only possible if the kinematic distributions of both samples are similar. While this is ensured by applying event reweighting, it is only possible if there is at least some overlap between both samples. In the regions where this is not the case, events have been removed from the measurement. The fiducial selection that was applied to equalise the kinematic distributions between both samples contains requirement in all kinematic variables that are used for event reweighting. These are p_T , p and η and the exact selection is listed in Table 4.4. Before the fiducial requirements are applied to the D^{*+} , its p_T is corrected for the missing neutrino momentum. This is explained in more detail in the next paragraph.

Table 4.4: Fiducial selection applied to both the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \mu^+ \nu_\mu$ samples to match the PID requirements in both samples and remove the kinematic regions in which there is no overlap between both samples.

	variable	requirement
K	$DLL_{K\pi}$	> 3.0
	p_T	$\in [1.7, 8.0] \text{ GeV}$
	p	$\in [10.0, 120.0] \text{ GeV}$
	η	$\in [2.1, 4.3]$
soft π	$DLL_{\mu\pi}$	< 1.0
	p_T	$\in [0.3, 1.4] \text{ GeV}$
	p	$\in [3.0, 17.0] \text{ GeV}$
	η	$\in [2.1, 4.2]$
D^{*+}	p_T	$\in [4.5, 18.0] \text{ GeV}$
	p	$\in [40.0, 210.0] \text{ GeV}$
	η	$\in [2.1, 4.2]$

Kinematic correction

The momentum of the D^{*+} candidate is used in the event reweighting of the samples. However, in the decay $D^{*+} \rightarrow D^0(\rightarrow K^-\mu^+\nu_\mu)\pi^+$, the momentum of the neutrino is not reconstructed such that the D^{*+} misses momentum. This is corrected using so-called kinematic correction factors, or k -factors. These k -factors are defined as

$$k = \frac{p_T^{\text{reco}}}{p_T^{\text{true}}}, \quad (4.23)$$

where p_T^{reco} is the transverse momentum reconstructed from the visible tracks, and p_T^{true} is the true transverse momentum.

The k -factors are determined from a simulated sample of $D^{*+} \rightarrow D^0(\rightarrow K^-\mu^+\nu_\mu)\pi^+$ decays. The distributions of the k -factors (left) and of the k -factors as a function of visible mass, m_{vis} , are shown in Figure 4.16 (right). At large values of the visible mass, little momentum is carried away by the neutrino and the k -factor tends to one.

To correct the values of the D^* p_T , the k -factor distribution is fitted as a function of m_{vis} . The simple linear fit shown in Figure 4.16 (right) yields the following expression of the k -factors as a function of visible mass, expressed in MeV:

$$k = 0.84 - 3.1 \times 10^{-4} m_{\text{vis}} + 2.1 \times 10^{-7} m_{\text{vis}}^2. \quad (4.24)$$

Hence, by dividing the measured p_T value of the D^{*+} by the k -factor consistent with its visible mass, the true p_T value is estimated per event.

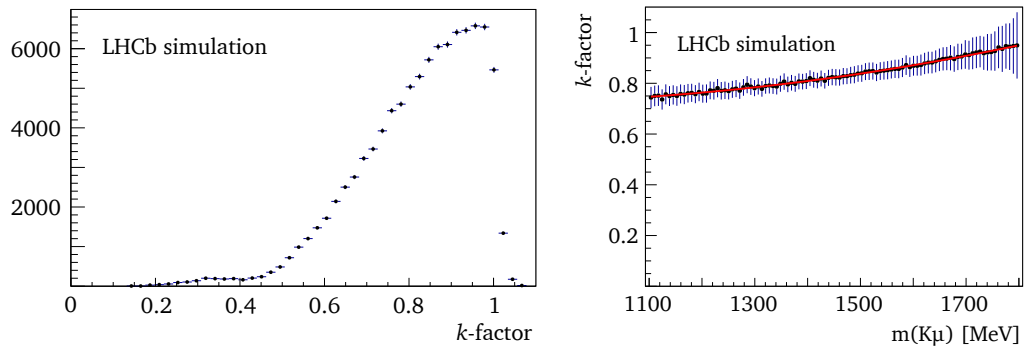


Figure 4.16: Distribution of the k -factors (left), and of the k -factors as a function of the visible mass of the $D^0 \rightarrow K^-\mu^+\nu_\mu$ decay (right), determined from simulation.

Event reweighting

To match the kinematic distributions of both samples, events are reweighted using two methods. Both these methods initially use the same variables for the reweighting: the D^{*+} p_T and η , and the kaon p_T .

The first method simply uses three-dimensional histograms in the three variables for both samples. Dividing the histogram from the $D^0 \rightarrow K^- \mu^+ \nu_\mu$ sample by that of the $D^0 \rightarrow K^- \pi^+$ sample, histograms are created from which event weights can be extracted. These weights are truncated if they have a value smaller than 0.01 or larger than 10 to avoid excessively reducing the effective statistical size of the samples. The weighted kinematic distributions of the D^{*+} , K^- show a good overlap, but the p_T distributions of the soft pions do not, as shown in Figure 4.17.

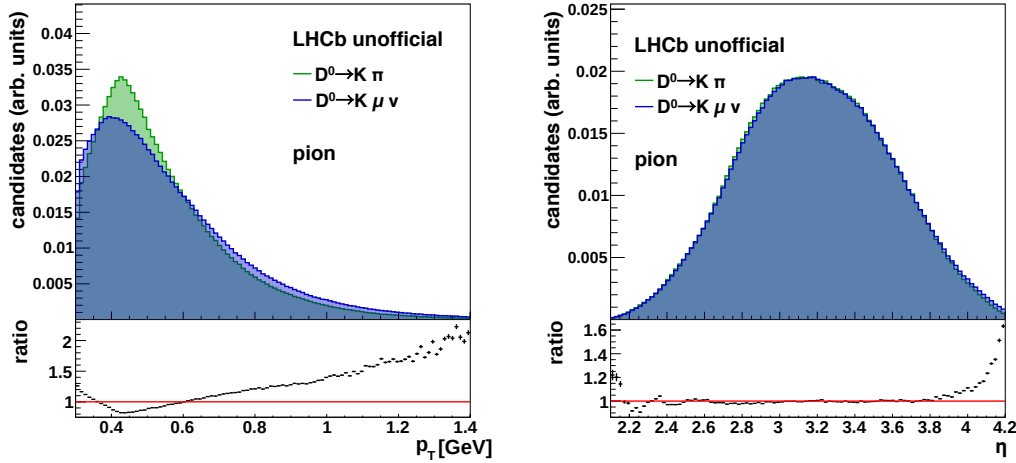


Figure 4.17: Reweighted transverse momentum (left) and pseudorapidity (right) distributions of the soft pions. The reweighting method uses 3-dimensional histograms and reweights in D^{*+} p_T and η .

The novel method using boosted decision trees to reweight samples, as described in Section 4.1.2, is used to implement an alternative version of the reweighting procedure. This elegant method yields comparable results for reweighting the kinematic distributions in the same variables and simplifies expanding the method to more variables. Finally, it was chosen to reweight in addition to the p_T and η of the D^{*+} meson and the kaon p_T , also in kaon η and pion p_T . These reweighted distributions are shown in Figure 4.18, showing the good performance obtained.

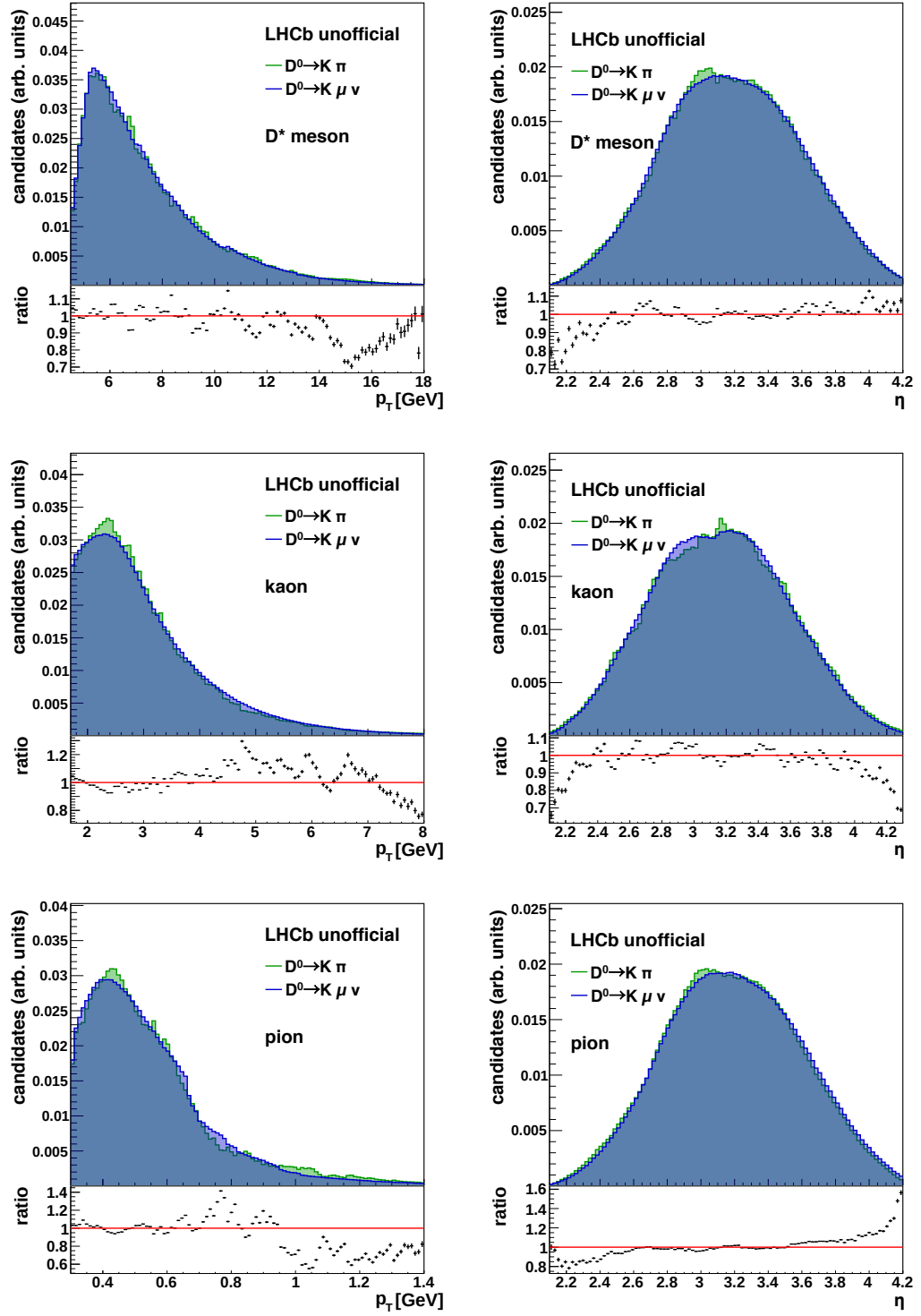


Figure 4.18: Reweighted transverse momentum (left) and pseudorapidity (right) distributions of the D^{*+} meson, kaon and soft pion. The reweighting method here uses the D^{*+} p_T and η , kaon p_T and η , and π^+ p_T distributions in a boosted decision tree.

Fit Strategy

After reweighting the samples, the yields are extracted with a binned maximum likelihood fit to the mass distributions. The fits to the control samples are performed simultaneously for the positively and negatively charged candidate, where all parameters, except for the signal and background yields, are shared. The $D^0 \rightarrow K^- \mu^+ \nu_\mu$ sample is complicated to fit due to the unreconstructed momentum of the neutrino. To compensate for this, the fit is performed on the mass difference between the D^{*+} and D^0 mass: the Δm distribution, which is defined as

$$\Delta m = m(\pi K \mu) - m(K \mu). \quad (4.25)$$

The fits for the $D^0 \rightarrow K^- \pi^+$ decay are shown in Figure 4.19. The signal shape of the $m(K^- \pi^+)$ distribution is modelled by the sum of three Gaussian distributions with two different means and three standard deviations. For the background distribution, the following function is used:

$$\text{bkg}_{K\pi}(\Delta m) = \left(\frac{\Delta m - a}{1000} \right)^b \times \exp[-c(\Delta m - a)], \quad (4.26)$$

where a describes the turn-on mass, which is fixed to a mass of 139.45 MeV, close to the pion mass. The variable b is the amount of curvature of the background and c describes the steepness of the exponential function.

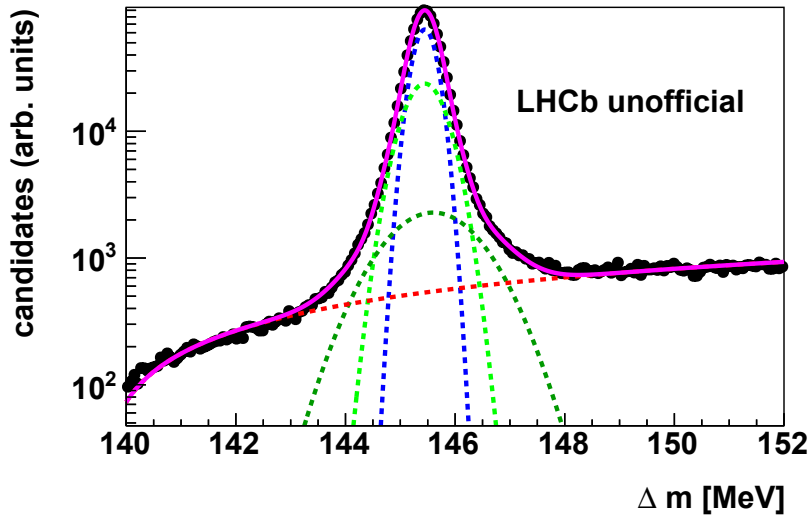


Figure 4.19: Mass fit to the Δm of the $D^0 \rightarrow K^- \pi^+$ decay.

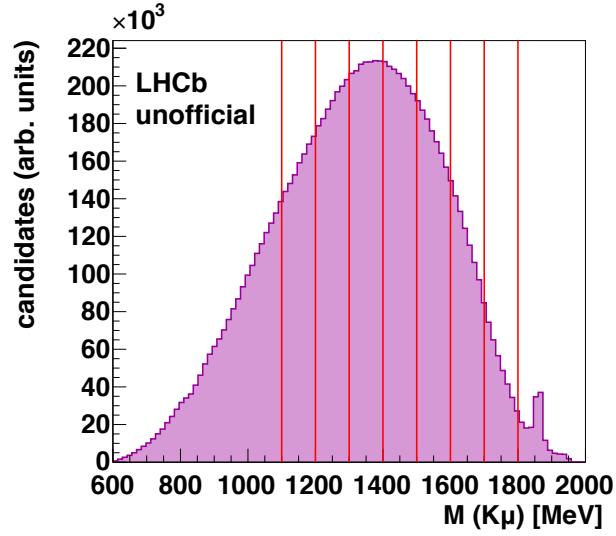


Figure 4.20: Visible D^0 mass bins used to split up the Δm fits for the $D^0 \rightarrow K^- \mu^+ \nu_\mu$ decay.

For the $D^0 \rightarrow K^- \mu^+ \nu_\mu$ decay, the fitting strategy is more complicated. The mass shape, and especially its width, vary a lot as a function of visible mass due to the missing neutrino momentum, which decreases as $m(K^- \mu^+)$ increases. Therefore, the fits are split up in bins of visible mass with a width of 100 MeV, in the mass region between 1200 and 1800 MeV. This is illustrated in Figure 4.20. The chosen mass region excludes the small peak coming from the $D^0 \rightarrow K^- \pi^+$ decay, where the pion is misidentified as a muon, which is visible in Figure 4.20 at a mass around $m(D^0)$.

The Δm distributions can be described by a function with a broad and flat peak. The peak has a shallow slope, depending on the visible mass bin. The shape can be described by the following function:

$$\begin{aligned} \text{sig}_{K\mu}(\Delta m) = & \left| \left[\tanh\left(\frac{\Delta m - l}{\sigma_l}\right) - \tanh\left(\frac{\Delta m - h}{\sigma_h}\right) \right] \right. \\ & \times \left[1 - \tanh\left(\left(\Delta m - \frac{l+h}{2}\right) \times \sigma_{\text{slope}}\right) \right] \\ & \times \left[1 - \frac{1}{d} \left(\Delta m - \frac{l+h}{2}\right)^2 \right] \Bigg|. \end{aligned} \quad (4.27)$$

This equation consists of three factors (between square brackets), of which the absolute value is taken to help the fit converge. The first factor is the difference between two hyperbolic tangents, which yields a top-hat-like function, with a

4. Detection asymmetries

smooth rise and fall. The low and high boundaries of the function are given by l and h , while the corresponding slopes are determined by the parameters σ_l and σ_h . Since the top of the data distribution is not flat, but shows a slight slope, the second factor is added. This is centred in the middle of the low and high boundary, $(l + h)/2$ and the steepness of the slope is described by σ_{slope} . Lastly, the third factor describes the curvature that is visible on top of the signal distribution and is also centred at the average of the boundaries, where the amount of curvature is given by the parameter d which is fixed in the fits.

The distribution of the combinatorial background has a clear turn-on around the pion mass and then rises. This can be described by the sum of the terms with $(\Delta m)^{1/2}$ and $(\Delta m)^{3/2}$, as

$$\text{bkg}_{K\mu}(\Delta m) = (\Delta m - a)^{1/2} + f \times (\Delta m - a)^{3/2}. \quad (4.28)$$

The value of a is again fixed to 139.45 MeV, close to the pion mass. Two resulting fits are shown in Figure 4.21: one in the low visible mass region between $1200 < m(K\mu) < 1300$ MeV with a very broad mass peak, and one in the highest visible mass region between $1700 < m(K\mu) < 1800$ MeV with a narrower peak.

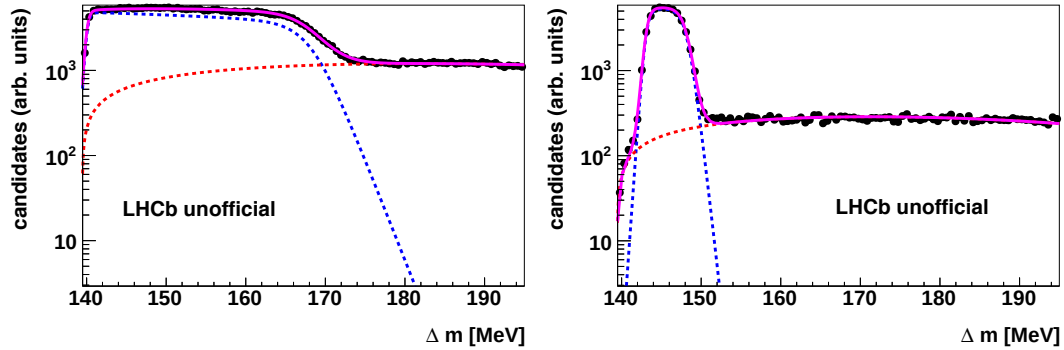


Figure 4.21: Fits of the Δm distribution of the $D^0 \rightarrow K^- \mu^+ \nu_\mu$ decay. On the left is a Δm fit in the visible mass region $1200 < m(K\mu) < 1300$ MeV, on the right in the visible mass region $1700 < m(K\mu) < 1800$ MeV.

Outcome and outlook

To evaluate the final asymmetry, the signal yields of the outcome of the different fits to the $D^0 \rightarrow K^- \mu^+ \nu_\mu$ decay are combined and the muon-pion asymmetry is found to be: $A_{(\text{track})}^{\mu^+ \pi^-} = (-0.41 \pm 0.12)\%$. In order to apply this method to the a_{sl}^s analysis, the events must be reweighted not only between the two control channels, but also to the pion and muon distributions of the a_{sl}^s signal sample.

A comparison of $A_{(\text{track})}^{\mu^+ \pi^-}$ measured by the method described in this section was made with the outcome of the partially reconstructed D^{*+} method, see Section 4.3, combined with the PID asymmetries that arise from the selection described above. This was done on the reweighted a_{sl}^s sample and the results are shown for all datasets used in the a_{sl}^s analysis in Figure 4.22. They include only statistical uncertainties, and show good agreement for the datasets recorded with the magnet polarity up. It is expected that including systematic uncertainties, there is also a good agreement with the magnet polarity down datasets. Besides systematic uncertainties from the signal fit and the reweighting strategies, a significant asymmetry is expected from the L0 TIS requirement, following the study described in Section 4.2.3. The L0 TIS asymmetry from the $D^0 \rightarrow K^- \mu^+ \nu_\mu$ decay does not completely cancel the TIS asymmetry coming from the $D^0 \rightarrow K^- \pi^+$ decay, because of the different number of tracks between these decays.

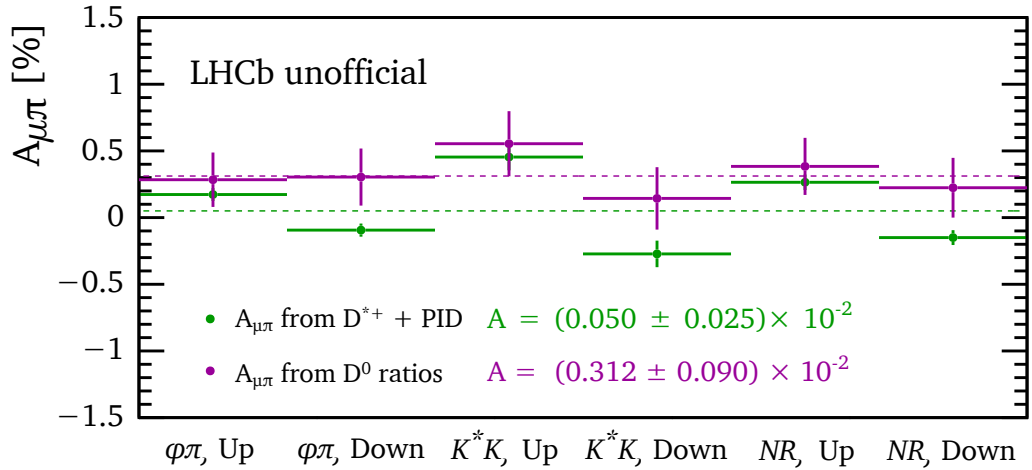


Figure 4.22: Comparison between the novel $A_{(\text{track})}^{\mu^+ \pi^-}$ method discussed in this section and the combination of the $A_{(\text{track})}^{\mu^+ \pi^-}$ asymmetries determined by the partially reconstructed D^{*+} method, corrected for PID asymmetries that arise from the signal selection. These asymmetries are determined for the reweighted a_{sl}^s dataset.

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Unfortunately, the multiple reweighting steps significantly reduce the statistical precision of the new method, to the order of 0.3%. In addition, it reweights the a_{sl}^s signal sample, which complicates the analysis. The other two methods used for determining $A_{(\text{track})}^{\mu^+\pi^-}$ for the a_{sl}^s analysis yield a combined statistical uncertainty of 0.05% and systematic uncertainty of 0.04%, such that in a weighted average, this method would not contribute to the precision and was abandoned.

Instead, however, this method provides an independent control sample with known asymmetries, and can be used to validate the other two tracking asymmetry methods. This will be crucial to reduce the systematic uncertainties of those methods when performing measurements in the future with high luminosities. In particular, it can help reducing the uncertainty on LHCb's material map by comparing this measurement to a combination of the $J/\psi \rightarrow \mu^+\mu^-$ tag-and-probe method combined with simulated material interaction asymmetries. At the moment, the material interaction is the limiting uncertainty in track efficiency determination [66], such that, for example, the difference in branching fractions of a two- versus four-body decay cannot be measured with a better precision than two percent.

5 CP violation in $B_s^0 - \bar{B}_s^0$ mixing

This chapter describes the study of the flavour-specific CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing (a_{sl}^s), measured by LHCb, using the full Run I dataset corresponding to a luminosity of 3 fb^{-1} . The previous measurement of a_{sl}^s from LHCb [29] used the dataset recorded in 2011, corresponding to a 1 fb^{-1} luminosity, and is extended and superseded by this measurement. To measure a_{sl}^s , the flavour specific decay $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu X$ is studied; the Feynman diagram showing this decay is displayed in Figure 5.1. From here, it is clear that the charge of the muon tags the flavour of the B_s^0 meson, since a positively charged muon always comes from a B_s^0 decay, and a negatively charged muon from a $\bar{B}_s^0$ decay.

The D_s^- meson is reconstructed in the $K^+ K^- \pi^-$ final state. The full phase space of the D_s^- decay is analysed, divided into three regions of the Dalitz plane, based on the invariant mass of the $K^+ K^-$ and $K^+ \pi^-$ pairs: the $\phi\pi$ region, in which most of the $K^+ K^-$ pairs go through the ϕ resonance, see Figure 5.2; the $K^* K$ region, where the majority of the $K^+ \pi^-$ pairs go through the $K^*(892)^0$ resonance, see Figure 5.3; and finally the non-resonant region, NR , see Figure 5.4. This is one of the main differences between the current and the previous analysis, which only studied the decays in the $\phi\pi$ resonant region.

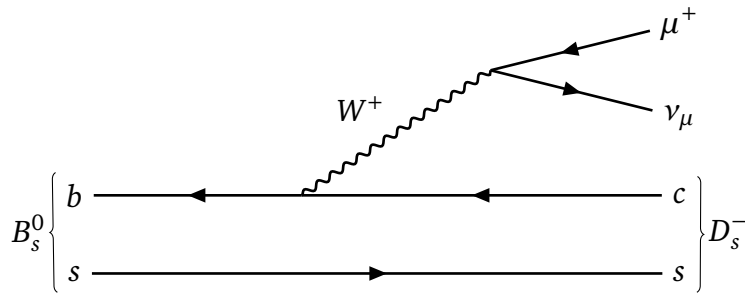


Figure 5.1: Feynman diagram of the decay $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$.

5. CP violation in $B_s^0\text{-}\bar{B}_s^0$ mixing

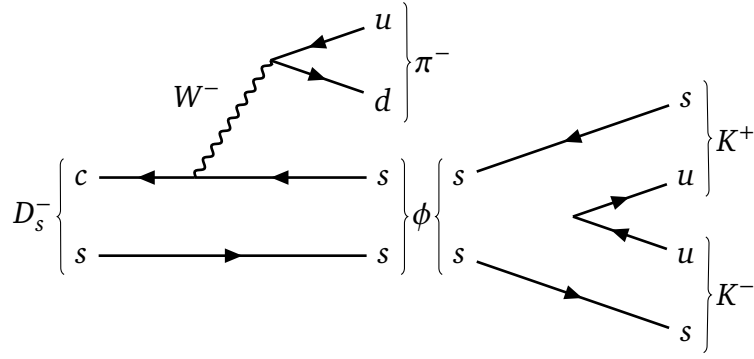


Figure 5.2: Quark flow diagram of the decay $D_s^- \rightarrow K^- K^+ \pi^-$, via the ϕ resonance.

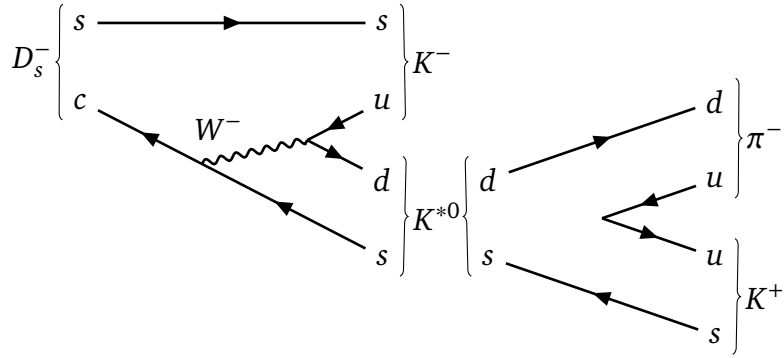


Figure 5.3: Quark flow diagram of the decay $D_s^- \rightarrow K^- K^+ \pi^-$, via the $K^{*}(892)^0$ resonance.

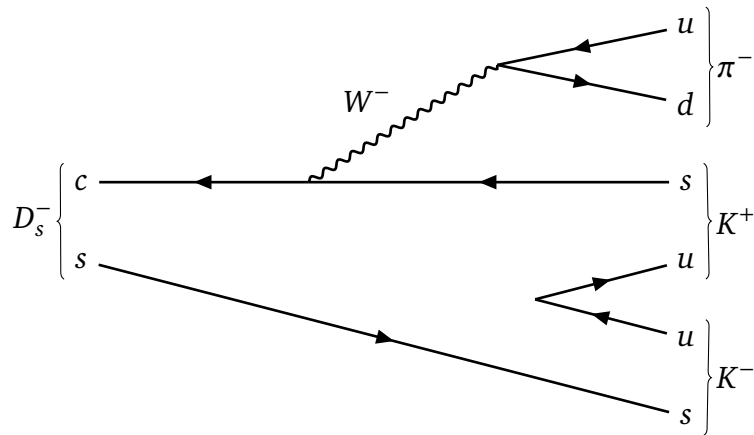


Figure 5.4: Feynman diagram of the non-resonant decay $D_s^- \rightarrow K^- K^+ \pi^-$.

This chapter is structured as follows. Section 5.1 derives the relevant expressions used in the a_{sl}^s analysis, following the expressions from Section 1.2. Section 5.2 describes the selection of the signal candidates and Section 5.3 the dilution from peaking backgrounds. This is followed by the signal extraction in Section 5.4, and a discussion on the various detection asymmetries in Section 5.5. The results, systematic uncertainties and cross-checks are described in Section 5.6 and the chapter finishes with the conclusion in Section 5.7.

5.1 Formalism of the a_{sl}^s measurement

While the flavour of the B_s^0 meson is known at decay, it is not known at production. Therefore, Equation (1.79) can be used to measure a_{sl}^s . Adjustments and simplifications to these equations are made in this section, concluding with a simple expression to perform a time-integrated measurement of a_{sl}^s in LHCb in Section 5.1.2.

5.1.1 The B_s^0 production asymmetry

The equations in Section 1.2 are only valid when an equal number of B_s^0 and $\bar{B}_s^0$ mesons are produced. However, the pp initial state is not symmetric, which causes a production asymmetry. Therefore, Equation (1.79) has to be rederived including these production asymmetries.

In the case of production asymmetries, the time-independent normalisation factor, $\mathcal{N}_f$, is not the same for both processes and is replaced by $\mathcal{N}$ and $\bar{\mathcal{N}}$. $\mathcal{N}$ is the production fraction of B_s^0 mesons and $\bar{\mathcal{N}}$ the fraction of $\bar{B}_s^0$ mesons produced. The decay rates of $B_s^0 \rightarrow f$ and $\bar{B}_s^0 \rightarrow f$ can be expressed as

$$\Gamma(B_s^0(t) \rightarrow f) = \mathcal{N} |A_f|^2 e^{-\Gamma_s t} \left\{ \frac{1}{2} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \frac{1}{2} \cos(\Delta m_s t) \right\}, \quad (5.1)$$

$$\Gamma(\bar{B}_s^0(t) \rightarrow f) = \bar{\mathcal{N}} |A_f|^2 \frac{1}{1 - a_{\text{sl}}^s} e^{-\Gamma_s t} \left\{ \frac{1}{2} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \frac{1}{2} \cos(\Delta m_s t) \right\}. \quad (5.2)$$

Adding the total number of decays into the final state f yields

$$\begin{aligned} \Gamma[f, t] &\equiv \Gamma(B_s^0(t) \rightarrow f) + \Gamma(\bar{B}_s^0(t) \rightarrow f) \\ &= |A_f|^2 \frac{e^{-\Gamma_s t}}{2} \left\{ \left(\mathcal{N} + \frac{\bar{\mathcal{N}}}{1 - a_{\text{sl}}^s} \right) \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \left(\mathcal{N} - \frac{\bar{\mathcal{N}}}{1 - a_{\text{sl}}^s} \right) \cos(\Delta m_s t) \right\}. \end{aligned} \quad (5.3)$$

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Similarly, the decay rates to final state $\bar{f}$, are given by

$$\Gamma(B_s^0(t) \rightarrow \bar{f}) = \mathcal{N} |A_f|^2 (1 - a_{sl}^s) e^{-\Gamma_s t} \left\{ \frac{1}{2} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \frac{1}{2} \cos(\Delta m_s t) \right\}, \quad (5.4)$$

$$\Gamma(\bar{B}_s^0(t) \rightarrow \bar{f}) = \bar{\mathcal{N}} |A_f|^2 e^{-\Gamma_s t} \left\{ \frac{1}{2} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \frac{1}{2} \cos(\Delta m_s t) \right\}, \quad (5.5)$$

and the sum yields

$$\begin{aligned} \Gamma[\bar{f}, t] &\equiv \Gamma(B_s^0(t) \rightarrow \bar{f}) + \Gamma(\bar{B}_s^0(t) \rightarrow \bar{f}) \\ &= |A_f|^2 \frac{e^{-\Gamma_s t}}{2} \left\{ \left(\mathcal{N}(1 - a_{sl}^s) + \bar{\mathcal{N}} \right) \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \right. \\ &\quad \left. + \left(\mathcal{N}(1 - a_{sl}^s) - \bar{\mathcal{N}} \right) \cos(\Delta m_s t) \right\}. \end{aligned} \quad (5.6)$$

It is useful to define the B_s^0 production asymmetry, A_P :

$$A_P \equiv \frac{\bar{\mathcal{N}} - \mathcal{N}}{\bar{\mathcal{N}} + \mathcal{N}}. \quad (5.7)$$

In addition, also the time-dependent acceptance function, $\varepsilon(t)$, must be added to evaluate the expression of the measurement of a_{sl}^s . This describes the probability that a $B_s^0 \rightarrow D_s^+ \mu \nu X$ candidate is reconstructed and accepted, as a function of decay time. To first order in a_{sl}^s , including both A_P and $\varepsilon(t)$, this gives

$$\frac{\Gamma[f, t] - \Gamma[\bar{f}, t]}{\Gamma[f, t] + \Gamma[\bar{f}, t]} = \frac{a_{sl}^s}{2} - \left[A_P + \frac{a_{sl}^s}{2} \right] \frac{e^{-\Gamma_s t} \cos(\Delta m_s t) \varepsilon(t)}{e^{-\Gamma_s t} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \varepsilon(t)}. \quad (5.8)$$

Since B_s^0 mesons oscillate rapidly into $\bar{B}_s^0$ mesons, and vice versa, the measurement of a_{sl}^s can be made time-integrated. Therefore, Equation (5.3) and Equation (5.6) can be integrated over time and, instead of Equation (5.8), yield [29]

$$\begin{aligned} \frac{\Gamma[f] - \Gamma[\bar{f}]}{\Gamma[f] + \Gamma[\bar{f}]} &= \frac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]} \\ &= \frac{a_{sl}^s}{2} - \left[A_P + \frac{a_{sl}^s}{2} \right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cos(\Delta m_s t) \varepsilon(t) dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \varepsilon(t) dt}. \end{aligned} \quad (5.9)$$

To evaluate the integral, the acceptance function must be determined. This is done using Monte Carlo simulations [117], which yields the following expression for $\varepsilon(t)$:

$$\varepsilon(t) = \frac{[1 + \beta(t - t_0)][a(t - t_0)]^n}{1 + [a(t - t_0)]^n}, \quad (5.10)$$

where $a = 1.4$, $n = 1.8$, $t_0 = 0.077$ and $\beta = -0.049$. Figure 5.5 shows the acceptance as a function of decay time.

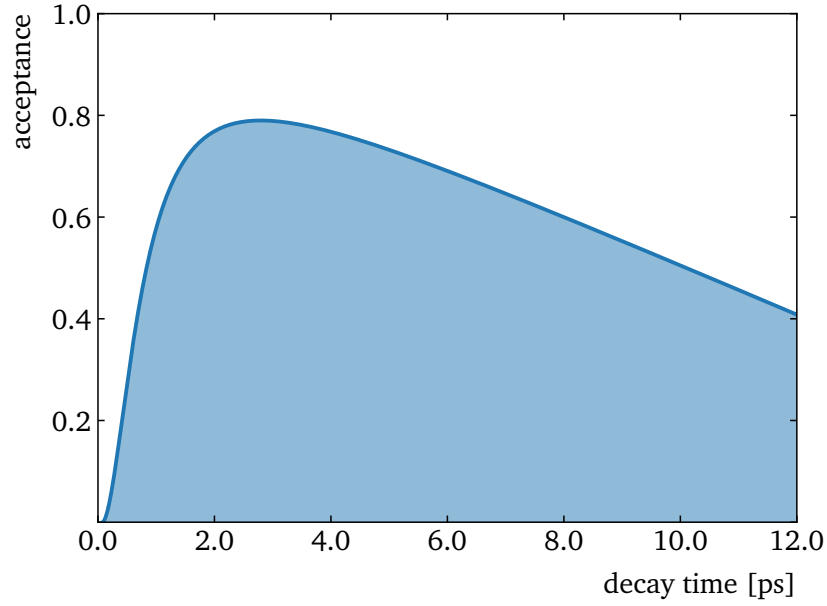


Figure 5.5: Plot of the B_s^0 acceptance efficiency in LHCb as a function of decay time, determined using Monte Carlo events. This figure is reproduced from [117].

The ratio of integrals can be calculated using this acceptance function and the known values, of Γ_s , $\Delta\Gamma_s$, and Δm_s (listed in Table 1.3). This yields a value of 0.002. Since the production asymmetry is of the order of a percent, this reduces the effect of the asymmetric initial state to below 10^{-4} , which is much smaller than the experimental precision of LHCb's a_{sl}^s measurement. Therefore, Equation (5.9) simplifies to

$$\frac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]} \approx \frac{a_{\text{sl}}^s}{2}. \quad (5.11)$$

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5.1.2 Analysis strategy for a_{sl}^s in LHCb

The asymmetry that is measured by a signal fit is called A_{raw} and measures the difference between the number of $D_s^-\mu^+X$ and $D_s^+\mu^-X$ candidates, determined from the $D_s^\pm$ invariant mass distributions

$$A_{\text{raw}} = \frac{N(D_s^-\mu^+X) - N(D_s^+\mu^-X)}{N(D_s^-\mu^+X) + N(D_s^+\mu^-X)}. \quad (5.12)$$

This raw asymmetry does not simply equal a_{sl}^s , but is contaminated by backgrounds of real D_s^- mesons that do not originate from a B_s^0 decay. These are called peaking backgrounds, because they have a mass peak at the B_s^0 mass. The fraction of these backgrounds is called f_{bkg} and their corresponding asymmetry is A_{bkg} .

Additionally, the measurement of the asymmetries is affected by detection asymmetries A_{D} . Therefore, A_{raw} measures to first order in the asymmetries

$$A_{\text{raw}} = (1 - f_{\text{bkg}}) \frac{a_{\text{sl}}^s}{2} + f_{\text{bkg}} A_{\text{bkg}} + A_{\text{D}}. \quad (5.13)$$

Equivalently:

$$\frac{a_{\text{sl}}^s}{2} = \frac{1}{1 - f_{\text{bkg}}} (A_{\text{raw}} - A_{\text{D}} - f_{\text{bkg}} A_{\text{bkg}}), \quad (5.14)$$

which can also be written as

$$\frac{a_{\text{sl}}^s}{2} = \frac{N_{\text{sig}} + N_{\text{bkg}}}{N_{\text{sig}}} (A_{\text{raw}} - A_{\text{D}}) - \frac{N_{\text{bkg}}}{N_{\text{sig}}} A_{\text{bkg}}, \quad (5.15)$$

where N_{sig} is the number of signal events, and N_{bkg} the number of peaking background events. These signal events are measured by making a fit to the D_s^- mass peak. Fitting the D_s^- mass distribution is preferred to using the B_s^0 mass peak, because part of the momentum information of the B_s^0 is carried away by the neutrino, resulting in a smeared mass peak for the partially reconstructed B_s^0 .

It is important to note that in this analysis three types of backgrounds are distinguished, of which the above-mentioned peaking background is one. Each of these backgrounds has its own treatment. Peaking backgrounds are those backgrounds coming from real D_s^- decays, which are hard to distinguish from the signal since these backgrounds have the same reconstructed D_s^- mass. They are discussed in more detail in Section 5.3.

The second type of backgrounds are combinatorial backgrounds, which come from random combinations of tracks that mimic the signal candidates. These are dealt with by including them in the fit model in Section 5.4. Lastly, there are non-peaking backgrounds, which mainly originate from misidentified particles. These are listed in Section 5.2.5 and largely removed in the candidate selection.

5.2 Selection

The selection of candidates is done in two stages. The first stage is the online stage, which is performed during data taking and comprises three trigger stages, see Section 2.2.6: the hardware (L0) trigger, followed by two software triggers (HLT1 and HLT2). The second stage is done offline. This consists of two parts, where the first is an LHCb general selection called stripping, which is followed by a specific selection for this analysis, including a generic selection and one to remove peaking backgrounds.

5.2.1 Hardware trigger

The L0 trigger used in this analysis is designed to trigger on muons, and is called L0Muon, which is chosen because it is a very efficient trigger. It is described in more detail in Section 2.2.6. It requires the particle with the highest transverse momentum to satisfy $p_T > 1.48$ GeV, while the p_T resolution of the L0 trigger is around 20%.

5.2.2 High level trigger

The first high-level trigger is the logical OR of the muon trigger, called Hlt1TrackMuon and the track trigger, Hlt1TrackAllL0. The former can be fired only by a muon, while the latter can come from any of the tracks from the B_s^0 decay, including the muon. The second high level trigger is also a logical OR of the muon trigger called Hlt2SingleMuon and a topological trigger on all B_s^0 decay products.

HLT1 selection

Both the HLT1 lines Hlt1TrackMuon and Hlt1TrackAllL0 are single track lines, which use one high p_T track to identify a decay from a B or D hadron. They reconstruct a track and require a pass from a specific L0 trigger, with a minimum p_T and p requirement. In addition, they require a minimum number of hits in the VELO stations, and a maximum number of “missing” VELO hits, that is where

5. CP violation in B_s^0 - $\bar{B}_s^0$ mixing

track extrapolation shows that there should have been a hit, while there is none. Moreover, there are requirements on a minimum number of hits for the track, and on the fit quality of the track. Lastly, the track is required to be displaced from the primary vertex by applying requirements on the impact parameter (IP).

Table 5.1: Selection applied in the HLT1 lines Hlt1TrackAllL0 and Hlt1TrackMuon.

variable	Hlt1TrackAllL0	Hlt1TrackMuon
L0	L0_DECISION_PHYSICS	L0_Muon or L0_DiMuon
p [GeV]	> 10.0	> 8.0
p_T [GeV]	> 1.7	> 1.0
# VELO hits	> 9	> 0
# VELO missing hits	< 3	< 999
# hits	> 16	> 0
track χ^2/ndf	< 2	< 2
χ_{IP}^2	> 16	> 16
IP [mm]	> 0.1	> 0.1

HLT2 selection

The HLT2 trigger comprises four trigger lines: the Hlt2SingleMuon and Hlt2TopoMu(2|3|4)BodyBBDT. The former is applied on the muon, and selects a clean sample of muons with large p_T and a large IP [118]. Since there is a large number of events with single muons in LHCb, a prescale is applied to reduce the rate. All selection requirements are listed in Table 5.2.

Table 5.2: Selection applied in the HLT2 Hlt2SingleMuon trigger line.

variable	Hlt2SingleMuon
prescale	0.5
HLT1	Hlt1SingleMuon
p_T	$> 1300 \text{ MeV}$
track χ^2/ndf	< 2
IP	$> 0.5 \text{ mm}$
χ_{IP}^2	> 200

The so-called topological triggers are designed to identify partially reconstructed b -hadron decays with 2, 3, or 4 tracks, of which one must be a muon. Input tracks are selected with the requirements listed in Table 5.3. This table also lists a selection for neutral particles that are built from 2-tracks, the so-called V^0 mesons. These are particles that have a lifetime of $\sim 10^{-10}$ s, such as Λ^0 or K_s^0 , which are treated as tracks by this trigger.

Two tracks are combined to make a 2-body proto-object. Afterwards, up to two more tracks can be added to form a 3-, or 4-body object. The selection applied to these n -track objects are shown in Table 5.4. The DOCA requirement, which is listed there, is not very tight, since for partially reconstructed decays, not all tracks originate from the same vertex. To clean up the signal, the selection is therefore continued using a multivariate analysis: Bonsai Boosted Decision Tree (BBDT) [119]. This uses as input variables the flight distance χ^2 , p_T sum of the selected tracks, minimum p_T , DOCA, mass and corrected mass. Different selection combinations of these variables allow a candidate to pass the topological trigger, which are listed in reference [120].

Table 5.3: Track selection for the HLT2 Hlt2TopoMu(2|3|4)BodyBBDT line.

	variable	requirement
K, π, p tracks	p_T	> 500 MeV
	p	> 5000 MeV
	χ_{IP}^2	> 4
	track χ^2/ndf	< 3
μ	track χ^2/ndf	< 4
		IsMUON
V^0 meson	track χ_{IP}^2	> 16
	χ_{vtx}^2	< 10
	p_T	> 500 MeV
	p	> 5000 MeV
	χ_{IP}^2	> 4
	DIRA	> 0
	χ_{VS}^2	> 1000
	$m(V^0)$	$\in m_{\text{PDG}}(K_s^0) \pm 45$ MeV
		OR $\in m_{\text{PDG}}(\Lambda^0) \pm 30$ MeV

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Table 5.4: n -body object selection in the HLT2 Hlt2TopoMu(2|3|4)BodyBBDT trigger line. The first requirements are applied to the proto-object, followed by the second set of tracks. The last set of tracks is applied to the n -body object as well, but these requirements are not applied when passing the n -body object on to the $n + 1$ -body line.

		$n = 2$	$n = 3$	$n = 4$
input $(n - 1)$ -track object	χ_{vtx}^2	–	< 10	–
	$m[\text{MeV}]$	–	< 6000	< 6000
n -track object	$m[\text{MeV}]$		7000	
	max. DOCA [mm]		< 0.2	
	DIRA		> 0	
	χ_{VS}^2		> 100	
n -body line	min. track χ^2/ndf		< 2.4	
	$\Sigma(p_T)[\text{MeV}]$	> 3000	> 4000	> 4000

5.2.3 Stripping selection

The first step in LHCb’s offline selection is called stripping. Two stripping lines have been used for this analysis. Firstly, the Strippingb2DsMuXB2DMuNuXLine inclusively selects events with a $B \rightarrow D_s^- \mu X$ decay, and is called the inclusive stripping line. The second line is called Strippingb2DsMuXPhiPiB2DMuNuXLine, called PhiPi, and is optimised to select events with a $B \rightarrow D_s^- \mu X$ decay where the D_s^- decays through the ϕ resonance. These two lines overlap, but the overlap is removed when processing the events. An overview of all stripping selection criteria is given in Table 5.5.

Both lines place requirements on the event, the tracks in this event, and the particles that can be reconstructed by combining tracks. In order to select good tracks, while reducing background, requirements are placed on p , p_T , as well as the quality of the track fit, and particle identification. To make sure that the tracks do not originate from the primary vertex (PV), a minimum requirement on χ_{IP}^2 is placed on all tracks. Since there can be multiple PVs per event, this requirement is performed on the PV with the smallest χ_{IP}^2 . In addition, a requirement on the ghost probability ensures that the tracks are unlikely to be fake [116].

In the PhiPi stripping line, an additional requirement is made on the K^+K^- vertex and mass. Combining the $K^+K^-\pi^+$ tracks to a D_s^- candidate, a minimum mass, p_T and good quality vertex are required. The distance of closest approach (DOCA) χ^2 selection checks if the distance between each combination of two tracks (K^- , K^+ , and π^-) is less than a certain value. The DIRA requirement ensures that the D_s^- comes from the direction of the PV, but need not point straight towards it. Lastly, requirements are applied on the B_s^0 mass and its vertex fit. The D_s^- is required to fly in the forward direction and the reconstructed B_s^0 should point towards the PV.

5.2.4 Dalitz regions

This analysis is split in three disjoint regions that are characterised by two resonant regions in the phase space of the $D_s^- \rightarrow K^-K^+\pi^-$ decay. The Dalitz plot of the signal in Figure 5.6 clearly shows two resonant regions. One is the region where the production of the kaon pair goes through the ϕ resonance, while the other is the one where the $K^+\pi^-$ pair is produced through the $K^*(892)^0$ resonance. The third region used in the analysis is the non-resonant region, which does not contain any resonances with a large branching fraction. The selection of the Dalitz regions is based only on the invariant mass of the K^+K^- and $K^+\pi^-$ pairs, and also includes a small number of non-resonant decays in the resonant regions.

The three regions which are referred to as Dalitz regions in this thesis, are defined as follows:

- $\phi\pi$: Invariant mass of the K^+K^- pair within ± 20 MeV of the nominal ϕ mass, selected by the PhiPi stripping line.
- K^*K : Invariant mass of the $K^+\pi^-$ pair within ± 90 MeV of the nominal K^{*0} mass, and not in the $\phi\pi$ region. These candidates are selected by the inclusive stripping line.
- NR (non-resonant): All remaining candidates, i.e. not in the $\phi\pi$ nor in the K^*K region, also selected by the inclusive stripping line.

The $\phi\pi$ region is the cleanest due to the more stringent requirements from the stripping and in particular the requirement on the invariant mass of the kaon pair. The NR region has the most background, which holds for both combinatorial and non-peaking backgrounds.

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Table 5.5: Selection applied in the two stripping lines. PhiPi refers to the Strippingb2DsMuXPhiPiB2DMuNuXLine and inclusive to Strippingb2DsMuX-B2DMuNuXLine. If a requirement differs in the inclusive line with respect to the PhiPi line, it is indicated in the corresponding column, otherwise they are the same.

		PhiPi	inclusive
event	# long tracks	< 250	
	# PVs	≤ 1	
μ^+	p	> 3.0 GeV	
	p_T	> 1.2 GeV	> 0.8 GeV
	track GhostProb	< 0.5	
	track χ^2/ndf	< 4.0	
	min. χ_{IP}^2 (PV)	> 9.0	
	DLL $_{\mu\pi}$	> 0.0	
$K^\pm$	p	> 2.0 GeV	
	p_T	> 300.0 MeV	
	track GhostProb	< 0.5	
	track χ^2/ndf	< 4.0	
	min. χ_{IP}^2 (PV)	> 4.0	> 9.0
	DLL $_{K\pi}$	> -5.0	> 4.0
π^-	p	> 2.0 GeV	
	p_T	> 300.0 MeV	
	track GhostProb	< 0.5	
	track χ^2/ndf	< 4.0	
	min. χ_{IP}^2 (PV)	> 4.0	> 9.0
	DLL $_{K\pi}$	–	< 10.0
ϕ	$m(K^+K^-)$	$\in m_{\text{PDG}}(\phi) \pm 40 \text{ MeV}$	–
	$\chi_{\text{vtx}}^2/\text{ndf}$	< 25.0	–
D^-	$m(K^-K^+\pi^-)$	$\in m_{\text{PDG}}(D_s^+) \pm 80 \text{ MeV}$	
	$\Sigma p_T(K^-K^+\pi^-)$	> 800 MeV	> 1800 MeV
	$\Sigma(\text{min. } \chi_{\text{IP}}^2(\text{PV}))$	> 4.0	–
	DOCA χ^2	–	< 20 mm
	$\chi_{\text{vtx}}^2/\text{ndf}$	< 6.0	
	PV vertex distance χ^2	> 100.0	
	PV DIRA	> 0.99	
B_s^0	$m(K^-K^+\pi^-\mu^+)$	$\in [2500, 6000] \text{ MeV}$	
	$\chi_{\text{vtx}}^2/\text{ndf}$	< 6.0	
	PV DIRA	> 0.999	
	$z_{\text{vtx}}(D_s^-) - z_{\text{vtx}}(D_s^-\mu^+)$	> 0	

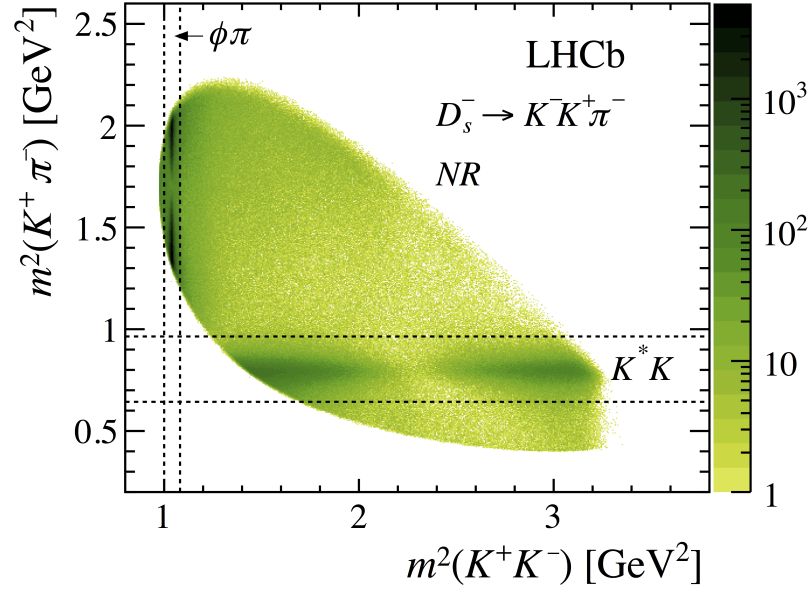


Figure 5.6: Dalitz plot of the $D_s^- \rightarrow K^- K^+ \pi^-$ decay from data with all selection applied. Overlaid are the definitions of the three Dalitz regions. In order to suppress backgrounds, only the region around the D_s^- mass peak is shown: $1950 < m(KK\pi) < 1990$ MeV.

5.2.5 Reducing non-peaking backgrounds

One type of background that can largely be removed from the data is the non-peaking background. This comes from events in which one or more particles are misidentified, for example when a proton is identified as a kaon. These backgrounds appear in different amounts across the Dalitz regions and hence the selection to suppress these varies per region. Several requirements have been applied to clean up the signal region and a complete list is given in Table 5.7. Only the most important ones are discussed here.

The most frequently misidentified particle in this decay is kaon with the same charge as the D_s^- meson, the K^- . When a particle is misidentified as a kaon, the reconstruction software uses the kaon mass hypothesis instead of the correct one. To reduce this background, a selection using the RICH PID information (PROBNNK) is applied, which is more stringent in the $K^* K$ and NR regions than in the $\phi\pi$ region. The difference between the reconstructed D_s^- mass and the invariant mass of the three D_s^- daughter particles, where one has a different mass hypothesis, can be studied to find and exclude these backgrounds. Since PID requirements are applied in this analysis, which strongly reduce the rate of misidentified particles, it is assumed that the number of events with multiple misidentified particles is negligible.

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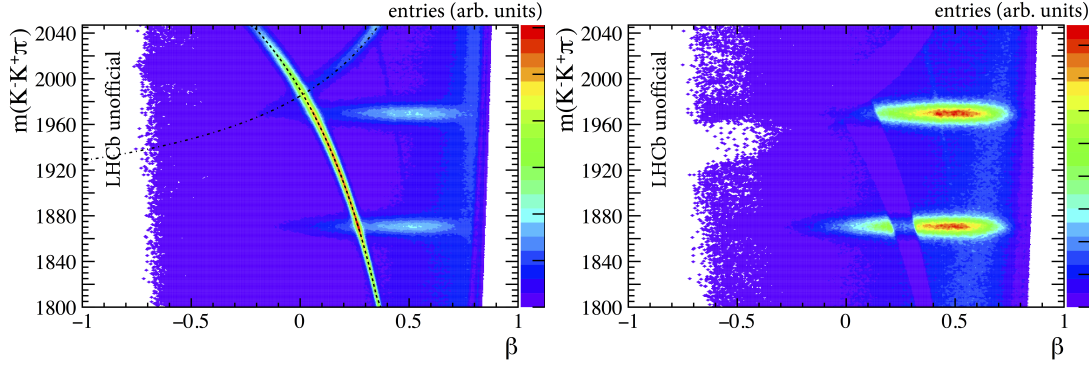


Figure 5.7: $m(K^-K^+\pi^-)$, β spectrum for the dataset recorded in 2011 and 2012, using both magnet polarities, in the NR Dalitz region. On the left before, and on the right after the reflection vetoes and $PROBNNK$ selection. Overlaid on the left are the predictions of the spectrum for misidentified pions in the dashed-dotted line (D^- background) and for misidentified protons in the dotted line (Λ_c^- background). The faint vertical band around $\beta = 0.8$ is due to $D^{*-} \rightarrow \bar{D}^0(\rightarrow K^+\pi^-\pi^+\pi^-)\pi^-$, where one of the pions is misidentified as a kaon.

To illustrate how the selection suppresses non-peaking backgrounds, the example of a misidentified $\Lambda_c^- \rightarrow \bar{p} K^+ \pi^-$ is used. Here, the $\bar{p}$ is misidentified as a K^- , indicated by $K_{\bar{p}}^-$, and resembles the $D_s^- \rightarrow K^- K^+ \pi^-$ decay. The mass difference between the D_s^- and the Λ_c^- mass hypotheses can be defined as

$$m^2(K^- K^+ \pi^-) - m^2(p^- K^+ \pi^-) = (m^2(K^-) - m^2(\bar{p})) \frac{2}{1 - \beta}. \quad (5.16)$$

In this equation, β is the momentum asymmetry parameter, which is defined as

$$\beta \equiv \frac{p(K^+) - p(K^-) + p(\pi^-)}{p(K^+) + p(K^-) + p(\pi^-)}. \quad (5.17)$$

Note that in this equation the misidentified particle, the same-sign kaon in this case, has a minus sign in front of its momentum.

Figure 5.7 (left) shows the distribution of $m(K^-K^+\pi^-)$ versus β for the NR region. The two horizontal bands at 1870 and 1970 MeV respectively are the D^- and D_s^- mass. In addition, two curved bands are visible and with the predictions for misidentified pions in the dashed-dotted line, and protons with the dotted line. The protons come from the decay $\bar{\Lambda}_b^0 \rightarrow \Lambda_c^- \mu^+ \nu_\mu X$, where $\Lambda_c^- \rightarrow \bar{p} K^+ \pi^-$ and are removed by applying a requirement on the $DLL_{p\pi}$ - $DLL_{K\pi}$ in the mass window around the Λ_c^- mass for $m(K_{\bar{p}}^- K^+ \pi^-)$.

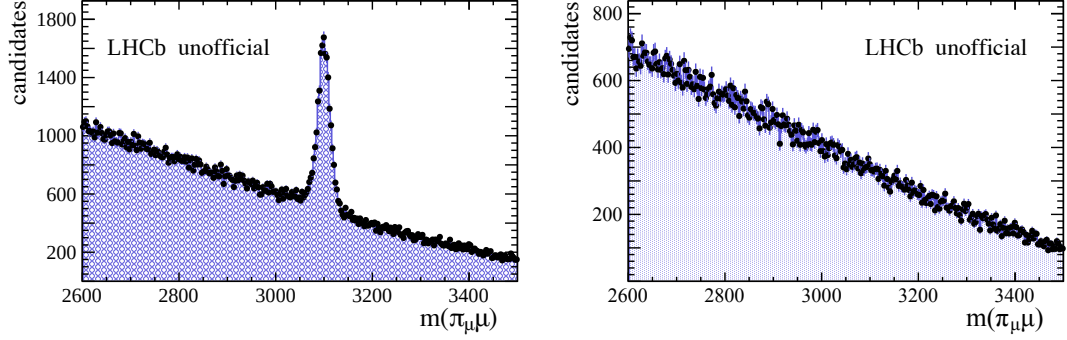


Figure 5.8: Misidentified $\mu^+\mu^-$ mass spectrum for the dataset from the 2012 data-taking year, recorded with the magnet polarity up, in the $\phi\pi$ Dalitz region. The final state pion has the muon-mass hypothesis imposed and is combined with the final state muon. On the left is the spectrum before, and on the right after applying the reflection vetoes and the PROBNNk requirements.

The misidentified pion in Figure 5.7 (left) comes from the $B^0 \rightarrow D^-\mu^+\nu_\mu$, where $D^- \rightarrow K^-\pi^+\pi^-X$ and is reduced by placing a requirement on the kaon identification for events around the D^- mass for $m(K_\pi^-K^+\pi^-)$. Figure 5.7 (right) shows the mass versus β distribution in the NR region after all requirements have been applied, and the bands where the D^- and Λ_c^- contributions have been removed, are clearly visible. The selection on the D^- background is not applied in the $\phi\pi$ region since this background is not visible there.

Another source of background are misidentified $J/\psi \rightarrow \mu^+\mu^-$ decays, where the J/ψ meson originates from a B decay. One of the muons is misidentified as a pion, while the B daughters can mimic a D_s^- decay. To remove this background, the invariant mass of the $\pi^-\mu^+$ pair is calculated while replacing the pion mass with the muon mass, indicated by $m(\pi_\mu^-\mu^+)$. The resulting histogram for the $\phi\pi$ region is demonstrated in Figure 5.8 (left) and shows a clear peak at the J/ψ mass. This background is removed by requiring that in the $m(\pi_\mu^-\mu^+)$ mass window around the J/ψ mass the pion does not satisfy ISMUON, resulting in Figure 5.8 (right). Also the same-sign kaon can be a misidentified muon and similar requirements are applied to remove this background. In the $\phi\pi$ region, however, this is not necessary since the tight mass requirement on the kaon pair already removes such backgrounds.

The selection on the non-peaking backgrounds is fully listed in Table 5.7 under the section “vetoes”, where the selection requirements described above correspond respectively to the J/ψ , Λ_c^- and D^- vetoes. Other backgrounds that are removed, are the following. Misidentified pions that come from a K^* decay are removed by the $K^*(892)^0$ veto. Misidentified $D^{*-} \rightarrow \bar{D}^0\pi^-$ decays, where $\bar{D}^0 \rightarrow K^+\pi^-X$ and

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pions are misidentified as kaons are reduced with the $D^{*-}(\rightarrow \bar{D}^0\pi^-)$ vetoes: one for pions misidentified as kaons with the same sign as the D_s^- meson, and one for those with the opposite sign. These requirements are quite tight and remove a significant amount of signal as well. However, it is preferred to remove some signal, since it is difficult to distinguish signal from this background in a mass fit.

To further suppress misidentified pions, at low $m(K_\pi^+K^-)$, there is a stringent requirement on the kaon identification. This also removes contributions from $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$. Lastly, a background that comes from correctly identified decays is the $D^{*-} \rightarrow \bar{D}^0 \pi^-$, where the $\bar{D}^0 \rightarrow K^+ K^-$. This is only visible in the NR region and is removed by applying a requirement on the $\Delta m = m(K^- K^+ \pi^-) - m(K^- K^+)$.

Table 5.6: Background vetoes applied to the signal sample after stripping. K^- refers to the same-sign kaon, while K^+ refers to the opposite-sign kaon.

vetoes	remove if	applied to
J/ψ veto	π^- isMUON AND $3042 < m(\pi_\mu^- \mu^+) < 3147$ MeV	$\phi\pi, K^*K, NR$
J/ψ veto	K^- isMUON AND $3042 < m(K_\mu^- \mu^+) < 3147$ MeV	K^*K, NR
Λ_c^- veto	K^- (DLL _{pπ} -DLL _{Kπ}) > 0.0 AND $2261 < m(K_p^- K^+ \pi^-) < 2315$ MeV	$\phi\pi$
Λ_c^- veto	K^- (DLL _{pπ} -DLL _{Kπ}) > -15.0 AND $2261 < m(K_p^- K^+ \pi^-) < 2315$ MeV	K^*K, NR
$K^*(892)^0$ veto	K^- DLL _{Kπ} < 8 AND $ m(K_\pi^- K^+) - 892 < 25$ MeV	K^*K, NR
D^- veto	K^- DLL _{Kπ} < 30 AND $ m(K_\pi^- K^+ \pi^-) - 1870 < 20$ MeV	K^*K, NR
low $m(K^+K^-)$ misID K^- veto	K^- DLL _{Kπ} < 7 AND $m(K_\pi^- K^+) < 800$ MeV	K^*K, NR
$D^{*-}(\rightarrow \bar{D}^0\pi^-)$ veto	$m(K_\pi^- K^+ \pi^-) - m(K^+ \pi^-) < 175$ MeV	K^*K, NR
$D^{*-}(\rightarrow \bar{D}^0\pi^-)$ veto	$m(K^- K_\pi^+ \pi^-) - m(K^- \pi^-) < 175$ MeV	K^*K, NR
$D^{*-} \rightarrow \bar{D}^0(K^- K^+) \pi^-$ veto	$135 < m(K^- K^+ \pi^-) - m(K^- K^+) < 152$ MeV	NR

5.2.6 Overview selection

Table 5.7 gives an overview of the entire signal selection of the candidates, after the stripping selection. The kinematic requirements on the final state particles are applied to match the detection asymmetry control samples. Moreover, the D_s^- candidate is required to move in the forward direction and prompt D_s^- background is almost entirely removed by applying a requirement on the $\log(IP)$, which is illustrated in Figure 5.9. To suppress background, a mass window around the B_s^0 mass and the B_s^0 corrected mass is selected. This corrected mass requirement is explained in more detail in Section 5.3.

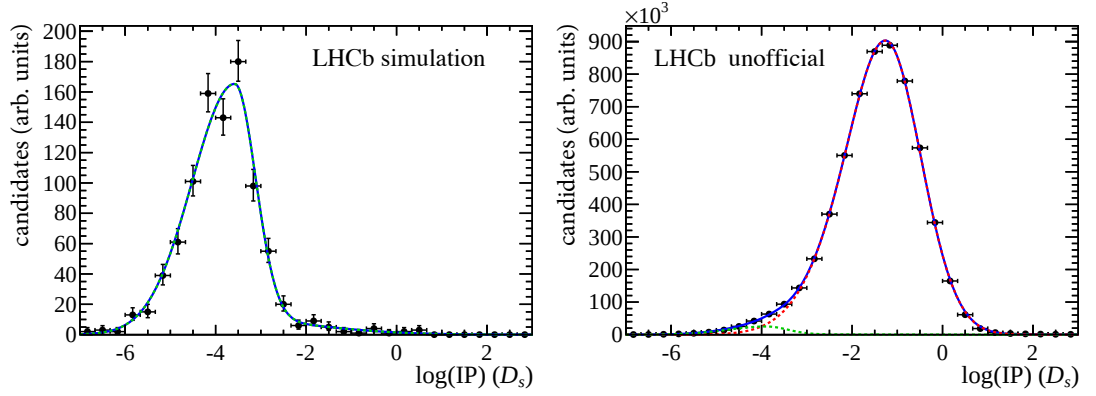


Figure 5.9: Logarithm of the impact parameter (IP) of the D_s^- in (left) prompt simulated inclusive $D_s^- \rightarrow K^- K^+ \pi^-$ decays, and (right) in data. The IP requirement of $\log(\text{IP}) > -3$ efficiently removes prompt decays, while retaining most of the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu X$ signal.

The requirement on the runNumbers comes from a data-taking period which is used to make a look-up table with L0Muon efficiencies. This table functions as a cross-check of the muon detection asymmetry and the corresponding data-taking period is thus excluded from this measurement.

Table 5.7: Selection applied to the signal sample after stripping. The resulting yields, after also applying the requirements listed in Table 5.6 can be seen in Figure 5.10.

	variable	requirement	
Dalitz regions	$\phi\pi$	$ m(K^- K^+) - 1020 \text{ MeV} < 20 \text{ MeV}$	
	$K^* K$	$ m(K^- K^+) - 1020 \text{ MeV} > 20 \text{ MeV}$ AND $ m(K^+ \pi^-) - 892 \text{ MeV} < 90 \text{ MeV}$	
	NR	$ m(K^- K^+) - 1020 \text{ MeV} > 20 \text{ MeV}$ AND $ m(K^+ \pi^-) - 892 \text{ MeV} > 90 \text{ MeV}$	
event and trigger	runNumber	$! \in [110000, 114000]$	
	L0	μ is L0Muon TOS	
	HLT1	B is Hlt1TrackAllL0 TOS	
		μ is Hlt1TrackMuon TOS OR	
	HLT2	B is Hlt2TopoMu(2 3 4)BodyBBDT TOS OR	
		μ is Hlt2SingleMuon TOS	
candidate B_s^0 and D_s^-	$z(D_s^-) - z(D_s^- \mu^+)$	$> 0.0 \text{ mm}$	
	$D_s^- \log(\text{IP})$	> -3.0	
	$m_{\text{corr}}(B_s^0)$	$> 4200 \text{ MeV}$	
	$m(B_s^0)$	$< 5200 \text{ MeV}$	
	$m(D_s^-)$	$\in [1800, 2047] \text{ MeV}$	
final state particles	μp_T	$> 1.2 \text{ GeV}$	
	μp	$> 6.0 \text{ GeV}$	
	πp_T	$> 400 \text{ MeV}$	
	πp	$> 5.0 \text{ GeV}$	
	same-sign K PROBNNK	> 0.1	applied to: $\phi\pi$ $K^* K, NR$
	same-sign K PROBNNK	> 0.15	

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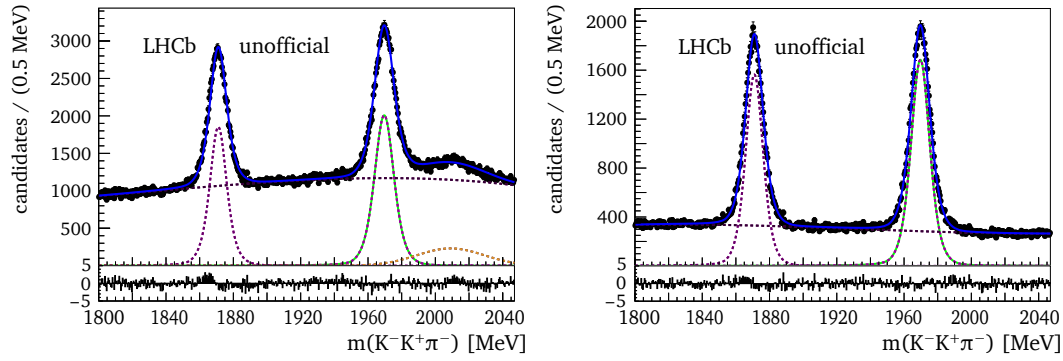


Figure 5.10: $m(K^-K^+\pi^-)$ spectrum, fits, and pulls before (left) and after (right) applying the reflection vetoes for the NR region. Fits are performed using the strategy explained in Section 5.4, including the D^- mass peak on the left and the D_s^- mass peak on the right. The orange dashed line in the left plots is the contribution from misidentified D^- decays.

After applying the full selection, the signal is much cleaner. The most striking difference before and after applying the background vetoes can be seen in the NR region. Figure 5.10 shows on the left a fit to the signal before, and on the right after the non-peaking backgrounds have been removed. On the left, a clear peaking contribution from the D^- is visible, which has disappeared on the right. Although also the signal yield is decreased, the background now is flat and decreasing, as can be expected from combinatorial background.

The efficiency of the three most prominent selection requirements is studied using data outside the signal region, and extrapolated to the signal region using Monte Carlo samples. An overview is given in Table 5.8, which also includes an overview of the signal purity both before and after the offline selection. This is defined as $S/(S + B)$, where S is the total number of D_s^- signal candidates in the entire fit range between 1800 and 2047 MeV, and B the yields of the combined combinatorial and non-peaking backgrounds in the same range.

Table 5.8: Overview of the efficiency of the main background vetoes per Dalitz region, determined from a combination of data recorded by LHCb and simulation, including the total background, which also contains the D^- mass peak on the left of Figure 5.10.

efficiency	$\phi\pi$	K^*K	NR
signal (S)	93.6%	67.5%	86.3%
total background (B)	30%	31%	15%
$J/\psi \rightarrow \mu^+\mu^-$	0.0%	0.0%	0.0%
$B^0 \rightarrow D^-\mu^+\nu_\mu$	50.1%	0.2%	0.2%
$\bar{\Lambda}_b^0 \rightarrow \Lambda_c^-\mu^+\nu_\mu X$	9.3%	0.7%	0.5%
signal purity $S/(S+B)$			
before selection:	46.5%	33.2%	8.6%
after selection:	72.5%	54.4%	24.9%

5.3 Peaking backgrounds

An inclusive Monte Carlo sample of $D_s^- \rightarrow K^- K^+ \pi^-$ candidates was used to study the backgrounds that contribute to the raw asymmetry. These backgrounds are peaking around the D_s^- mass, just like the signal, since they come from real D_s^- decays. Due to their associated production asymmetries, these need to be corrected for. There are several sources of backgrounds. First, there are those coming from prompt D_s^- decays that have picked up a random muon. As discussed in Section 5.2, the amount of prompt background is negligible due to the selection on $\log(IP)$.

The second source of peaking backgrounds are b -hadron decays where the W^- decays into a D_s^- meson. Since the b quark usually decays into a c quark as well, the backgrounds are called “double D ” decays. Lastly, there are the colour-suppressed B decays in which the charm quark picks up a strange quark, grouped together as the $B \rightarrow D_s^- K X$ decays.

The simulated mass distributions from the relevant background processes are shown in Figure 5.11 (left). While the signal has a higher mass, the backgrounds are difficult to distinguish using a mass fit. A more useful variable to look at, when studying partially reconstructed decays, is the corrected mass, m_{corr} , described in Section 2.2.6. The distributions of the corrected mass of the signal and peaking backgrounds is shown in Figure 5.11 (right). This distinguishes signal from background better than the normal mass variable, and a requirement of $m_{\text{corr}} > 4200 \text{ GeV}$ is applied to reduce these backgrounds.

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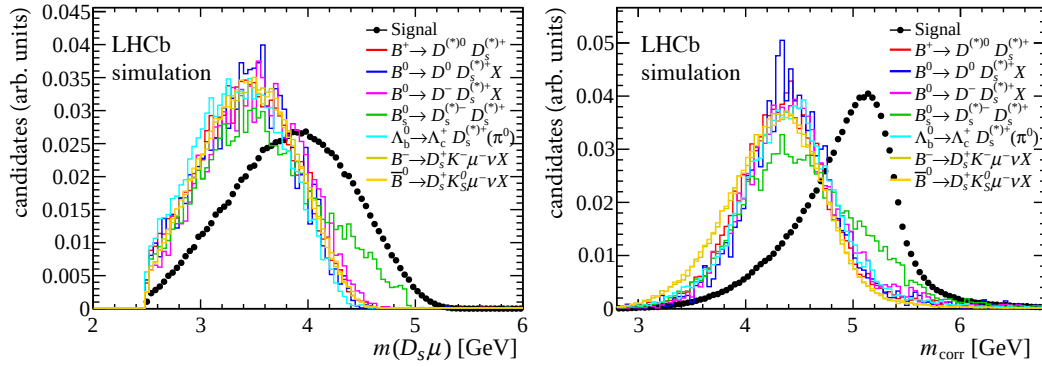


Figure 5.11: Visible (left) and corrected B_s^0 mass (right) of the signal, double D backgrounds and $B \rightarrow D_s^+ K X$ backgrounds from Monte Carlo simulations. The default selection requirement is $m_{\text{corr}} > 4200$ GeV.

5.3.1 Background fractions

While reducing the background, the requirement on the corrected mass does not remove all peaking backgrounds and a calculation of the remaining background fraction, f_{bkg} , and the contribution to the asymmetry, $f_{\text{bkg}} A_P$ is necessary. First, the b -hadron fractions of all background decays are determined to indicate how much more of a specific b hadron there is produced compared to a B_s^0 meson. Then, the branching fractions of the b hadron decay into the state that mimics the signal sample is determined. Combined with the reconstruction efficiencies of the various backgrounds compared to the signal, finally the background fractions can be determined, which are shown in Table 5.9.

b -hadron fractions

The ratio of the fragmentation fractions f_s/f_d has been measured in several papers [121–124]. The most precise one [123] reports a combination of B_s^0 production fractions and gives $f_s/f_d = 0.259 \pm 0.015$. Table 5.9 uses the inverse of this: $f_d/f_s = 3.86 \pm 0.22$. For f_u/f_s , the same number is used, assuming isospin symmetry.

For the Λ_b^0 production fraction, a measurement of $f_{\Lambda_b^0}/(f_u + f_d)$ is used [125]:

$$\left[\frac{f_{\Lambda_b^0}}{f_u + f_d} \right] (p_T) = (0.404 \pm 0.017 \pm 0.027 \pm 0.105) \times [1 - (0.031 \pm 0.004 \pm 0.003) \times p_T \text{ (GeV)}].$$

Here, the first uncertainty is statistical, the second systematic, and the third theoretical, coming from the uncertainty on $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$. The last uncertainty is ignored, since it is already used in the production asymmetry uncertainty. Integrating over the p_T spectrum yields a value of

$$\frac{f_{\Lambda_b^0}}{f_u + f_d} = 0.303 \pm 0.036.$$

Using the values of f_u/f_s and f_d/f_s , this results in $f_{\Lambda_b^0}/f_s = 2.32 \pm 0.31$.

Branching fractions

Not all branching fractions needed for the determination of the background dilution and asymmetry have been measured, hence some are estimated and explained here. The values of the branching fractions come from the Particle Data Group (PDG) [7]. The value for $\mathcal{B}(B_s^0 \rightarrow D_s^{(*)-} D_s^{(*)+})$ comes directly from the PDG, and so does the value for $\mathcal{B}(B^+ \rightarrow D_s^- K^+ \mu^+ \nu_\mu X)$. For $\mathcal{B}(B^0 \rightarrow D_s^- K_s^0 \mu^+ \nu_\mu X)$, no measurement is available, but as the Feynman diagram for $B^+ \rightarrow D_s^- K^+ \mu^+ \nu_\mu X$ is equivalent, the branching fraction for this decay is used.

For $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{*-} X$ also no measurement is available, and the branching fraction is taken to be the same as the inclusive $\mathcal{B}(B^0 \rightarrow D_s^+ X)$, which has the same Feynman diagram. The value for $\mathcal{B}(B^- \rightarrow \bar{D}^{(*)0} D_s^{*-} X)$ is taken to be the same as $\mathcal{B}(B^+ \rightarrow D_s^+ X)$, because the dominant decay for $B^+ \rightarrow D_s^+ X$ is $b \rightarrow c W^+$, where $W^+ \rightarrow D_s^+ X$. The remaining c quark will almost always form a $D^{(*)0}$. Lastly, for $\bar{B}^0 \rightarrow \bar{D}^0 D_s^{(*)-} X$ and $\bar{B}^0 \rightarrow D^+ D_s^{(*)-} X$, the inclusive value for $\mathcal{B}(B^0 \rightarrow D_s^+ X)$ is used. This is split between the D^- and D^0 decays, using the D^{*+}/D^+ ratio (since $D^{*+} \rightarrow D^0 \pi^+$), which is measured in exclusive states and an uncertainty of 20% is added to this model.

For the double D backgrounds, the branching fractions for the transition $c \rightarrow \mu X$ need to be included. For this, the branching fractions of $D^0 \rightarrow e^+ X$ is used for D^0 mesons, assuming lepton universality. The D^- decays use the value of $\mathcal{B}(D^+ \rightarrow e^+ \text{semileptonic})$, and for the Λ_c^- decay, there is $\mathcal{B}(\Lambda_c^- \rightarrow e^- X)$. Lastly, the D_s^- decay uses the sum of the fully leptonic $\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu)$ and the value from CLEO for $\mathcal{B}(D_s^+ \rightarrow e^+ \text{semileptonic})$ [126].

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Overview background fractions

Finally, an overview of all relevant modes and computation to calculate f_{bkg} is shown in Table 5.9, listing the decays in the first column. The second column in the table, the b -hadron fraction, gives the ratio of the fragmentation fraction of the background contribution over that of the signal contribution; this is f_u/f_s , f_d/f_s , $f_{\Lambda_b^0}/f_s$. The third column gives the branching fraction of the decay, followed by the fourth containing the $c \rightarrow \mu X$ branching fraction, where relevant. The selection efficiency ratio, $\varepsilon_{\text{bkg}}/\varepsilon_{\text{sig}}$, is determined using MC samples, and is listed in the fifth column.

Lastly, the ratio of the signal and background fractions can be determined by multiplying all previous columns, and dividing over the signal branching ratio, $\mathcal{B}(B_s^0 \rightarrow D_s^- \ell^+ \nu X) = (7.9 \pm 2.4)\%$. Summing up all the background contributions yields a value of

$$f_{\text{bkg}}/f_{\text{sig}} = (22.6 \pm 7.3)\%,$$

or

$$f_{\text{bkg}} = (18.4 \pm 6.0)\%.$$

Table 5.9: Background contributions, efficiency ratios and their effective asymmetries. The branching fractions are obtained from the Particle Data Group [7]. The signal branching ratio is $\mathcal{B} = (7.9 \pm 2.4)\%$. The b -hadron fractions are defined as f_u/f_s , f_d/f_s , $f_{\Lambda_b^0}/f_s$. The signal and background fractions, f_{sig} and f_{bkg} , are defined as the number of signal or background events over the sum. The ratio $f_{\text{bkg}}/f_{\text{sig}}$ does not include the uncertainty on the signal branching fraction.

mode	b -hadron fraction [%]	$\mathcal{B}$ [%]	$\mathcal{B}(c \rightarrow \mu X)$ [%]	$\varepsilon_{\text{bkg}}/\varepsilon_{\text{sig}}$	$f_{\text{bkg}}/f_{\text{sig}}$
$B^- \rightarrow \bar{D}^{(*)0} D_s^{(*)-} X$	3.86 ± 0.22 [123]	7.9 ± 1.4	6.5 ± 0.1	0.23	5.8 ± 1.1
$\bar{B}^0 \rightarrow \bar{D}^0 D_s^{(*)-} X$	3.86 ± 0.22 [123]	5.7 ± 1.2	6.5 ± 0.1	0.24	4.4 ± 1.0
$\bar{B}^0 \rightarrow D^+ D_s^{(*)-} X$	3.86 ± 0.22 [123]	4.6 ± 1.2	16.1 ± 0.3	0.16	5.6 ± 1.5
$B_s^0 \rightarrow D_s^{(*)-} D_s^{(*)+}$	1	4.5 ± 1.4	8.1 ± 0.4	0.27	1.0 ± 0.3
$\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{(*)-} X$	2.32 ± 0.31 [127]	10.3 ± 2.1	4.5 ± 1.7	0.22	3.0 ± 1.4
$B^+ \rightarrow D_s^- K^+ \mu^+ \nu_\mu X$	3.86 ± 0.22 [123]	$(6.1 \pm 1.0) \times 10^{-2}$	–	0.41	1.3 ± 0.2
$B^0 \rightarrow D_s^- K_s^0 \mu^+ \nu_\mu X$	3.86 ± 0.22 [123]	$(6.1 \pm 1.0) \times 10^{-2}$	–	0.35	1.1 ± 0.2

5.3.2 Production asymmetries

Except for the symmetric $B_s^0 \rightarrow D_s^{(*)-} D_s^{(*)+}$ background, all peaking backgrounds have production asymmetries that distort the measurement of a_{sl}^s . Some of these production asymmetries have been measured, and estimates are made for the remaining ones. All measurements used are made using LHCb data, such that their kinematic acceptance matches with that of the backgrounds.

B^- production asymmetry

An estimate for the B^- production asymmetry is provided through the information in Reference [128], where $A_{\text{raw}}(J/\psi K^-) = (-1.3 \pm 0.1)\%$ is measured. This number is corrected for the measured CP asymmetry $A_{CP}(B^- \rightarrow J/\psi K^-) = (0.3 \pm 0.6)\%$ from the PDG [129] and the kaon detection asymmetry $(-1.0 \pm 0.2)\%$ [130]. Finally, the estimate for $A_P(B^-)$ is

$$A_P(B^-) = (-0.6 \pm 0.6)\% .$$

$\bar{B}^0$ production asymmetry

The $\bar{B}^0$ background not only has a production asymmetry, but also a potential mixing asymmetry, a_{sl}^d . Both of these were measured in Reference [32]:

$$\begin{aligned} A_P(\bar{B}^0) &= (-0.66 \pm 0.26 \pm 0.22)\% \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_P(\bar{B}^0) &= (-0.48 \pm 0.15 \pm 0.17)\% \quad \text{at } \sqrt{s} = 8 \text{ TeV} , \\ a_{\text{sl}}^d &= (-0.02 \pm 0.19 \pm 0.30)\% , \end{aligned}$$

where the first uncertainty is statistical and the second systematic.

The production asymmetry is diluted by the oscillations, which is quantified by $\cos(\Delta m_{dt})$, analogous to Equation (5.9). Integrated over time, and including the decay time acceptance, this dilution factor is determined using MC to be 0.36. The mixing asymmetry is diluted by a factor $1 - \cos(\Delta m_{dt})$, which equals 0.64, integrated over time. This results in an effective asymmetry of

$$\begin{aligned} A_P^{\text{eff}}(\bar{B}^0) &= (-0.23 \pm 0.12)\% \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_P^{\text{eff}}(\bar{B}^0) &= (-0.17 \pm 0.08)\% \quad \text{at } \sqrt{s} = 8 \text{ TeV} , \\ (a_{\text{sl}}^d/2)^{\text{eff}} &= (-0.01 \pm 0.11)\% , \end{aligned}$$

where the uncertainty is the sum of the systematic and statistical uncertainty. Ignor-

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ing the correlation between $a_{\text{sl}}^d/2$ and A_P , the asymmetries from $\bar{B}^0$ backgrounds are

$$\begin{aligned} A_{P+CP}^{\text{eff}}(\bar{B}^0) &= (-0.22 \pm 0.16)\% \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_{P+CP}^{\text{eff}}(\bar{B}^0) &= (-0.16 \pm 0.14)\% \quad \text{at } \sqrt{s} = 8 \text{ TeV} , \end{aligned}$$

which average to

$$A_{P+CP}^{\text{eff}}(\bar{B}^0) = (-0.18 \pm 0.13)\% .$$

Λ_b^0 production asymmetry

An estimate for the Λ_b^0 production asymmetry is obtained from the combined CP and production asymmetry in $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays that is reported to be $(-0.1 \pm 0.7)\%$ in Reference [131]. An estimate for the direct CP asymmetry comes from measurements in Reference [132] and the method proposed in Reference [133]. This yields a value of $A_{\text{direct}}(\Lambda_b^0 \rightarrow J/\psi p K^-) = (-0.56 \pm 0.32)\%$. Combining both values yields

$$A_P(\Lambda_b^0) = (0.5 \pm 0.8)\% .$$

Overview background asymmetries

An overview of all background fractions, f_{bkg} , with their production asymmetries, and their product is given in Table 5.10. Also the sign, $\text{sign}(A_P)$, of the production asymmetries because, for example, production asymmetries from B^0 and $\bar{B}^0$ backgrounds enter with an opposite sign. The sum of the products of background fractions and asymmetries is

$$\sum_i f_{\text{bkg}}^i A_{\text{bkg}}^i = f_{\text{bkg}} A_{\text{bkg}} = (-0.023 \pm 0.031)\% .$$

Table 5.10: Background fractions (f_{bkg}), production asymmetries and their product for the listed peaking backgrounds. The uncertainty on f_{bkg} does not include the uncertainty on the signal branching fraction, which is only included in the total; the same holds for the uncertainty on $f_{\text{bkg}}A_{\text{P}}$.

decay	f_{bkg} [%]	$A_{\text{P}}(B)$ [%]		sign(A_{P})	$f_{\text{bkg}}A_{\text{P}}(B)$ [$\times 10^{-4}$]
$B^- \rightarrow \bar{D}^{(*)0} D_s^{(*)-} X$	4.7 ± 0.9	-0.6 ± 0.6	[128, 129]	+	-2.8 ± 0.6
$\bar{B}^0 \rightarrow \bar{D}^0 D_s^{(*)-} X$	3.6 ± 0.8	-0.18 ± 0.13	[32]	+	-0.7 ± 0.1
$\bar{B}^0 \rightarrow D^+ D_s^{(*)-} X$	4.6 ± 1.3	-0.18 ± 0.13	[32]	+	-0.8 ± 0.2
$B_s^0 \rightarrow D_s^{(*)-} D_s^{(*)+}$	1.0 ± 0.3	N/A		N/A	N/A
$\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{(*)-} X$	2.5 ± 1.1	0.5 ± 0.8	[132]	+	1.2 ± 0.9
$B^+ \rightarrow D_s^- K^+ \mu^+ \nu_\mu X$	1.1 ± 0.2	-0.6 ± 0.6	[128, 129]	-	0.6 ± 0.1
$B^0 \rightarrow D_s^- K_s^0 \mu^+ \nu_\mu X$	0.9 ± 0.2	-0.18 ± 0.13	[32]	-	0.2 ± 0.0
total	18.4 ± 6.0				-2.3 ± 3.1

5.4 Signal yields

The raw asymmetries are obtained from a binned maximum likelihood fit to the $K^- K^+ \pi^-$ invariant mass distributions. The D_s^- signal peak is modelled by a double-sided Hypatia function [109] that is described below, and the combinatorial background by a second-order Chebyshev polynomial. This background shape needs a large mass range to be constrained properly, so a mass window of [1800, 2047] MeV is chosen. This not only contains the D_s^- mass, but also a clear peak from the Cabbibo-suppressed $D^- \rightarrow K^- K^+ \pi^-$ decay, at a mass of 1870 MeV. This peak is also modelled by a Hypatia function.

Simultaneous fits are performed between the positively and negatively charged signal candidates. Most of the fit parameters are shared between the two charges, except for the yields, the mean mass, and the background parameters. Separate asymmetry parameters are used for the combinatorial background, and for the D^- mass.

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5.4.1 Hypatia function

Assuming that the peak is symmetric, the Hypatia function is given by

$$I(m; \mu, \sigma, \lambda, \zeta, a_I, a_{II}, n_I, n_{II}) \propto \begin{cases} \frac{A}{(B+m-\mu)^{n_I}} & \text{if } m - \mu < -a_I\sigma, \\ \frac{C}{(D+m-\mu)^{n_{II}}} & \text{if } m - \mu > a_{II}\sigma, \\ ((m - \mu)^2 + \delta^2)^{\frac{1}{2}\lambda - \frac{1}{4}} K_{\lambda - \frac{1}{2}} \left(\alpha \sqrt{(m - \mu)^2 + \delta^2} \right) & \text{otherwise,} \end{cases} \quad (5.18)$$

where $K_\nu(z)$ is the modified Bessel function of the second kind,

$$\delta \equiv \sigma \sqrt{\frac{\zeta K_\lambda(\zeta)}{K_{\lambda+1}(\zeta)}}, \quad \alpha \equiv \frac{1}{\sigma} \sqrt{\frac{\zeta K_{\lambda+1}(\zeta)}{K_\lambda(\zeta)}}, \quad (5.19)$$

and A, B, C, D are obtained by imposing continuity and differentiability at the transition points a_I and a_{II} .

The variables to fit are the mean position (μ) and width (σ) of the signal peak, the variables λ and ζ that together describe the shape of the peak, and the tail parameters $a_{I,II}$ and $n_{I,II}$. These are labelled I for the left-hand side tail, and II for the right-hand side, and are similar to the tail parameters of the Crystal Ball function. The variable λ is dependent on the kinematic distribution of the D_s^- meson.

Table 5.11: Values of the tail parameters used to fit the signal D_s^+ distributions. These parameters are fixed during the signal fit.

parameter	$\phi\pi$	K^*K	NR
λ	-3.07 ± 0.06	-4.09 ± 0.16	-3.82 ± 0.12
ζ	0.01 ± 0.01	0.00 ± 0.09	0.00 ± 0.08
a_I	2.60 ± 0.04	2.06 ± 0.09	2.32 ± 0.06
a_{II}	4.95 ± 0.28	4.99 ± 0.18	2.16 ± 0.10
n_I	2.01 ± 0.07	5.00 ± 0.09	1.02 ± 0.05
n_{II}	3.60 ± 0.17	4.97 ± 0.24	3.60 ± 0.10

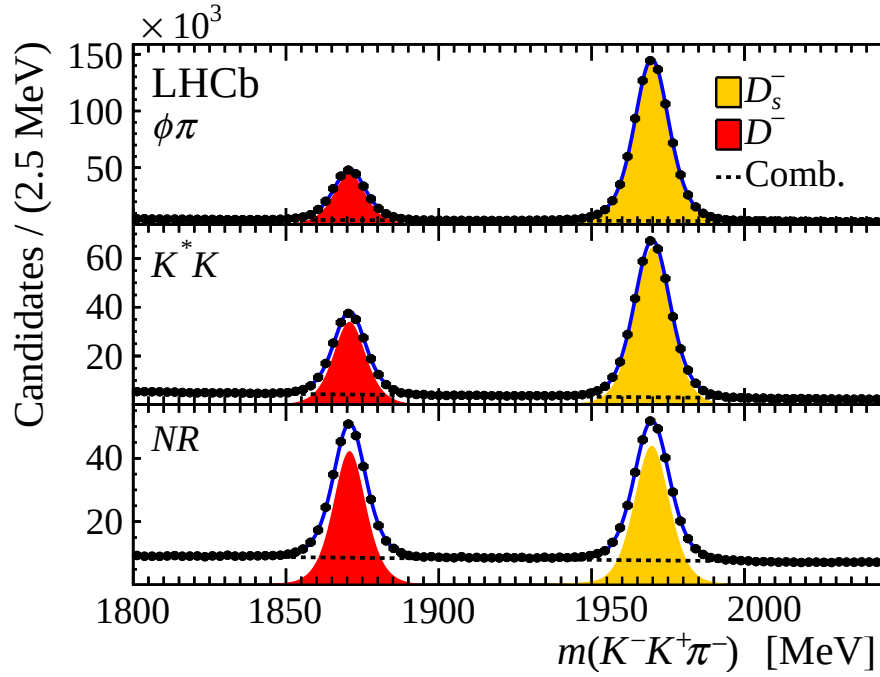


Figure 5.12: $m(K^- K^+ \pi^-)$ signal fits for the three Dalitz regions, the red peak (left) represents the D^- candidates, while the yellow peak (right) is the D_s^- peak.

The Hypatia function has many parameters and to improve the stability of the fits, the tail parameters are fixed. They are determined by performing a fit to combined data sets: the samples from the data-taking years and magnet polarities are combined, while the Dalitz regions are kept separate as the parameters may depend on the kinematic variations across the phase space. Three fits are then performed and the tail parameters resulting from this are listed in Table 5.11. The final fits are shown in Figure 5.12, in which the positively and negatively charged candidates are added.

5.4.2 Systematics uncertainties

To assess any bias on the raw asymmetry coming from the fit model, an alternative fit model using a double-sided Crystal Ball function combined with a Gaussian function is used. This combination of functions has a comparable number of degrees of freedom, and the resulting fits have similar χ^2/ndf 's for all Dalitz regions. When comparing the fit results from the nominal and alternative fit model directly from their fit on data, the statistical uncertainty of the fit is double-counted. Hence, simplified simulation studies are performed to quantify the systematic uncertainty; the statistical uncertainty decreases when more events are generated.

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For these simulation studies, $m(K^-K^+\pi^-)$ events are generated using the probability density functions (PDFs) that are extracted from data using the alternative fit model. This has the same second-order Chebyshev polynomial for the combinatorial background, and the Hypatia function for the D^- peak. However, for the D_s^- peak, it uses the double-sided Crystal Ball with Gaussian functions.

The asymmetry in the generated events is the same as given by the fit from data both for the background and D^- region, but is set to 0 for the D_s^- region. Hence, any deviation from 0 in the fitted raw asymmetry in the D_s^- region indicates a systematic uncertainty. The generated events are normalised such that $N(D^-) = N(\text{bkg}) = N(D_s^-)$.

As a check, the simulated events are fitted using the same PDFs that were used to generate them and while no bias is found in the $\phi\pi$ and K^*K region, a small bias of 0.02% is visible in the NR region. This is thought to be caused by the asymmetric background in this region. Afterwards, the simulations are fitted again, but now using the default PDFs, and the resulting pull distributions are shown in Figure 5.13. Again, an insignificant bias of $(4.3 \pm 2.6) \times 10^{-5}$ is observed for the $\phi\pi$ region and $(1.1 \pm 3.8) \times 10^{-5}$ for the K^*K region. For the NR region, a similar bias is found as before: $(-19 \pm 4) \times 10^{-5}$. The widths of the pulls are consistent with 1, which indicates that the statistical uncertainties are correctly estimated.

Another systematic uncertainty is determined by quantifying the uncertainty on the fixed tail parameters. The parameters are varied within their fit uncertainty and the raw asymmetry is fit with the new parameters. This is in principle also sensitive to the statistical uncertainty, however, the resulting fluctuations in A_{raw} are very small, mostly smaller than 0.01%, such that this overestimate can safely be ignored. In conclusion, the combination of the systematic uncertainties on the fit function and its tail parameters is 0.018%. An overview of all systematic uncertainties in this measurement is given in Table 5.17 in Section 5.6.

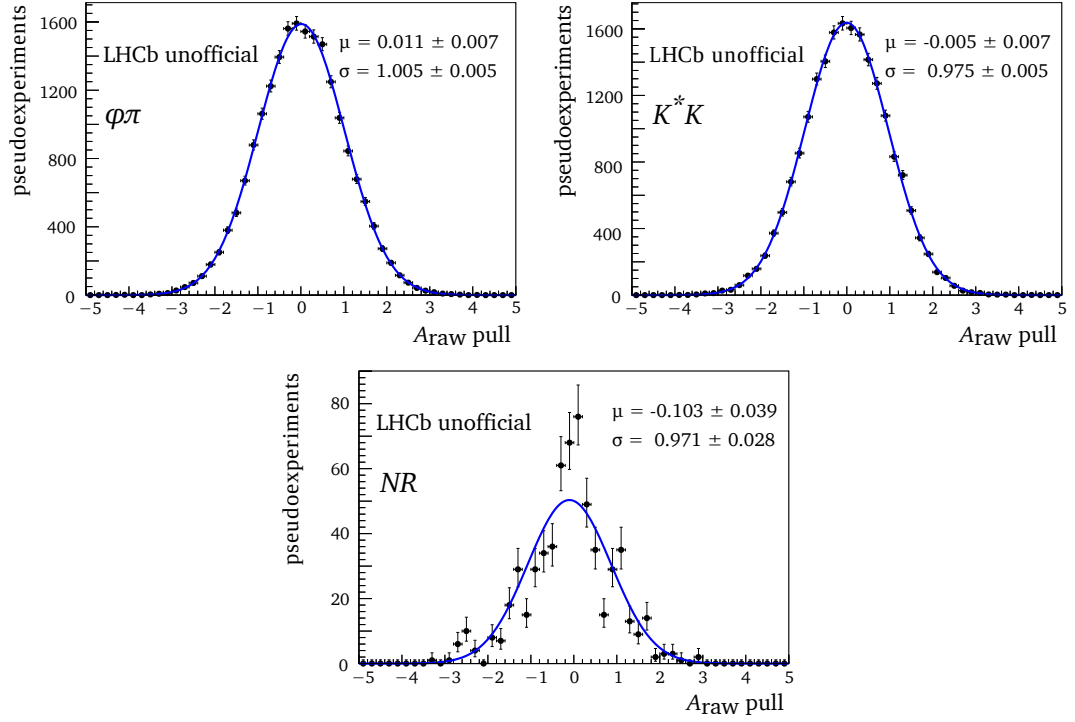


Figure 5.13: A_{raw} pull distributions for $\phi\pi$, K^*K and NR respectively. Data are generated using a double-sided Crystal Ball and a Gaussian function, and are fitted using the Hypatia PDF.

5.5 Detection asymmetries

The detection asymmetry in the a_{sl}^s measurement is a combination of many detection asymmetries coming from the three trigger levels, as well as from the track reconstruction, and particle identification. This section gives an overview of each of these contributions and summarises how they are measured. The detection asymmetries are determined using the sWeighted signal sample and the sWeights come from the same fit as discussed in Section 5.4.

Assuming all contributions have small asymmetries, the value of the total detection asymmetry, A_D , can be written as the sum of the components:

$$A_D = A_{(\text{track})}^{\mu^+\pi^-} + A_{(\text{track})}^{K^+K^-} + A_{(\text{PID}|\text{track})}^{K^-K^+\pi^-} + A_{(\text{PID}+\text{L0}|\text{track})}^{\mu^+} + A_{(\text{HLT1}|\text{track}+\text{PID}+\text{L0})}^{\mu^+\pi^-K^+K^-}. \quad (5.20)$$

In this equation $A_{(\text{track})}^{\mu^+\pi^-}$ is the tracking asymmetry originating from the $\mu^+\pi^-$ pair described in Section 5.5.4, and $A_{(\text{track})}^{K^+K^-}$ that from the kaon pair, which is covered in Section 5.5.5. $A_{(\text{PID}|\text{track})}^{K^-K^+\pi^-}$ is the PID asymmetry of the hadrons with respect to the reconstructed tracks, see Section 5.5.6, while the PID asymmetry of the muon

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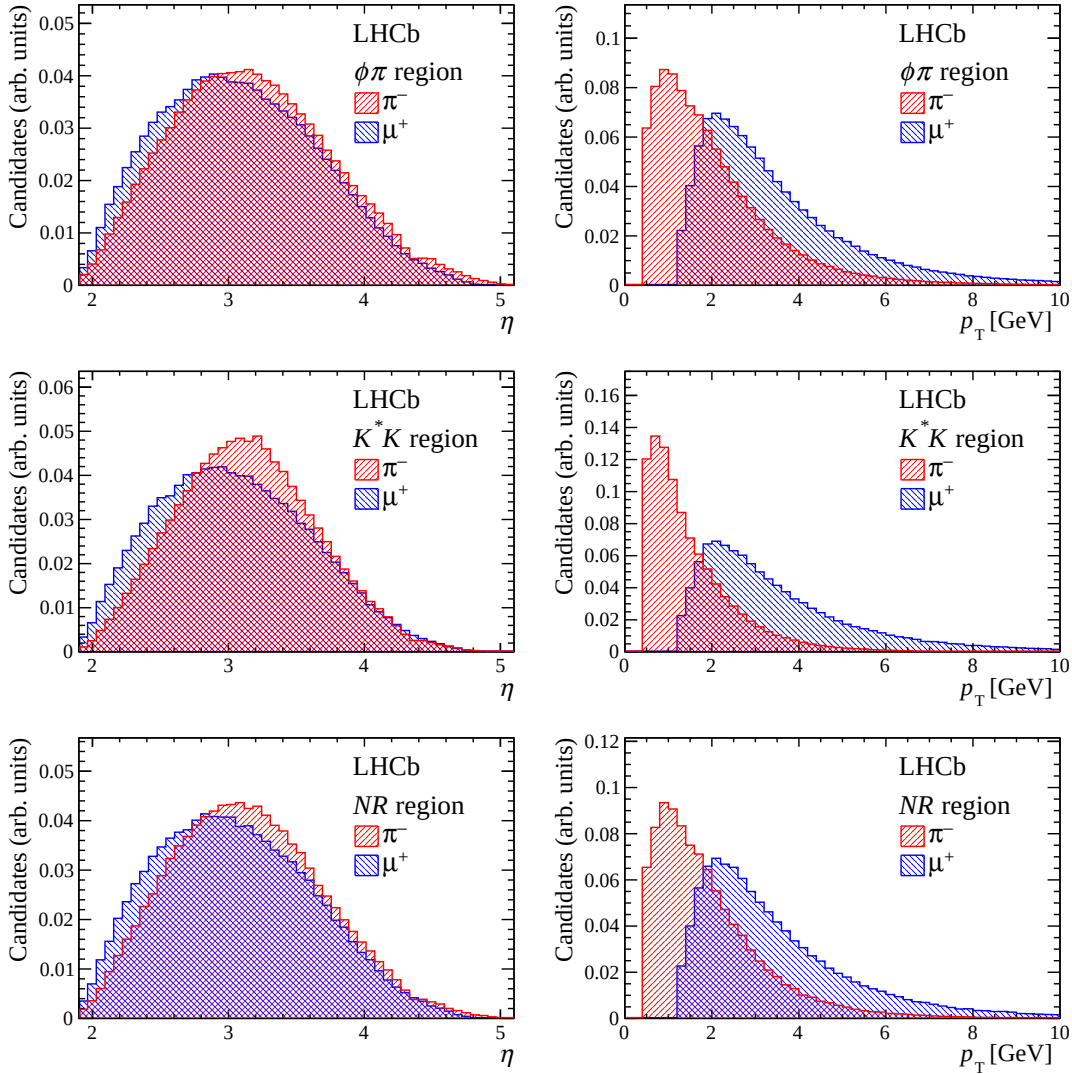


Figure 5.14: sWeighted p_T and η distributions of the final state pion and muon. These histograms include data from both data-taking years and both magnet polarities.

is combined with its L0 asymmetry in $A_{(\text{PID}+\text{L0}|\text{track})}^{\mu^+}$ described in Section 5.5.1. Lastly, $A_{(\text{HLT1}|\text{track}+\text{PID}+\text{L0})}^{\mu^+\pi^-K^+K^-}$ is the asymmetry introduced by the HLT1 selection which is summarised in Section 5.5.2, while the contribution from HLT2 can safely be neglected, see Section 5.5.3.

As discussed in Section 4.1.1, it is often beneficial to combine two oppositely charged tracks and determine their combined detection asymmetry. This is done for $\mu^+\pi^-$ pairs, as well as for K^+K^- pairs. The kinematic distribution for the $\mu^+\pi^-$ pairs are shown in Figure 5.14, and those for the K^+K^- pairs in Figure 5.15. Especially the overlap between the muon and pion transverse momentum distributions vary a lot between the different Dalitz regions due to differences in phase space of the

decays.

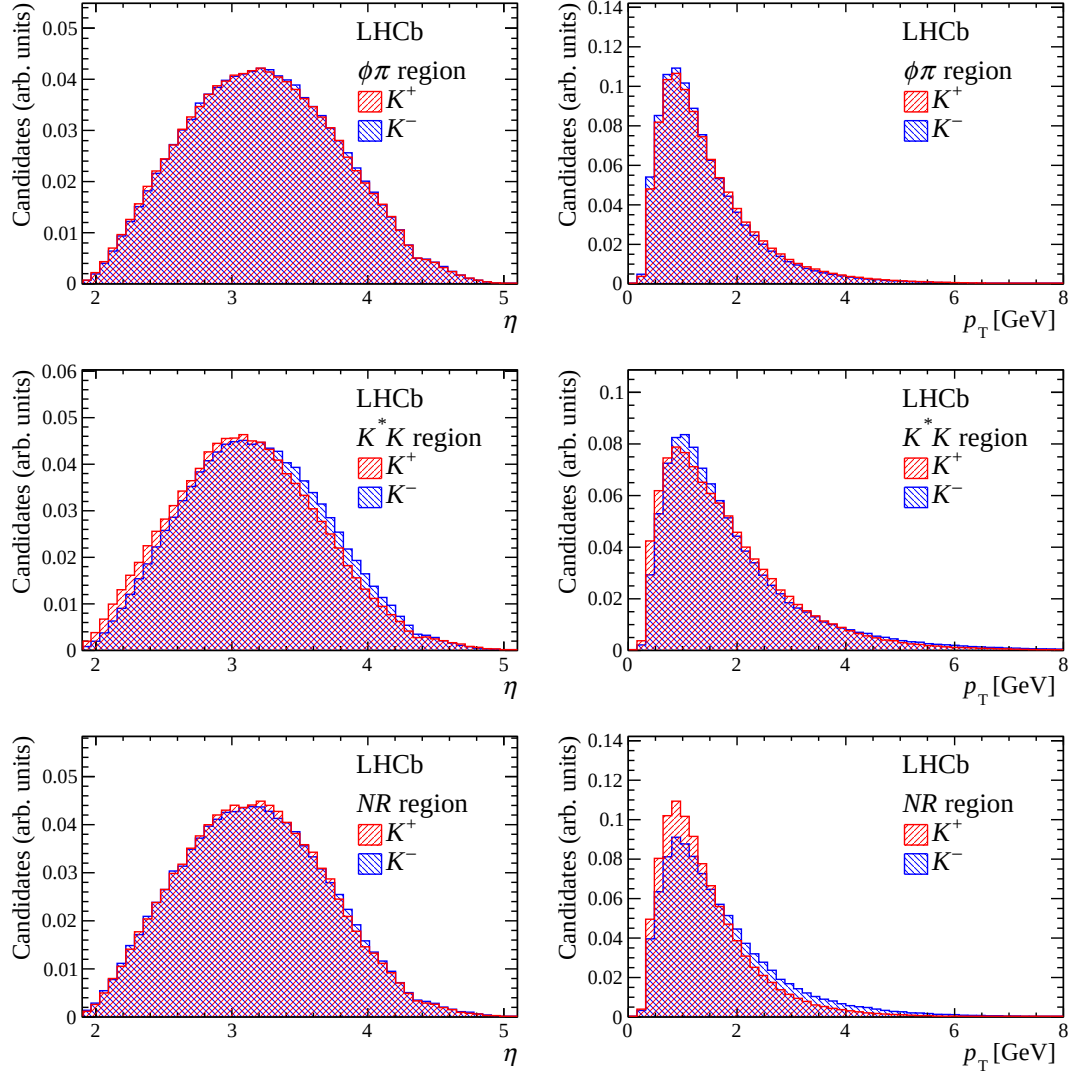


Figure 5.15: sWeighted p_T and η distributions of the final state kaons. These histograms include data from both data-taking years and both magnet polarities.

5.5.1 L0 asymmetry

The L0 asymmetry is studied with the $J/\psi \rightarrow \mu^+ \mu^-$ tag-and-probe method described in Section 4.2.1. It is combined with the muon PID asymmetry by applying the same PID requirements on the reference sample as are applied on the signal sample (IsMUON and $DLL_{\mu\pi} > 0$). The p_T - η distributions of the $B \rightarrow J/\psi X$ calibration sample are reweighted to match to the signal sample to obtain the combined L0 and PID asymmetries. The statistical uncertainties come directly from the signal fits of the reweighted calibration samples.

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Systematic uncertainties are determined by varying the binning scheme such that instead of using the p_T - η binning, a p - η and a 3D binning scheme in p_T - η - ϕ are used. In addition, the fit variables are varied to measure a bias coming from the fit model. Finally, the systematic uncertainty is calculated by taking the variations of the asymmetries with respect to the nominal value and adding them in quadrature. Averaged over samples from the different data-taking years, magnet polarities, and Dalitz regions, this yields a value of 0.022%.

5.5.2 HLT1 asymmetry

The HLT1 requirement for a_{sl}^s is TOS (trigger on signal) of the muon track from Hlt1TrackMuon OR TOS of any of the B_s^0 decay tracks from Hlt1TrackAllL0. This means that the hadronic tracks (K^+ , K^- , π^-) can trigger Hlt1TrackAllL0, while the μ^+ can trigger Hlt1TrackAllL0 and Hlt1TrackMuon. The trigger requirements for both lines are listed in Table 5.1 and show a large overlap. Approximately 80% of candidates are triggered by both lines, while each of the lines adds roughly another 10%; for the $\phi\pi$ region the number of events triggered per trigger line are shown in Equation (5.21).

Table 5.12: Number of events in the $\phi\pi$ region that are triggered by only Hlt1TrackAllL0, only Hlt1TrackAllMuon, both, and either of these lines.

$\phi\pi$	$N_{\text{evt}}(\text{only TrackAllL0})$	$N_{\text{evt}}(\text{only TrackMuon})$	$N_{\text{evt}}(\text{TrackAllL0 AND TrackMuon})$	$N_{\text{evt}}(\text{Total})$
2011 MagUp	20528 [11%]	20336 [11%]	146332 [78%]	187196
2011 MagDown	20811 [8%]	25591 [10%]	203498 [79%]	257762
2012 MagUp	38074 [7%]	73987 [13%]	436463 [80%]	548524
2012 MagDown	35292 [7%]	67983 [13%]	405775 [80%]	509050

The HLT1 efficiencies for K^- , K^+ and π^- tracks can be determined as described in Section 4.2.2 using the prompt D_s^+ sample. They are determined in bins of p_T - η , that are defined such that within a bin, the efficiency does not vary significantly. For the muon, the tag-and-probe method using $J/\psi \rightarrow \mu^+\mu^-$ events is used, as described in Section 4.2.1. For this measurement, the probe-track is required to be triggered by Hlt1TrackMuon OR Hlt1TrackAllL0, such that the overlap of the two triggers is covered. Also here the binning is chosen such that the efficiencies do not vary much within a bin. The track efficiencies can then be combined to

define event efficiencies using

$$\begin{aligned} \varepsilon_{B_s^0} = \frac{1}{\sum w_i} \sum_i^{N_{\text{evts}}} w_i & \left(\varepsilon_{K^+}^i + \varepsilon_{K^-}^i + \varepsilon_{\pi^-}^i + \varepsilon_{\mu^+}^i - \varepsilon_{K^+}^i \varepsilon_{K^-}^i - \varepsilon_{K^+}^i \varepsilon_{\pi^-}^i - \varepsilon_{K^+}^i \varepsilon_{\mu^+}^i \right. \\ & - \varepsilon_{K^-}^i \varepsilon_{\pi^-}^i - \varepsilon_{K^-}^i \varepsilon_{\mu^+}^i - \varepsilon_{\pi^-}^i \varepsilon_{\mu^+}^i + \varepsilon_{K^+}^i \varepsilon_{K^-}^i \varepsilon_{\pi^-}^i + \varepsilon_{K^+}^i \varepsilon_{K^-}^i \varepsilon_{\mu^+}^i \\ & \left. + \varepsilon_{K^+}^i \varepsilon_{\pi^-}^i \varepsilon_{\mu^+}^i + \varepsilon_{K^-}^i \varepsilon_{\pi^-}^i \varepsilon_{\mu^+}^i - \varepsilon_{K^+}^i \varepsilon_{K^-}^i \varepsilon_{\pi^-}^i \varepsilon_{\mu^+}^i \right), \end{aligned} \quad (5.21)$$

where w_i are the sWeights of the signal sample. This equation sums the efficiencies of the tracks, while avoiding double-counting the overlapping regions where two or more tracks fired the trigger. The efficiencies for pions and kaons are treated separately.

To determine the statistical uncertainty, the value of the per-track mean efficiency and asymmetry in each of the bins is varied by taking a Gaussian function distributed random number in each of the efficiency bins. The Gaussian function has the central value in that bin as the mean, and the uncertainty as the standard deviation. Using these varied values, the HLT1 asymmetry is calculated and this is repeated 50 times. The statistical uncertainty is taken as the RMS of these asymmetries. The HLT1 asymmetries are less than a per mille in every region and are dominated by the muonic trigger.

The systematic uncertainty is determined by varying the binning schemes of the per-track efficiencies to check any effects from the binning variables. Instead of the default p_T - η binning, a binning in p - η is used. Repeating the measurement of the HLT1 asymmetry, and taking the maximum difference between the two binning schemes, yields a systematic uncertainty of 0.005% to be assigned to the magnet-polarity- and Dalitz-averaged value of a_{sl}^s .

5.5.3 HLT2 asymmetry

The HLT2 selection requires the OR of Hlt2SingleMuon and Hlt2TopoMu(2|3|4)BodyBBDT. The asymmetry of the HLT2 muon topological lines Hlt2TopoMu(2|3|4)BodyBBDT has been limited to a few times 10^{-4} [134], with respect to all other selections. This value is not used as a correction, only added as a systematic uncertainty. Since the HLT2 asymmetry is due to the difference in the online and offline track reconstruction, which is the same for the topological and muon lines, any additional HLT2 asymmetry coming from Hlt2SingleMuon can be neglected.

5.5.4 Pion-muon asymmetry

The combined $\mu\pi$ tracking asymmetry was the largest source of systematic uncertainties in the previous a_{sl}^s analysis [29] and therefore, several new methods were developed to reduce this systematic uncertainty. The first is based on the $J/\psi \rightarrow \mu^- \mu^+$ tag-and-probe method, which is detailed in Section 4.2.1. The second is the same as was used for the previous analysis and is based on partially reconstructed D^* decays, see Section 4.3.

The first method is fully based on muons, the second on pions, while what is needed for the analysis is the combination of muons and pions. In principle, the pure tracking asymmetry is the same for muons and pions, but the methods determining these will also include additional asymmetries. The tag-and-probe method includes a bias in the acceptance, which is due to the fact that only reconstructed muons are selected in this method. This confines the acceptance to tracks that could be reconstructed by the muon stations. The partially reconstructed D^* method, on the other hand, also accepts other tracks, and includes a component from pion nuclear interaction asymmetries.

Systematic uncertainties regarding the acceptance and nuclear interactions are determined using simulations which are detailed in Section 4.4.1. The acceptance asymmetry largely cancels when combining the samples recorded with both magnet polarities. While the acceptance effect is only relevant for the $J/\psi \rightarrow \mu^- \mu^+$ method, both methods are affected by nuclear interaction asymmetries corrections: the $J/\psi \rightarrow \mu^- \mu^+$ method because of the lack of nuclear interactions, and the partially reconstructed D^* method because it falsely cancels them between two pions. Instead of correcting the measured asymmetries, a systematic uncertainty is assigned for both effects. After adding this, a weighted average of the two methods is determined, which is used as the input of $A_{(\text{track})}^{\mu^+ \pi^-}$.

A third method was developed to assess $A_{(\text{track})}^{\mu^+ \pi^-}$, using the ratio of charm decays as described in Section 4.5.2. Due to the badly overlapping kinematic distributions of the control samples with the signal sample, this method had a relatively large statistical uncertainty compared to the methods described above. It was therefore not used in the a_{sl}^s analysis.

5.5.5 Kaon asymmetry

In the $\phi\pi$ region, the kinematic distributions of the two kaons are almost exactly the same as each other, such that the detection asymmetry resulting from the kaon pair is negligible. However, for the two other Dalitz regions, this is not the

case. The overlap between the kinematic distributions of K^+ and K^- in the K^*K region is increased by applying the background vetoes. However, this is not the case for the NR region in which it is clearly visible that most PID requirements are placed on the same-sign kaon, K^- . This is illustrated in Figure 5.16. The detection asymmetry from the non-overlapping parts of the distributions is assessed using the method described in Section 4.5.1.

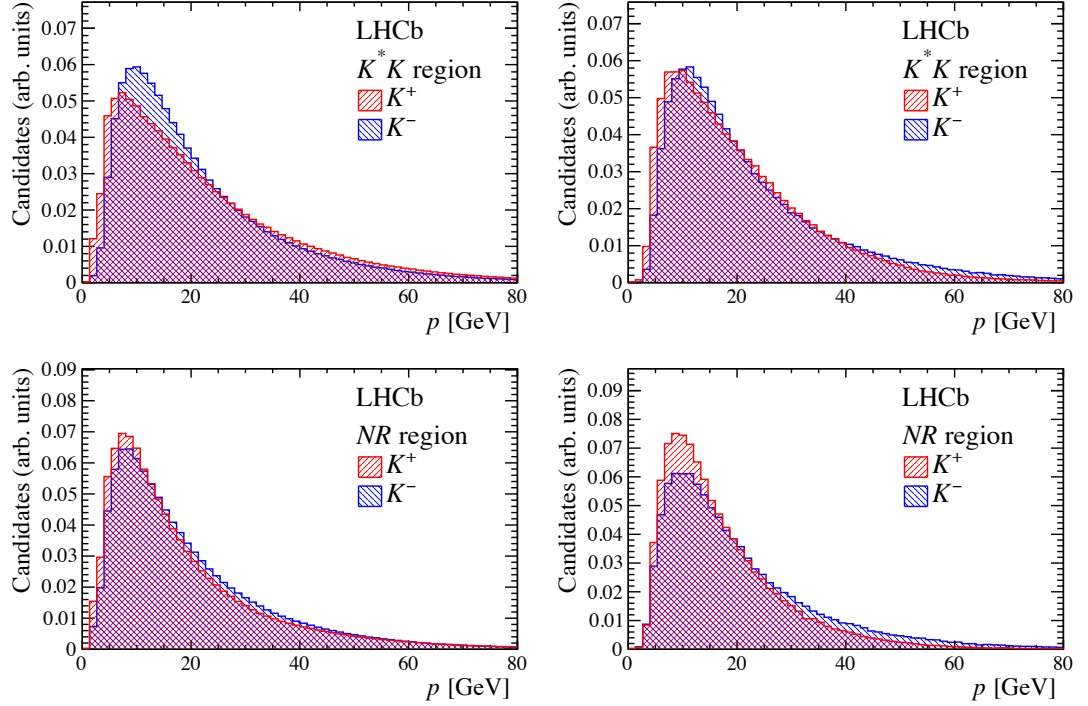


Figure 5.16: Momentum spectra of the kaons in the full data set, before (left) and after (right) reflection vetoes and background subtraction. The K^- in this figure has the same charge as the D_s^- , while the K^+ has the opposite charge. The spectra before reflection vetoes are without background subtraction applied and for a window of 25 MeV around the nominal D_s^- mass. For the spectra with reflection vetoes the sWeights from the nominal fit method are applied to reduce backgrounds.

The calibration samples have a requirement on particle identification information from the RICH detector. This is tighter than for the signal selection and this is corrected by measuring the PID asymmetries as discussed in Section 5.5.6. The calibration samples are reweighted to the p_T and η distributions of the same-sign kaon to match the sWeighted signal samples and a value for $A_D(K^- \pi^+)$ is obtained. This is repeated for the opposite-sign kaon to obtain $A_D(K^+ \pi^-)$, and the difference between $A_D(K^+ \pi^-)$ and $A_D(K^- \pi^+)$ gives the value for $A_{(\text{track})}^{K^+ K^-}$. This only holds if the pion asymmetries between both measurements cancel, which is true if their kinematics are the same.

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Validating the assumption that the kinematics of the pions are the same determines the systematic uncertainty. When taking the results from using the data taken with both polarities of the magnet, the residual pion asymmetry mostly cancels; hence, due to averaging over the magnet polarities, the resulting asymmetry is mostly due to the nuclear interaction asymmetry of the kaon. To check this assumption, the pions in the control samples are in addition reweighted to the signal pions to alter the pion distributions. The difference in the resulting kaon asymmetries with respect to the nominal kaon asymmetry is taken as the systematic uncertainty.

Another possible effect on the kaon asymmetries can come from neutral kaon nuclear interaction asymmetries, because the control samples include K_s^0 mesons. However, the K_s^0 mesons only travel through a relatively small fraction of material, typically decaying before RICH1. In addition, the K_s^0 kinematic distributions are very similar between the $A_D(K^+\pi^-)$ and $A_D(K^-\pi^+)$. Taking the averaged asymmetry $A_D(K^0) = (-0.054 \pm 0.011)\%$ from Reference [114], the influence on $A_{\text{(track)}}^{K^+K^-}$ is estimated to be of the order of 10^{-5} , which is negligible. The total systematic uncertainty on $A_{\text{(track)}}^{K^+K^-}$ is 0.034%.

5.5.6 PID asymmetry

The PID asymmetries are determined with a large sample of $D^0 \rightarrow K^-\pi^+$ decays, as described in Section 4.2.4. The kinematics of the calibration samples are reweighted to the sWeighted signal sample, in bins of p_T - η . This is done both before and after applying the PID selection, and the difference in the charge asymmetry before and after a selection is applied, is the PID asymmetry. Many PID requirements are applied in this analysis, which are applied globally (for example PROBNNK), but the reflection vetoes are only applied to certain mass windows.

First, the global PID asymmetries are determined. Then, one by one, the PID asymmetries from the reflection vetoes with respect to the global asymmetries are determined in their mass window. The Λ_c^- and D^- mass windows have a large overlap, hence for these PID asymmetries also the overlap is determined to avoid double-counting. The other reflection vetoes only remove small numbers of events and have different mass windows, hence it is assumed there is no overlap between them.

Once all PID asymmetries are determined, they are added to determine the overall PID asymmetry. The PID asymmetries coming from the reflection vetoes are weighted using the fraction of signal in the relevant mass window. The various

components of the PID asymmetries are highly correlated, since they use the same reference sample to assess them. This correlation is assumed to be 100%.

The PID efficiencies for a $D_s^- \rightarrow K^- K^+ \pi^-$ candidate is the product of the per-track efficiencies, which are dependent on the track kinematics. Because these efficiencies are all determined from the same control sample, they are correlated and the statistical uncertainty on the D_s^+ PID efficiency is determined by varying the PID efficiencies within their uncertainty.

The statistical uncertainties are obtained using a study in which the particle efficiencies are varied within their uncertainty; this is repeated 100 times. The mean of the asymmetry distribution is taken as the default PID asymmetry, while the standard deviation is assigned as the statistical uncertainty. These variations can also be used to assess the correlation of the PID asymmetries between the Dalitz regions. It is found that for many PID requirements, there is a large correlation between the Dalitz regions and a value of 100% is used.

The systematic uncertainty is studied using two methods. First, the kinematic sampling is studied by varying the bins in which the calibration sample is reweighted. This check mainly concerns the low p_T region in which the overlap between the signal and calibration samples is rather poor, while there is also a steep dependence on PID efficiency. The binning is varied to finer schemes, and $p\text{-}\eta$, $p_T\text{-}\phi$, $p_T\text{-}\eta\text{-}\phi$, $p\text{-}\eta\text{-}\phi$ binning. The largest difference between the binning schemes is chosen as a systematic uncertainty for each of the Dalitz regions.

The second systematic uncertainty comes from the fact that the sWeights of the control samples are determined globally, but are applied in kinematic bins. The invariant mass, however, may vary significantly between these bins and the kinematics are affected by the PID selection. To assess if these effects are captured, sWeights are determined in kinematic bins for the global PID selection and the asymmetries are evaluated again, yielding differences of around 0.3%.

5.5.7 Summary of detection asymmetries

To summarise the corrections from the detection asymmetries, all are listed in Table 5.13. These are the corrections that are applied to the raw asymmetry before calculating α_{sl}^s . They are averaged over the results obtained for data samples taken with both magnet polarities, by taking the arithmetic mean, and over the two data-taking years by taking the weighted average. The Dalitz averaged value is calculated with the weights that are described in Section 5.6, assuming 100% correlation between the Dalitz regions for each of the detection asymmetries. For

5. CP violation in $B_s^0\text{-}\bar{B}_s^0$ mixing

the total detection asymmetry value, the uncertainties are added in quadrature. From this table, it is clear that all corrections on A_{raw} are reasonably compatible with zero, and the largest uncertainty on the correction comes from the combined L0 and PID asymmetries of the muon.

Table 5.13: Detection asymmetry corrections to A_{raw} including statistical uncertainties, split by, and averaged over, the Dalitz regions. The magnet polarity of the data sample is averaged first, followed by the weighted average over the two data-taking years.

A_D [%]	$\phi\pi$	K^*K	NR	average
$A_{(\text{track})}^{\mu^+\pi^-}$	-0.01 ± 0.05	0.00 ± 0.06	0.00 ± 0.05	-0.01 ± 0.05
$A_{(\text{track})}^{K^+K^-}$	0.01 ± 0.00	-0.03 ± 0.00	-0.05 ± 0.01	-0.01 ± 0.00
$A_{(\text{PID} \text{track})}^{K^-K^+\pi^-}$	-0.00 ± 0.02	0.04 ± 0.03	0.02 ± 0.03	0.01 ± 0.02
$A_{(\text{PID+L0} \text{track})}^{\mu^+}$	-0.03 ± 0.02	-0.03 ± 0.02	-0.07 ± 0.02	-0.03 ± 0.02
$A_{(\text{HLT1} \text{track+PID+L0})}^{\mu^+\pi^-K^+K^-}$	0.00 ± 0.01	0.01 ± 0.01	0.00 ± 0.01	0.00 ± 0.01
total	-0.03 ± 0.06	-0.01 ± 0.07	-0.09 ± 0.06	-0.03 ± 0.06

5.6 Results

Finally, the results of the measurement of a_{sl}^s can be determined using

$$\frac{a_{\text{sl}}^s}{2} = \frac{1}{1 - f_{\text{bkg}}} (A_{\text{raw}} - A_D - f_{\text{bkg}} A_{\text{bkg}}), \quad (5.22)$$

where f_{bkg} is the fraction of peaking backgrounds, A_{bkg} their corresponding production asymmetries, A_{raw} the raw asymmetry, and A_D the sum of the detection asymmetries:

$$A_D = A_{(\text{track})}^{\mu^+\pi^-} + A_{(\text{track})}^{K^+K^-} + A_{(\text{PID}|\text{track})}^{K^-K^+\pi^-} + A_{(\text{PID+L0}|\text{track})}^{\mu^+} + A_{(\text{HLT1}|\text{track+PID+L0})}^{\mu^+\pi^-K^+K^-}. \quad (5.23)$$

Equation (5.22) yields twelve values of a_{sl}^s from the data taken with two magnet polarities, two years of data-taking, and three Dalitz regions. The results are shown in Table 5.14 for the central values including the statistical uncertainties. The statistical uncertainties here also include those from the reference samples. A break-down of the contributions from the various reference samples to the statistical uncertainty is given in Table 5.15.

To combine these twelve results into a single value, the following procedure is followed. Firstly, the Dalitz regions are averaged using weights. These weights

Table 5.14: Results of the a_{sl}^s measurements for each Dalitz region and dataset, including statistical uncertainties. Also listed are the weights that are assigned to the three Dalitz regions in the average, and the resulting average values.

a_{sl}^s [%]		$\phi\pi$	K^*K	NR	weights	average
2011	MagUp	0.95 ± 0.87	0.52 ± 1.27	0.43 ± 1.65	[0.61, 0.25, 0.14]	0.77 ± 0.72
	MagDown	-2.07 ± 0.74	0.10 ± 1.08	-0.82 ± 1.40	[0.61, 0.25, 0.14]	-1.36 ± 0.62
2012	MagUp	0.55 ± 0.52	0.91 ± 0.76	3.02 ± 0.97	[0.62, 0.24, 0.14]	0.98 ± 0.44
	MagDown	0.37 ± 0.52	0.26 ± 0.77	0.62 ± 1.01	[0.63, 0.24, 0.13]	0.38 ± 0.44

are chosen such that they minimise the total statistical uncertainty according to the best linear unbiased estimator (BLUE) method [135, 136] and are listed in Table 5.14, after which also the average result is shown. Since the control samples for the detection asymmetries are largely correlated, a value of 100% correlation between the Dalitz regions is assumed when determining the weights.

Secondly, the results from the data taken with the two magnet polarities are averaged using the arithmetic mean, which is chosen such that any magnet-dependent asymmetries cancel out. These results are shown in Table 5.16, which also lists the magnet polarity averaged values for each of the Dalitz regions. Lastly, a weighted average of the 2011 and 2012 data samples is performed, to account for the larger sample size of the 2012 data. These results are shown in Table 5.16. A value of $a_{\text{sl}}^s = (0.39 \pm 0.26)\%$ is measured.

Table 5.15: Overview of the contributions to the statistical uncertainty of the a_{sl}^s measurements for each dataset, originating from the A_{raw} signal sample and the control samples used to determine the detection asymmetries.

	2011		2012	
σ_{stat} [%]	MagUp	MagDown	MagUp	MagDown
A_{raw}	0.61	0.51	0.36	0.36
$A_{(\text{track})}^{\mu^+\pi^-}$	0.33	0.28	0.21	0.20
$A_{(\text{track})}^{K^+K^-}$	0.01	0.01	0.01	0.01
$A_{(\text{PID} \text{track})}^{K^-K^+\pi^-}$	0.15	0.12	0.09	0.09
$A_{(\text{PID}+\text{L0} \text{track})}^{\mu^+}$	0.15	0.15	0.09	0.09
$A_{(\text{HLT1} \text{track}+\text{PID}+\text{L0})}^{\mu^+\pi^-K^+K^-}$	0.04	0.06	0.04	0.03
Total	0.72	0.62	0.44	0.44

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Table 5.16: Results of the a_{sl}^s measurements for each Dalitz region and dataset including statistical uncertainties. They are averaged over the datasets recorded using both magnet polarities and data-taking years.

a_{sl}^s [%]	$\phi\pi$	K^*K	NR	average
2011	-0.56 ± 0.57	0.31 ± 0.83	-0.19 ± 1.08	-0.29 ± 0.48
2012	0.46 ± 0.37	0.58 ± 0.54	1.82 ± 0.70	0.68 ± 0.31
Run I	0.16 ± 0.31	0.50 ± 0.45	1.22 ± 0.59	0.39 ± 0.26

5.6.1 Systematic uncertainties

The various contributions to the systematic uncertainty on a_{sl}^s have been discussed in the previous sections. This section gives an overview of all systematic uncertainties and the combination to a single value for the a_{sl}^s measurement. Table 5.17 lists all systematic uncertainties that contribute with a corresponding reference. The statistical uncertainties of all reference samples are not included here, since they are already contained in the statistical uncertainty. This is different compared to the previous analysis [29], where these were added to the systematic uncertainty.

Table 5.17: Overview of the systematic uncertainties coming from the detection asymmetries and the backgrounds. The uncertainty is given with respect to the corrected A_{raw} . The systematic uncertainty on a_{sl}^s is determined by multiplying these numbers by $2/(1 - f_{\text{bkg}})$ (see Equation (5.14)).

source	contribution (%)	reference
fit model	0.018	Section 5.4.2
$A_{(\text{track})}^{\mu^+\pi^-}$	0.042	Section 5.5.4
$A_{(\text{track})}^{K^+K^-}$	0.034	Section 5.5.5
$A_{(\text{PID} \text{track})}^{K^-K^+\pi^-}$	0.028	Section 5.5.6
$A_{(\text{PID+L0} \text{track})}^{\mu^+}$	0.022	Section 5.5.1
$A_{(\text{HLT1} \text{track+PID+L0})}^{\mu^+\pi^-K^+K^-}$	0.005	Section 5.5.2
$A_{(\text{HLT2})}$	0.020	Reference [134]
backgrounds ($f_{\text{bkg}}A_{\text{bkg}}$)	0.031	Section 5.3
total syst. A_{raw}	0.077	
$1/(1 - f_{\text{bkg}})$	1.23 ± 0.09	Section 5.3
total syst. a_{sl}^s	0.20	

The values in the table are given for the averaged results of a_{sl}^s , as described above. Also here, the uncertainties on the detection asymmetries are assumed to be 100% correlated between the Dalitz regions. The table first lists the uncertainties with respect to A_{raw} . Then, the systematic uncertainty on a_{sl}^s is calculated by multiplying by $2/(1 - f_{\text{bkg}})$. This yields a value of the systematic uncertainty on a_{sl}^s of 0.20%, where the largest contribution comes from the detection asymmetries.

5.6.2 Consistency between the Dalitz regions

An overview of the twelve values that are found for a_{sl}^s , including both the statistical and systematic uncertainty, is shown in Figure 5.17. To check if the backgrounds in the K^*K and NR region are well-understood, a comparison is made with the $\phi\pi$ region. From Table 5.16, it is found that the statistical uncertainty on the $\phi\pi$ region is 0.25%, and that of the combined K^*K and NR region is 0.30%. A 1σ deviation thus corresponds to a difference of 0.39%. The difference between the value of a_{sl}^s in the $\phi\pi$ (0.16%) and combined K^*K and NR region (0.76%) is 0.60%, which corresponds to a 1.5σ deviation and is considered negligible.

A second method to check if the differences between the Dalitz regions, in particular the different sources of background, are under control, is by measuring the D_s^+ production asymmetry using the same regions of phase space. This is described in more detail in Chapter 6 and uses as much as possible the same selection of the signal candidates, treatment of the background and detection asymmetry corrections. Also here it is found that all Dalitz regions are in agreement with one another, as described in Section 6.7.1.

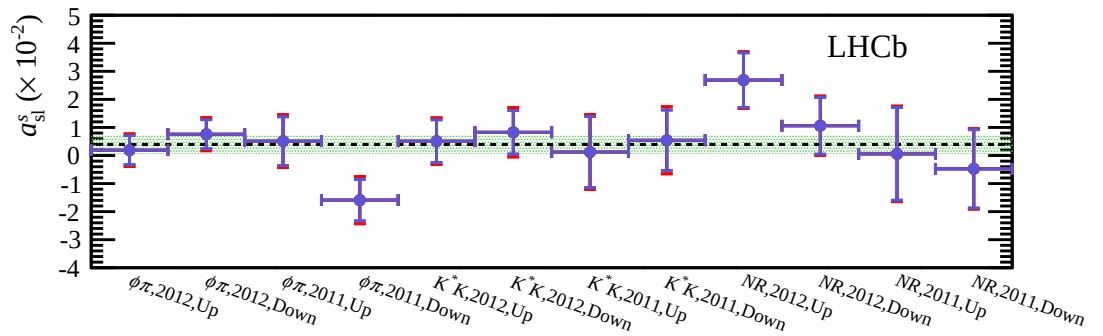


Figure 5.17: Resulting values of the measurement of a_{sl}^s for the three Dalitz regions, measured in two data-taking years using two magnet polarities. The blue error bars represent the statistical uncertainties. The red error bars represent the systematic uncertainties, which are added to the statistical uncertainties in quadrature. The dashed line shows the resulting value of a_{sl}^s averaged over all datasets, with the total uncertainty indicated in green.

5.6.3 Consistency with the previous analysis

The previous analysis of a_{sl}^s [29] had a rather different analysis strategy than the current one. First of all, it only used the $\phi\pi$ resonant region, such that any asymmetries from kaons could be neglected. In addition, the mass fit was two-dimensional, both in invariant D_s^- mass and in the D_s^- impact parameter, to distinguish the signal from prompt background, which usually has a lower value for IP. This was done in bins of muon momentum, to make corrections from the muon asymmetry more straightforward. In addition, the signal selection was different.

A comparison with the previous analysis was made, by redoing the previous analysis with both the 2011 and 2012 datasets. The selection of this is the same as in the paper [29]. It is more stringent than the current one, resulting in less background, but also in 30% fewer signal candidates. The resulting values are comparable with the current analysis in the $\phi\pi$ region within one standard deviation, taking into account the 66% statistical overlap between both samples.

5.6.4 Correlation with measurement of a_{sl}^d

The measurement of a_{sl}^d by LHCb [137] follows much of the same analysis strategy and detection asymmetry corrections. Therefore, there is a correlation ρ between these two measurement which is determined as follows.

The measurements share the approach to determine the combined L0 and PID asymmetry for the muon. In both measurements, this correction yields $\sqrt{\rho} = 0.23$ of the total uncertainty, giving a correlation of $\rho = 0.05$. The systematic uncertainty coming from the difference in cross-sections between positively and negatively charged pions is estimated using the same data set for a_{sl}^s and a_{sl}^d . This uncertainty is 0.14 of the total uncertainty, yielding a value of $\rho = 0.02$ for this overlap.

Lastly, the determination of the background asymmetries from B^0 decays uses the measured value of a_{sl}^d . The contribution of a_{sl}^d on the B^0 production asymmetries is $(-0.01 \pm 0.11)\%$, see Section 5.3.2. The total fraction of background from B^0 decays is 7.2% on A_{raw} . Accounting from the dilution going from A_{raw} to a_{sl}^s adds a factor 2.45, such that the correlation coefficient is calculated multiplying these numbers over the total uncertainty on a_{sl}^s . This yields a value of $\rho = +0.06$. Adding the correlations yields an overall value of $\rho = 0.13$ for the correlation between the LHCb measurements of a_{sl}^s and a_{sl}^d .

5.7 Conclusion

In conclusion, using the full 3 fb^{-1} of the Run I data sample, LHCb found a value [138] for the semileptonic asymmetry in $B_s^0\text{-}\bar{B}_s^0$ mixing of

$$a_{\text{sl}}^s = (0.39 \pm 0.26 (\text{stat}) \pm 0.20 (\text{syst}))\% ,$$

where the systematic uncertainty is dominated by the uncertainty on the detection asymmetries. This is the world's most precise measurement of a_{sl}^s . The measurement was performed in three regions of D_s^- decay phase space, corresponding to the $\phi\pi$ resonant region, the K^*K resonant region and the non-resonant region. The measured values are consistent between these three Dalitz regions and the result is compatible with no CP violation in $B_s^0\text{-}\bar{B}_s^0$ mixing. It is in agreement with, and supersedes, the previous LHCb value of a_{sl}^s [29].

Figure 5.18 shows an overview of all pure a_{sl}^s measurements to date. This includes the semileptonic D0 [27], and the two measurements from LHCb. The green band shows the average of the D0 and the new LHCb measurements, which is $(-0.48 \pm 0.48)\%$.

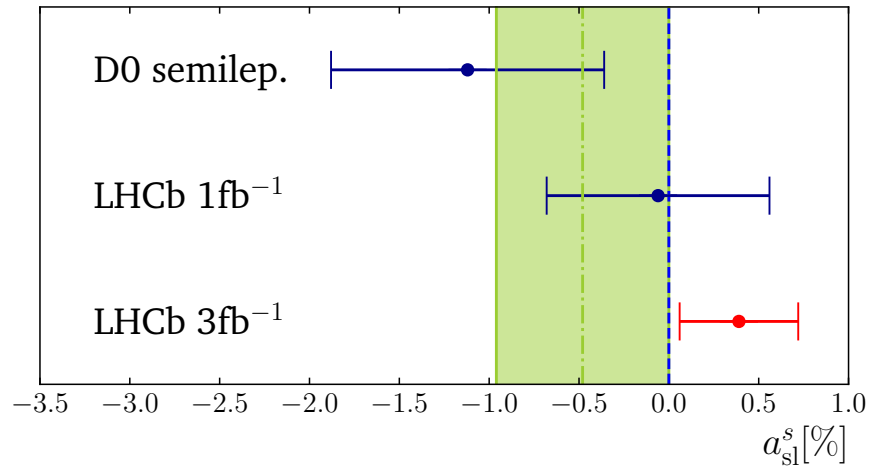


Figure 5.18: Overview of the outcome of a_{sl}^s measurements from the D0 experiment [27], the previous LHCb measurement [29], and the current measurement [138]. The figure also shows the average (green band) of the current LHCb and the D0 semileptonic measurement, which is $(-0.48 \pm 0.48)\%$. The blue dashed line indicates the Standard Model prediction, which is $(-0.48 \pm 0.48)\%$.

5. *CP violation in B_s^0 - $\bar{B}_s^0$ mixing*

6 The D_s^+ production asymmetry

This chapter discusses the measurement of the D_s^+ production asymmetry in pp collisions at centre-of-mass energies of $\sqrt{s} = 7$ and 8 TeV, in the kinematic region $2.5 < p_T < 25.0$ GeV and $2.0 < y < 4.5$ using $D_s^+ \rightarrow K^+ K^- \pi^+$ decays. It uses data corresponding to the full 3 fb^{-1} of integrated luminosity recorded in Run I.

The $D_s^+ \rightarrow K^+ K^- \pi^+$ Dalitz phase space includes the $\phi\pi$ and $K^* K$ resonant regions. For the measurement of the production asymmetry, only the mass region around the ϕ resonance is used. As a cross-check for the a_{sl}^s analysis, also the mass region around the K^{*0} resonance, and the remaining phase space are analysed. Due to different backgrounds in each of these regions, this analysis is split up into these three Dalitz phase space regions. In many aspects, this analysis is similar to the a_{sl}^s analysis, reported in Chapter 5. Wherever relevant, a reference is given to that chapter, to avoid unnecessary repetition.

The D_s^+ production asymmetry can be used to tune QCD models, as explained in Section 1.3, and is also an essential input for any analysis measuring global direct CP violation in D_s^+ mesons in LHCb. Additionally, it provides a cross-check for the understanding of the backgrounds in the three Dalitz regions in the a_{sl}^s analysis, since $A_P(D_s^+)$ should be the same in every region, if the kinematics are the same.

This chapter is divided as follows. Section 6.1 details the analysis strategy and discusses the similarities and differences with respect to the a_{sl}^s analysis. Section 6.2 describes the production asymmetries that can be expected in the LHCb acceptance, generated by PYTHIA 8.2.

The candidate selection is listed in Section 6.3, and a background estimate from secondary D_s^+ decays is described in Section 6.4. Section 6.5 concerns the signal extraction. The detection asymmetries contributing to this measurement are listed in Section 6.6. Section 6.7 discusses the results of the measurement, the consistency between the Dalitz regions, an overview of the systematics, and a comparison with the PYTHIA predictions. Lastly, Section 6.8 describes the conclusions.

6. The D_s^+ production asymmetry

6.1 Method

The D_s^+ production asymmetry is the difference between the inclusive cross-sections of $pp \rightarrow D_s^+$ and $pp \rightarrow D_s^-$, and is defined as:

$$A_P(D_s^+) = \frac{\sigma(pp \rightarrow D_s^+) - \sigma(pp \rightarrow D_s^-)}{\sigma(pp \rightarrow D_s^+) + \sigma(pp \rightarrow D_s^-)}. \quad (6.1)$$

This includes excited D_s^+ states, such as $pp \rightarrow D_s^{*+}$, where $D_s^{*+} \rightarrow D_s^+ \gamma$ or $D_s^{*+} \rightarrow D_s^+ \pi^0$. When measuring this asymmetry, a fit to the D_s^+ and D_s^- mass is performed, to discriminate signal from combinatorial background, and measures the so-called raw asymmetry, A_{raw} :

$$A_{\text{raw}} = \frac{N(D_s^+) - N(D_s^-)}{N(D_s^+) + N(D_s^-)}, \quad (6.2)$$

where $N(D_s^+)$ is the number of observed D_s^+ candidates.

The raw asymmetry must be corrected for detection asymmetries, A_D , and asymmetries arising from secondary D_s^+ mesons. The raw asymmetry can be expressed as:

$$\begin{aligned} A_{\text{raw}} &= f_{\text{prompt}} A_P(D_s^+) + f_{\text{secondary}} A_P(B) + A_D \\ &= (1 - f_{\text{secondary}}) A_P(D_s^+) + f_{\text{secondary}} A_P(B) + A_D, \end{aligned} \quad (6.3)$$

where $f_{\text{secondary}}$ is the fraction of D_s^+ events coming from B 's and $A_P(B)$ their corresponding production asymmetry. Since backgrounds from misidentified decays are strongly suppressed in the signal selection, which is explained in Section 6.3.5, and combinatorial backgrounds are accounted for in the signal fits described in Section 6.5, backgrounds from secondaries are the only ones to take into account in this expression. The fraction of prompt D_s^+ candidates is called f_{prompt} and is equal to $1 - f_{\text{secondary}}$. The production asymmetry can thus be evaluated using:

$$A_P(D_s^+) = \frac{1}{1 - f_{\text{secondary}}} (A_{\text{raw}} - A_D - f_{\text{secondary}} A_P(B)). \quad (6.4)$$

Each of these components is evaluated in the following sections.

6.1.1 Kinematic bins

Since it is expected that production asymmetries may depend on kinematics, the measurement is performed in kinematic bins in rapidity (as defined in Equation (1.90)) and transverse momentum. The kinematic distributions of the D_s^+ can vary between the three Dalitz regions, hence the cross-check between the Dalitz regions is performed within the kinematic bins. To keep the comparison with the previous measurement [55] of $A_P(D_s^+)$ feasible, the measurement uses the same bins in p_T and y . These bins were chosen such that the number of events per p_T or y bin is the same. To reduce the number of events per bin in the low p_T region, an extra bin was introduced for the current measurement.

Hence, the measurement is performed in 12 bins:

$$p_T : 2.5 - 4.7; 4.7 - 6.5; 6.5 - 8.5; 8.5 - 25.0 \text{ [GeV]},$$

$$y : 2.0 - 3.0; 3.0 - 3.5; 3.5 - 4.5.$$

An overview of the binning scheme projected onto the data, after selection, is shown in Figure 6.1.

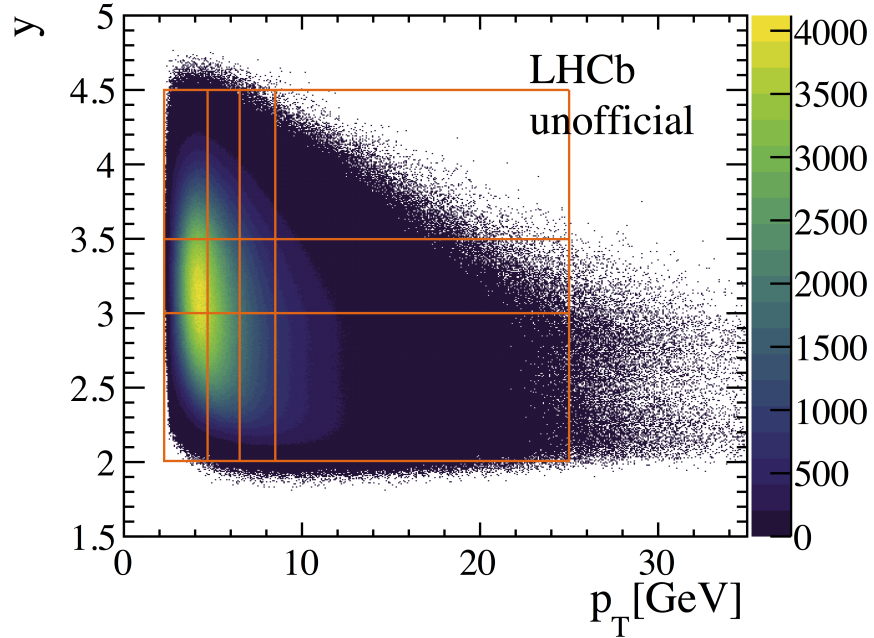


Figure 6.1: Binning scheme used for the $A_P(D_s^+)$ measurement determined using the D_s^+ transverse momentum and rapidity variables. The binning is plotted on top of the full dataset after selection.

6. The D_s^+ production asymmetry

6.1.2 Comparisons with the a_{sl}^s analysis

While there is a large overlap between the analysis procedures of a_{sl}^s and $A_P(D_s^+)$, there are also significant differences. First of all, the data sample for $A_P(D_s^+)$ is much larger, which allows for tighter requirements on the selection and therefore lowers the contributing backgrounds significantly. While this simplifies the final analysis, the different trigger strategy complicates the determination of the trigger asymmetry. Moreover, the tracking asymmetries are much larger in the $A_P(D_s^+)$ analysis because the pion in $D_s^+ \rightarrow K^+ K^- \pi^+$ is not matched with another track to cancel the majority of the tracking asymmetry.

6.2 Expectations from PYTHIA 8.2

The production asymmetry of charm and beauty hadrons depends on the production environment [46]. Therefore, no first-principle theoretical predictions exist. However, several models to represent the processes responsible for production asymmetries have been implemented in Monte Carlo generators, such as the beam drag model, described in Section 1.3.3, in PYTHIA. To obtain a prediction of the D_s^+ production asymmetry as a function of p_T and y , a stand-alone setup of PYTHIA 8.2 [43, 139] was used. To use the most recent advancements of PYTHIA, the standard LHCb tuning [81], was not used, but instead the default PYTHIA settings were changed when necessary and are described below.

6.2.1 PYTHIA settings

Most of the PYTHIA settings were kept to the default. Those that are not, are outlined in Table 6.1 and described in this section.

To match the conditions in the data-taking years 2011 and 2012, the beam parameters were set to the centre-of-mass energy of 7 and 8 GeV and the momenta are smeared out around their nominal values. Unlike the LHCb tuning, it was decided not to apply any beam crossing angles, because the $A_P(D_s^+)$ measurement corrects for these through the detection asymmetry corrections and thus measures the production asymmetry of head-on pp collisions.

To simulate the dominating $c\bar{c}$ production processes, following the description from Norrbin and Sjöstrand [46], the HardQCD processes $gg \rightarrow c\bar{c}$ and $q\bar{q} \rightarrow c\bar{c}$ are simulated. These processes are produced with a minimum p_T of 400 MeV, which is the same as the LHCb default setting.

The colour flow in the various simulated processes is connected to the colour flow in the beam remnant. The model that was implemented in PYTHIA 8 does not agree well with experimental data, *e.g.* the meson to baryon ratio differed compared to LHC data [140]. A new model was introduced in PYTHIA 8.2 [140] implementing more QCD knowledge, which is used for these simulations.

Lastly, in PYTHIA, fragmentation is based on the Lund string model [42, 141], which is adapted by the Bowler modification for heavy quarks [142], giving an extra parameter r_Q . This r_Q used to be the same for all quark flavours, but this did not match the experimental data very well [143]. Recently, this has been updated such that this parameter can be set differently for each flavour, which is used here. A value of $r_B = 0.67$ is found to work well for fragmentation of b quarks and is the default for the LHCb setting. Upon the recommendation in Reference [144], the same value is used for r_C in this simulation for c quarks.

6.2.2 PYTHIA simulation results

500 million events were generated both for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. Of these events, approximately 67% were generated with a $p_T < 2$ GeV, and about 60% with a rapidity that is not within the LHCb's acceptance. Hence, 12 million events for both samples are in the region of interest. The generated p_T and y distributions are shown in Figure 6.2. This shows nearly identical p_T distributions at the two centre-of-mass energies and a slight increase in the mean y for $\sqrt{s} = 8$ TeV.

The results of this study for the production asymmetry at $\sqrt{s} = 8$ TeV are shown in bins of p_T or y in Figure 6.3. At $\sqrt{s} = 7$ TeV, the production asymmetry is almost exactly the same as at $\sqrt{s} = 8$ TeV, which was expected, as explained in Section 1.3.5.

Table 6.1: Settings of PYTHIA 8.2 that are used for this prediction. This table only lists those settings that are different from the default PYTHIA 8.2 settings.

PYTHIA settings		
beam parameters	$\sqrt{s} = 7, 8$ TeV	"Beams:eCM = 7000." or 8000.
	momentum spread	"Beams:AllowMomentumSpread = on"
production processes	$gg \rightarrow c\bar{c}$	"HardQCD:gg2ccbar = on"
	$q\bar{q} \rightarrow c\bar{c}$	"HardQCD:qqbar2ccbar = on"
	minimum p_T	"PhaseSpace:pTHatMin = 0.4"
colour flow	reconnection	"ColourReconnection:mode = 1"
fragmentation	Bowler modification r_C	"StringZ:rFactC = 0.67"

6. The D_s^+ production asymmetry

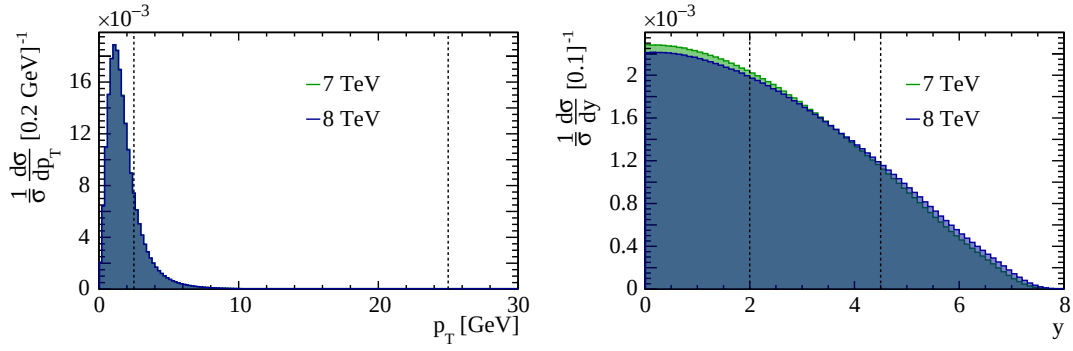


Figure 6.2: p_T (left) and y (right) distributions of the D_s^+ generated by PYTHIA at $\sqrt{s} = 7$ and 8 TeV in the full generated phase space. The black dashed lines indicate the region in which this measurement is performed.

The production asymmetry shows an increase as a function of p_T in the LHCb acceptance, but no significant variation as a function of y in the LHCb acceptance.

The values found for the production asymmetry are

$$A_P(D_s^+) = (-0.268 \pm 0.011)\% \text{ at } \sqrt{s} = 7 \text{ TeV},$$

$$A_P(D_s^+) = (-0.267 \pm 0.011)\% \text{ at } \sqrt{s} = 8 \text{ TeV},$$

in the full phase space. The uncertainties are purely statistical. Within the LHCb acceptance, $2.5 < p_T < 25.0 \text{ GeV}$ and $2.0 < y < 4.5$, these values are

$$A_P(D_s^+) = (-0.289 \pm 0.036)\% \text{ at } \sqrt{s} = 7 \text{ TeV},$$

$$A_P(D_s^+) = (-0.231 \pm 0.036)\% \text{ at } \sqrt{s} = 8 \text{ TeV}.$$

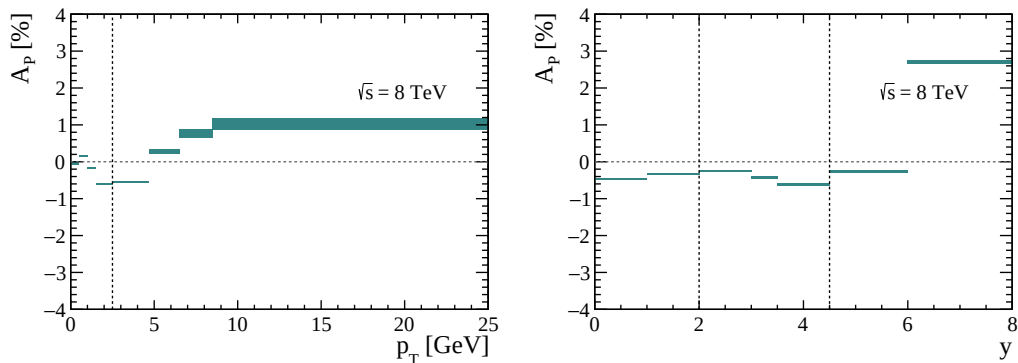


Figure 6.3: D_s^+ production asymmetries from PYTHIA 8.2 for $\sqrt{s} = 8 \text{ TeV}$ in bins of p_T (left) and y (right) in the full phase space that is generated by PYTHIA. The black dashed lines indicate the region of phase space in which this measurement is performed.

6.3 Selection

The selection of the D_s^+ candidates consists of the trigger requirements, followed by the offline selections. The latter consists of a stripping line, a division in Dalitz phase space regions, requirements on non-peaking backgrounds from misidentified particles, and extra selection to align the signal sample with several control samples. The full selection is described in this section.

6.3.1 Hardware trigger

The LHCb hardware trigger (L0) is described in more detail in Section 2.2.6. For the analysis of the D_s^+ production asymmetry, the bias from the L0 trigger was minimised by requiring it to trigger on the rest of the event rather than the signal. This is called TIS (trigger independent of signal). The L0 trigger line that is used, is a combination (the OR) of all of the L0 physics lines: L0Muon, L0DiMuon, L0Photon, L0Electron, L0Hadron and is called L0Global. Unfortunately, it was found that the L0 TIS trigger does have a large associated detection asymmetry which is discussed in more detail in Section 6.6.1.

6.3.2 High level trigger

After the hardware trigger, events are passed on to the first (HLT1) and second (HLT2) software triggers, which are described in more detail in Section 2.2.6. The HLT1 trigger line selects clean and high transverse momentum tracks, whereas the HLT2 trigger line specifically reconstructs charm mesons decaying into three hadrons.

HLT1 selection

The Hlt1TrackAllL0 trigger line is described in more detail in Section 5.2.2. In this analysis, it is required that a charge-neutral combination of the D_s^+ daughters fires the HLT1 trigger. This is done to reduce the asymmetry coming from the HLT1 selection. To avoid biasing either the $K^- K^+$ combination, or the $K^- \pi^+$ combination, the requirement is defined as follows:

$$\text{HLT1 TOS on } \begin{cases} K^- \text{ or } K^+, & \text{for even event numbers} \\ K^- \text{ or } \pi^+, & \text{for odd event numbers.} \end{cases} \quad (6.5)$$

6. The D_s^+ production asymmetry

This selection is asymmetric on the same-sign and opposite-sign kaon, as both conditions involve the opposite-sign kaon, and thus introduces an extra kaon asymmetry. However, kaon asymmetries, described in Section 6.6.5 have been studied in more detail and have been applied in more analyses than HLT1 asymmetries. They are therefore considered to be more reliable than the HLT1 asymmetries, which are determined in Section 6.6.2.

HLT2 selection

The `Hlt2CharmHadD2HHH` trigger line reconstructs the whole decay: charged charm mesons to three charged hadrons (kaons or pions). This trigger line comprises two stages. In the first stage (`Hlt2CharmHadTwoBodyForMultiBody`), two hadrons (h_1 and h_2) are combined (which can have charge 0 or ± 2). In the second stage, a third hadron (h_3) is added and additional requirements are applied.

First, each of the hadrons are required to have a minimum (transverse) momentum and good track quality. Then, to remove more background, mass and p_T requirements are applied on the h_1 and h_2 combination, as well as a maximum distance between these tracks (DOCA) to ensure they come from the same vertex. Because of the lifetime of the charm mesons, these criteria are complemented by a requirement on the flight distance (VS) of the $h_1 h_2$ combination.

Lastly, the third hadron (h_3) is added and to reduce background coming from a random combination of tracks, additional requirements on the flight distance, the minimum distance between all the three track combinations, and the vertex quality are applied. To select D_s^+ and D^+ candidates, the mass of the candidate is demanded to be between 1800 and 2040 MeV. The full HLT2 selection is listed in Table 6.2.

6.3.3 Stripping selection

The first stage of the offline reconstruction is the stripping, which selects D^+ and D_s^+ to $K^+ K^- \pi^+$ decays. This particular stripping line is called `StrippingD2hhh_KKP` and its requirements are listed in Table 6.3. It selects clean tracks by applying requirements on the p , p_T , and particle identification on each of the tracks.

For the D^+/D_s^+ candidate, it places requirements on the scalar sum of the p_T of the daughters, since this is much larger for signal than for background. In addition, it selects on the p_T of the D candidate and its mass. To ensure the signal is prompt and does not have missing momentum, the D_s^+ candidate is demanded to come from the primary vertex by a requirement on the direction angle (DIRA).

Table 6.2: Requirements for the HLT2 trigger line: Hlt2CharmHadD2HHH. VS is the flight distance, and DOCA the distance of closest approach between two tracks.

	variable	requirement
Event	# forward tracks	< 110
$h_{1,2}^\pm$	track χ^2/ndf	< 3
	p	> 5000 MeV
	p_T	> 500 MeV
	χ_{IP}^2	> 10
$h_1 h_2$ combination	$\sum_{h_1}^{h_2} p_T$	> 2000 MeV
	DOCA	< 0.1 mm
	$m(h_1 h_2)$	< 2100 MeV
	VS	> 3.0 mm
	χ_{VS}^2	> 40.0
	m_{corr}	< 3500 MeV
$h_3^\pm$	track χ^2/ndf	< 3
	χ_{IP}^2	> 5
$h_1 h_2 h_3$ combination	$\sum_{h_1}^{h_3} p_T$	> 2500 MeV
	DOCA	< 0.08 mm
	$\chi_{\text{vtx}}^2/\text{ndf}$	< 20
	χ_{IP}^2	< 15
	χ_{VS}^2	> 150
	m_{corr}	< 3500 MeV
	$m(K^+ K^- \pi^+)$	[1800, 2040] MeV
	HLT1 TOS	Hlt1Track

The selection is further improved by requiring a minimum flight distance which is typical for a charm or beauty meson decay. The D_s^+ candidate is ensured to come from the primary vertex by a requirement on the impact parameter χ^2 .

Compared to the a_{sl}^s selection, the PID requirements are much tighter, especially for the kaons, which are $\text{DLL}_{K\pi} > 7.0$ instead of $\text{DLL}_{K\pi} > -5.0$, which improves the signal purity. These requirements can afford to be tighter than those for the a_{sl}^s analysis due to the vast amount of prompt D_s^+ signal candidates, which is largely reduced when the D_s^+ comes from a B_s^0 decay as was the case in the a_{sl}^s analysis.

6. The D_s^+ production asymmetry

Table 6.3: Selection applied in the StrippingD2hhh_KKP stripping line. $N_{\text{daughters}}(\chi_{\text{IP}}^2(\text{PV}) > 10)$ is a requirement on the number of daughters passing the χ_{IP}^2 requirement. DIRA refers to the direction angle and the DLL variables are defined in Section 2.2.5.

	variable	requirement
event	# tracks	< 500
	# PVs	> 1
π	p_{T}	> 250 MeV
	p	> 2000 MeV
	$\chi_{\text{IP}}^2(\text{PV})$	> 4.0
	$\text{DLL}_{K\pi}$	< 3.0
$K^\pm$	p_{T}	> 250 MeV
	p	> 2000 MeV
	$\chi_{\text{IP}}^2(\text{PV})$	> 4.0
	$\text{DLL}_{K\pi}$	> 7.0
D^+/D_s^+	$\Sigma p_{\text{T}}(K^+K^-\pi^+)$	> 2800 MeV
	$N_{\text{daughters}}(\chi_{\text{IP}}^2(\text{PV}) > 10)$	≥ 2
	P_T	> 1000 MeV
	vertex χ^2/ndf	< 10.0
	DIRA (PV)	> 0.0
	$\chi_{\text{IP}}^2(\text{PV})$	< 12.0
	$\chi_{\text{VS}}^2(\text{PV})$	> 125.0
	$m(K^+K^-\pi^+)$	$\in [1800, 2040] \text{ MeV}$

6.3.4 Dalitz regions

The $A_P(D_s^+)$ analysis is split into exactly the same Dalitz regions as the a_{sl}^s analysis as defined in Section 5.2.4. Since this is a vital part of the analysis, the definitions are repeated here. The Dalitz plot of the signal in Figure 6.4 clearly shows two resonant regions. One is the region where the production of the kaon pair goes through the ϕ resonance, while the other is the one where the $K^+\pi^-$ pair is produced through the $K^*(892)^0$ resonance. The third region used in the analysis is the non-resonant region, which does not contain any resonances with a large branching fraction.

The three regions which are referred to as Dalitz regions in this thesis, are defined as follows:

- $\phi\pi$: Invariant mass of the K^+K^- pair within ± 20 MeV of the nominal ϕ mass.
- K^*K : Invariant mass of the $K^-\pi^+$ pair within ± 90 MeV of the nominal K^{*0} mass, and not in the $\phi\pi$ region.
- NR (non-resonant): All remaining candidates, i.e. not in the $\phi\pi$ nor in the K^*K region.

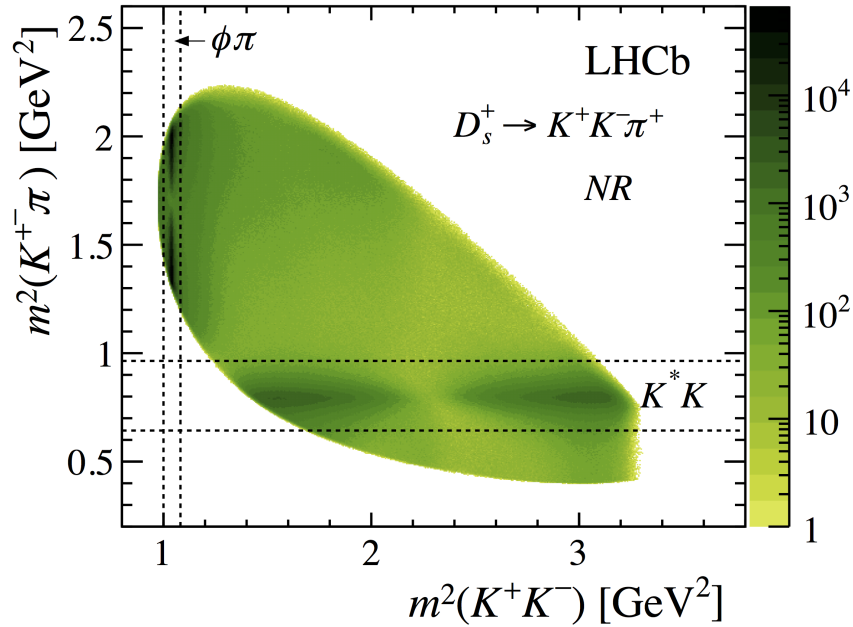


Figure 6.4: Dalitz plot of the $D_s^+ \rightarrow K^+ K^- \pi^+$ decay, using the full dataset and indicating the three regions of the Dalitz plane that are used in this analysis. In order to suppress backgrounds, only the region around the D_s^+ mass peak is shown: $1950 < m(KK\pi) < 1990$ MeV.

6.3.5 Reducing non-peaking backgrounds

The requirements to reduce the non-peaking backgrounds are strongly based on the a_{sl}^s selection (Section 5.2.5) to keep the analyses as similar as possible. Naturally, the selection to reduce the $J/\psi \rightarrow \mu^+\mu^-$ background in the a_{sl}^s analysis, are redundant for the $A_P(D_s^+)$ analysis, since there are no muons. A description of the requirements placed to reduce the backgrounds is given here and summarised in Table 6.4.

There are requirements to reduce the backgrounds from the Λ_c^+ and $K^*(892)^0$, where respectively a proton or a pion is misidentified as a kaon. This selection is kept the same as it is in the a_{sl}^s analysis. The prompt $D_s^+ \rightarrow K^+K^-\pi^+$ signal showed a visible contribution from D^+ , also in the $\phi\pi$ Dalitz region. Therefore the selection to reduce this background was extended to include also the $\phi\pi$ region, where a more stringent requirement on the kaon PID information was applied to remove residual backgrounds.

The backgrounds from misidentified pions in the low $m(K^+K^-)$ region are negligible due to the tight kaon identification requirements in the stripping selection. The $D^* \rightarrow D^0\pi$ selection criteria are kept the same. Lastly, the $D^{*+} \rightarrow D^0(K^+K^-)\pi^+$ veto is extended from only the NR Dalitz region in the a_{sl}^s selection, to the full Dalitz phase space, because also the $\phi\pi$ and K^*K region showed contributions from this background.

Table 6.4: Reflection vetoes applied to the prompt D_s^+ sample. K^+ refers to the same-sign kaon, while K^- refers to the opposite-sign kaon. The DLL and PROBNNK variables are explained in more detail in Section 2.2.5. The third column specifies the Dalitz regions in which these requirements are applied.

vetoes	remove if	applied to
Λ_c^+ veto	$K^+ (\text{DLL}_{p\pi} - \text{DLL}_{K\pi}) > 0.0$ AND $2261 < m(K_p^+ K^- \pi^+) < 2315$ MeV	$\phi\pi$
Λ_c^+ veto	$K^+ (\text{DLL}_{p\pi} - \text{DLL}_{K\pi}) > -15.0$ AND $2261 < m(K_p^+ K^- \pi^+) < 2315$ MeV	K^*K, NR
$K^*(892)^0$ veto	$K^+ \text{ DLL}_{K\pi} < 8$ AND $ m(K_\pi^+ K^-) - 892 < 25$ MeV	K^*K, NR
D^+ veto	$K^+ \text{ DLL}_{K\pi} < 20$ AND $ m(K_\pi^+ K^- \pi^+) - 1870 < 20$ MeV	$\phi\pi$
D^+ veto	$K^+ \text{ DLL}_{K\pi} < 30$ AND $ m(K_\pi^+ K^- \pi^+) - 1870 < 20$ MeV	K^*K, NR
$D^* \rightarrow D^0\pi$ veto	$m(K_\pi^+ K^- \pi^+) - m(K^- \pi^+) < 175$ MeV	K^*K, NR
$D^* \rightarrow D^0\pi$ veto	$m(K^+ K_\pi^- \pi^+) - m(K_\pi^- \pi^+) < 175$ MeV	K^*K, NR
$D^{*+} \rightarrow D^0(K^+K^-)\pi^+$ veto	$135 \leq m(K^+ K^- \pi^+) - m(K^+ K^-) \leq 152$ MeV	$\phi\pi, K^*K, NR$

6.3.6 Overview of selection

An overview of the selection that is applied, not including the background vetoes, is given in Table 6.5. To match the a_{sl}^s selection, a selection is applied on the track ghost probability for the pions and kaons. The overlap in the kinematic phase space between the signal and the detection asymmetry control samples is guaranteed by demanding a minimum value for the pion and kaon p and p_T .

Events coming from the D^+ decays, which are selected through the mass region in the stripping, are removed by applying a requirement on $m(K^+K^-\pi^+)$. Unlike for the a_{sl}^s analysis, these events are not necessary for the signal mass fit. To improve the signal purity, a selection is applied to the distance of closest approach (DOCA) χ^2 , and the vertex quality. These are less tight than for the a_{sl}^s analysis because the signal sample already is very pure.

Table 6.5: Selection of prompt $D_s^+ \rightarrow K^+K^-\pi^+$ events, including offline selection, but without the reflection vetoes that are in Table 6.4. The p_T requirement in the HLT1 selection corresponds to the HLT1 requirements in these years: 1.7 GeV in 2011 and 1.6 GeV in 2012. The track ghost probability, `PROBNNK` and DOCA variables are explained in more detail in Section 4.5 and Section 2.2.5.

	variable	requirement	
Dalitz regions	$\phi\pi$	$ m(KK) - 1020 \text{ MeV} < 20 \text{ MeV}$	
	K^*K	$ m(KK) - 1020 \text{ MeV} > 20 \text{ MeV}$ AND $ m(K^-\pi^+) - 892 \text{ MeV} < 90 \text{ MeV}$	
	NR	$ m(KK) - 1020 \text{ MeV} > 20 \text{ MeV}$ AND $ m(K^-\pi^+) - 892 \text{ MeV} > 90 \text{ MeV}$	
event and trigger	L0	L0Global TIS	applied to:
	HLT1	K^- OR K^+ : Hlt1TrackAllL0 TOS AND $p_T > 1.7(1.6) \text{ GeV}$ AND $IP > 0.1 \text{ mm}$	odd event numbers
	HLT1	K^- OR π^+ : Hlt1TrackAllL0 TOS AND $p_T > 1.7(1.6) \text{ GeV}$ AND $IP > 0.1 \text{ mm}$	even event numbers
	HLT2	Hlt2CharmHadD2HHH TOS	
	stripping	StrippingD2hhh_KKP	
pions	p_T	$> 400 \text{ MeV}$	
	p	$> 5.0 \text{ GeV}$	
	track GhostProb	< 0.5	
kaons	p_T	$> 300 \text{ MeV}$	
	p	$> 3.0 \text{ GeV}$	
	track GhostProb	< 0.5	applied to:
	same-sign <code>PROBNNK</code>	< 0.10	$\phi\pi$
	same-sign <code>PROBNNK</code>	< 0.15	K^*K, NR
candidate D_s^+	DOCA χ^2	< 30	
	vertex χ^2/ndf	< 8.0	
	$m(K^+K^-\pi^+)$	$\in [1900, 2035] \text{ MeV}$	

6. The D_s^+ production asymmetry

After the selection, there are 29 million events from the data collected in 2012 sample, and 9 million events from the data collected in 2011. The $\phi\pi$ Dalitz region contributes 44%, K^*K 27%, and the NR region 29% of the total number of events, including background. The signal purity differs between the Dalitz regions, where the $\phi\pi$ region is the cleanest with signal purities of 97%, and the non-resonant contains most background with a signal purity of 55% over the full mass range. The yields of signal and background events, and the signal purity for the three Dalitz regions and both data-taking years are shown in Table 6.6. These are based on the signal fits shown in Figure 6.5, which are integrated over both magnet polarities and all kinematic bins, using the same fit method that is described in Section 6.5. It shows that there is approximately three times as much signal in the 2012 data-taking year as in 2011, which is due to the higher luminosity and improved software triggers.

Table 6.6: Overview of the number of signal and background candidates, per Dalitz region and data-taking year. These numbers are obtained using the same fit method as the one described in Section 6.5.

$N_{\text{cand}} [\times 10^6]$	$\phi\pi$	K^*K	NR
2011:			
signal (S)	4.57	2.52	1.82
total background (B)	0.16	0.48	1.46
2012:			
signal (S)	14.63	8.09	5.83
total background (B)	0.52	1.66	4.84
signal purity $S/(S + B)$:			
2011	0.97	0.84	0.55
2012	0.97	0.83	0.55

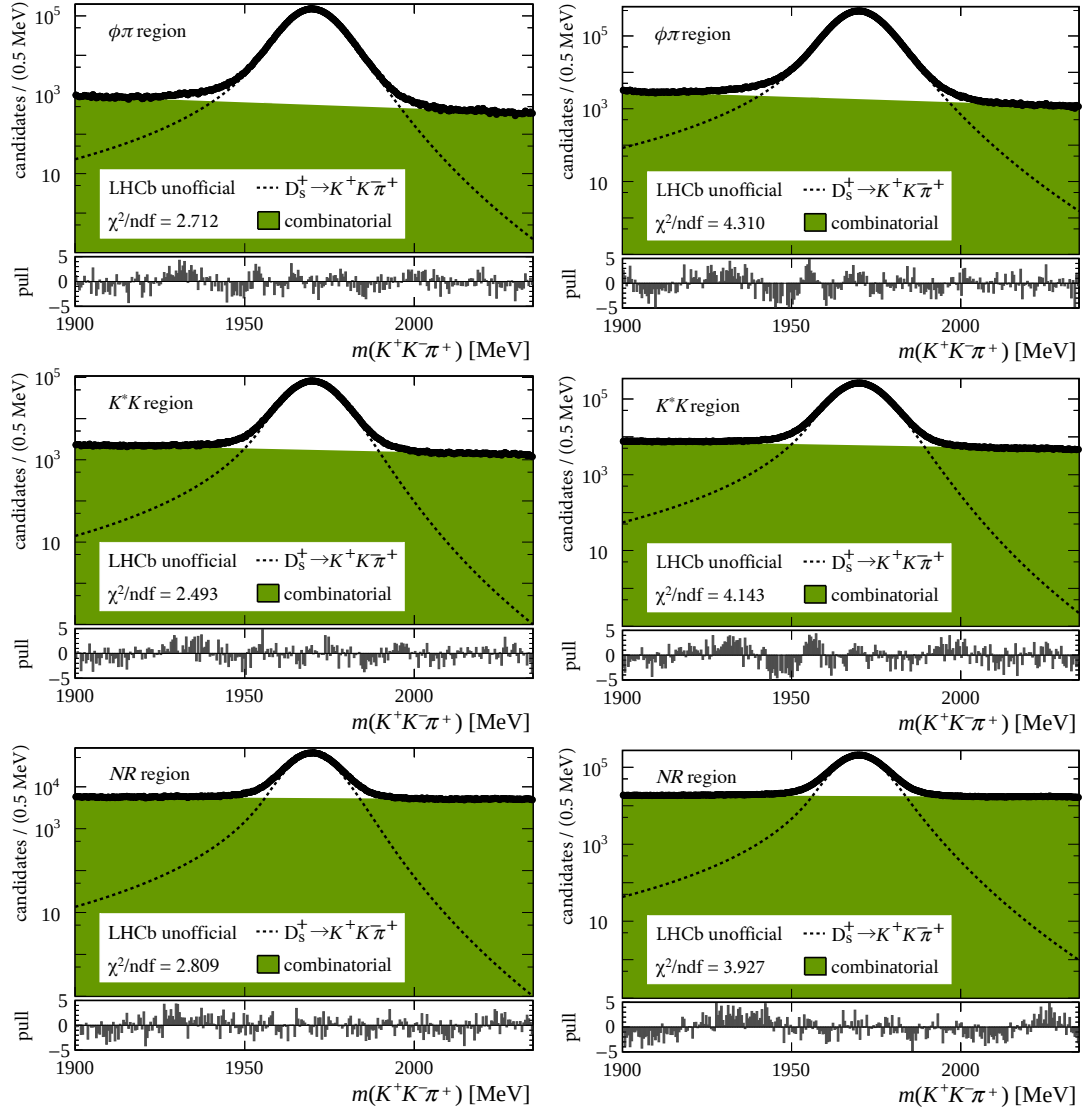


Figure 6.5: Mass distributions of the kinematically integrated signal samples, for which data from both magnet polarities are combined. The rows show fit results and pulls from the $\phi\pi$, K^*K , and NR Dalitz regions. The left column shows the data recorded in 2011, and the right from the 2012 data-taking year.

6.4 Peaking backgrounds

The D_s^+ production asymmetry is measured using an inclusive sample of D_s^+ mesons. Besides prompt D_s^+ mesons, this sample also includes a small number of secondary D_s^+ mesons, which originate from B decays. These backgrounds dilute the measurement of the production asymmetry, but also come with their own production asymmetries. Therefore, an estimate is made of the contamination by these secondary D_s^+ decays in this section.

6. The D_s^+ production asymmetry

Table 6.7: List of decays of b mesons and baryons contributing to the D_s^+ production asymmetry, accompanied by their production cross-sections and branching fractions to D_s^+ . For comparison: $\sigma(pp \rightarrow D_s^+) = 197 \pm 31 \text{ } \mu\text{b}$ [145].

$\sigma(pp \rightarrow B) [\text{ } \mu\text{b}]$	branching fraction [%]	$\sigma(pp \rightarrow B \rightarrow D_s^+ X)$
$\sigma(pp \rightarrow B^+ X) = 38.9 \pm 2.8$ [146]	$\mathcal{B}(B^+ \rightarrow D_s^+ X) = 7.9 \pm 1.4$	$3.1 \pm 0.6 \text{ } \mu\text{b}$
	$\mathcal{B}(B^- \rightarrow D_s^+ X) = 1.1 \pm 0.4$	$0.4 \pm 0.2 \text{ } \mu\text{b}$
$\sigma(pp \rightarrow B^0 X) = 38.1 \pm 6.0$ [146]	$\mathcal{B}(B^0 \rightarrow D_s^+ X) = 10.3 \pm 2.1$	$3.9 \pm 1.0 \text{ } \mu\text{b}$
	$\mathcal{B}(\bar{B}^0 \rightarrow D_s^+ X) < 2.6$	$< 1.0 \pm 1.0 \text{ } \mu\text{b}$
$\sigma(pp \rightarrow B_s^0 X) = 10.5 \pm 1.3$ [146]	$\mathcal{B}(\bar{B}_s^0 \rightarrow D_s^+ X) = 93 \pm 25$	$9.8 \pm 2.9 \text{ } \mu\text{b}$
$\sigma(pp \rightarrow \Lambda_b^0 X) = 17.7 \pm 2.9$ [147]	$\mathcal{B}(\Lambda_b^0 \rightarrow D_s^+ X) = 10 \pm 2$	$1.8 \pm 0.5 \text{ } \mu\text{b}$
Total		$20.0 \pm 3.3 \text{ } \mu\text{b}$

6.4.1 Background fractions

First, the cross-section for prompt D_s^+ production is compared to those of b mesons and baryons combined with their branching fractions to decays with D_s^+ mesons. The decays considered are listed with their cross-sections and branching fractions in Table 6.7.

The values for the cross-sections for the b mesons are taken from cross-section measurements in LHCb at $\sqrt{s} = 7 \text{ TeV}$ [146], where the statistical, systematical and normalisation uncertainties have been combined. For the Λ_b^0 baryon, no cross-section measurement is available and an estimate is made based on the fragmentation fraction ratio $\mathcal{R} = f_{\Lambda_b^0}/f_d$. From Reference [147], it is found that:

$$\mathcal{R}(\eta) = a + b \times (\eta - \bar{\eta}), \quad (6.6)$$

with

$$\begin{aligned} a &= 0.464 \pm 0.003^{+0.008}_{-0.010}, \\ b &= 0.081 \pm 0.005^{+0.013}_{-0.009}, \\ \bar{\eta} &= 3.198. \end{aligned}$$

Taking $\eta = \bar{\eta}$ as a typical value for the pseudorapidity, yields $\mathcal{R} = 0.464 \pm 0.017$. Using that $\sigma(pp \rightarrow B^0 X) = 38.1 \pm 6.0 \text{ } \mu\text{b}$, this yields $\sigma(pp \rightarrow \Lambda_b^0 X) = 17.7 \pm 2.9 \text{ } \mu\text{b}$.

The branching fractions of most of the decays are taken from the PDG [7] and when the uncertainty is asymmetric, the largest one is given. For the Λ_b^0 decay, it is assumed that the branching fraction is similar to that of $B^+ \rightarrow D_s^+ X$ or $B^0 \rightarrow D_s^+ X$, because it has a similar Feynman diagram, and a conservative value of $\mathcal{B}(\Lambda_b^0 \rightarrow D_s^+ X) = (10 \pm 2)\%$ is used.

Summing the contributions, the total cross-section of $pp \rightarrow B \rightarrow D_s^+ X$ is estimated at $20.3 \pm 3.3 \mu\text{b}$. To calculate this number, a value of $\mathcal{B}(\bar{B}^0 \rightarrow D_s^+ X) = 2.6\%$ is used. The D_s^+ cross-section at $\sqrt{s} = 7 \text{ TeV}$ is $\sigma(pp \rightarrow D_s^+) = 197 \pm 31 \mu\text{b}$ [145], which is thus nearly a factor of 10 higher than the cross-section of D_s^+ coming from B decays.

To give an estimate for the contamination of the D_s^+ production asymmetry from B decays, the reconstruction efficiencies for the various decays must be compared with the efficiency of the prompt decay. These efficiencies are determined from an inclusive D_s^+ Monte Carlo sample [55]. The values of the reconstruction efficiencies that were found are: $\varepsilon_{\text{prompt}} = 1.33\%$ for the prompt decay and $\varepsilon_{\text{secondary}} = 0.54\%$ for the D_s^+ from B decays.

The MC sample had a requirement to select prompt decays to match the signal selection from the previous $A_p(D_s^+)$ analysis [55]. This requirement on the impact parameter ($\ln(\chi_{\text{IP}}^2) < 2.2$, equivalent to $\chi_{\text{IP}}^2 < 9.0$) is tighter than for the current analysis ($\chi_{\text{IP}}^2 < 12.0$). Looking at the χ_{IP}^2 distributions, it was concluded that this requirement removes slightly more secondary background and an uncertainty of 20% on the efficiency ratio is assigned to reflect this.

Table 6.8 shows the fraction of background, $f_{\text{secondary}}$ at $\sqrt{s} = 7 \text{ TeV}$ from the different B decays in the D_s^+ sample, which is calculated as:

$$f_{\text{secondary}} = \frac{\sigma(pp \rightarrow B)}{\sigma(pp \rightarrow D_s^+)} \times \mathcal{B}(B \rightarrow D_s^+ X) \times \frac{\varepsilon_{\text{secondary}}}{\varepsilon_{\text{prompt}}}. \quad (6.7)$$

The expected percentage of D_s^+ from B decays in the prompt D_s^+ sample is thus:

$$f_{\text{secondary}} = (4.12 \pm 1.23)\%.$$

The cross-section values used here are determined on $\sqrt{s} = 7 \text{ TeV}$, while the $A_p(D_s^+)$ measurement is also performed at $\sqrt{s} = 8 \text{ TeV}$. Heavy flavour cross-sections approximately scale with centre-of-mass energy at the LHC [148, 149]. However, as the scaling is approximately the same for the prompt D_s^+ and for the B backgrounds, the ratios determined at $\sqrt{s} = 7 \text{ TeV}$ are still representative at $\sqrt{s} = 8 \text{ TeV}$, within their significant uncertainties.

6. The D_s^+ production asymmetry

6.4.2 B production asymmetries

To determine the influence of the sample of D_s^+ from B on the measured $A_P(D_s^+)$, the production asymmetries of the b mesons and Λ_b^0 are taken into account. Recently, new measurements from LHCb have been published, such that these can be used instead of the estimates made in the earlier analysis described in Section 5.3.2.

B^- production asymmetry

For B^+ , there are two recent measurements from LHCb. The first uses $B^+ \rightarrow \bar{D}^0 \pi^+$ decays, where the $\bar{D}^0$ is reconstructed both in the $K^+ \pi^-$ and $K^+ \pi^- \pi^+ \pi^-$ final states [57]. The following values are found:

$$\begin{aligned} A_P(B^-) &= (-0.41 \pm 0.49 (\text{stat}) \pm 0.10 (\text{syst}))\% \quad \text{at } \sqrt{s} = 7 \text{ TeV}, \\ A_P(B^-) &= (-0.53 \pm 0.31 (\text{stat}) \pm 0.10 (\text{syst}))\% \quad \text{at } \sqrt{s} = 8 \text{ TeV}. \end{aligned}$$

The second measurement [58] uses $B^+ \rightarrow J/\psi K^+$ decays, where $J/\psi \rightarrow \mu^+ \mu^-$, measuring values of

$$\begin{aligned} A_P(B^-) &= (-0.23 \pm 0.24 (\text{stat}) \pm 0.37 (\text{syst}))\% \quad \text{at } \sqrt{s} = 7 \text{ TeV}, \\ A_P(B^-) &= (-0.74 \pm 0.15 (\text{stat}) \pm 0.32 (\text{syst}))\% \quad \text{at } \sqrt{s} = 8 \text{ TeV}. \end{aligned}$$

These measurements are compatible and have similar values for the uncertainties. Hence, an average of the two is used as input for the B^+ production asymmetry:

$$\begin{aligned} A_P(B^-) &= (-0.32 \pm 0.33)\% \quad \text{at } \sqrt{s} = 7 \text{ TeV}, \\ A_P(B^-) &= (-0.64 \pm 0.24)\% \quad \text{at } \sqrt{s} = 8 \text{ TeV}. \end{aligned}$$

$\bar{B}^0$ production asymmetry

In addition to the measurement of the $\bar{B}^0$ production asymmetry mentioned in Section 5.3.2, it is measured using $B^0 \rightarrow J/\psi K^{*0}$ decays, where $J/\psi \rightarrow \mu^+ \mu^-$ and $K^{*0} \rightarrow K^- \pi^+$ [58]:

$$\begin{aligned} A_P(\bar{B}^0) &= (0.44 \pm 0.88 (\text{stat}) \pm 0.11 (\text{syst}))\% \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_P(\bar{B}^0) &= (-1.40 \pm 0.55 (\text{stat}) \pm 0.10 (\text{syst}))\% \quad \text{at } \sqrt{s} = 8 \text{ TeV} . \end{aligned}$$

Combining the two measurements yields the following result:

$$\begin{aligned} A_P(\bar{B}^0) &= (-0.52 \pm 0.32)\% \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_P(\bar{B}^0) &= (-0.61 \pm 0.21)\% \quad \text{at } \sqrt{s} = 8 \text{ TeV} , \end{aligned}$$

where the statistical and systematic uncertainties are combined.

Due to the mixing of B^0 to $\bar{B}^0$ and vice versa, these production asymmetries are diluted [32]. In addition, they are affected by the potential mixing asymmetry, a_{sl}^d , as explained in Section 5.3.2. Including a dilution factor of 0.36 for the production, and 0.64 for the mixing asymmetry, these asymmetries become

$$\begin{aligned} A_P^{\text{eff}}(\bar{B}^0) &= (-0.19 \pm 0.12)\% \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_P^{\text{eff}}(\bar{B}^0) &= (-0.22 \pm 0.08)\% \quad \text{at } \sqrt{s} = 8 \text{ TeV} , \\ (a_{\text{sl}}^d/2)^{\text{eff}} &= (-0.01 \pm 0.11)\% . \end{aligned}$$

Finally, the effective production asymmetries, including the mixing asymmetry, is

$$\begin{aligned} A_{P+\text{CP}}^{\text{eff}}(\bar{B}^0) &= (-0.19 \pm 0.16)\% \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_{P+\text{CP}}^{\text{eff}}(\bar{B}^0) &= (-0.21 \pm 0.14)\% \quad \text{at } \sqrt{s} = 8 \text{ TeV} . \end{aligned}$$

6. The D_s^+ production asymmetry

$\bar{B}_s^0$ production asymmetry

The $\bar{B}_s^0$ production asymmetry is measured to be [58]:

$$\begin{aligned} A_P(\bar{B}_s^0) &= (-0.65 \pm 2.88 (\text{stat}) \pm 0.59 (\text{syst}))\% \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_P(\bar{B}_s^0) &= (1.98 \pm 1.90 (\text{stat}) \pm 0.59 (\text{syst}))\% \quad \text{at } \sqrt{s} = 8 \text{ TeV} , \end{aligned}$$

using $B_s^0 \rightarrow D_s^- \pi^+$ decays, where $D_s^- \rightarrow K^+ K^- \pi^-$. Similarly as for the $\bar{B}^0$ production asymmetry, the $\bar{B}_s^0$ production asymmetry is diluted due to the B_s^0 - $\bar{B}_s^0$ oscillations. However, as the B_s^0 mesons oscillate rapidly, their dilution is much larger, and the dilution factor is found to be around 0.2%, see Section 5.1.1. This yields an effective time-integrated B_s^0 production asymmetry of:

$$\begin{aligned} A_P(\bar{B}_s^0) &= (-0.13 \pm 0.59) \times 10^{-4} \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_P(\bar{B}_s^0) &= (0.40 \pm 0.40) \times 10^{-4} \quad \text{at } \sqrt{s} = 8 \text{ TeV} , \end{aligned}$$

which can safely be neglected and consequently the effect of the mixing asymmetry, a_{sl}^s , can also be neglected.

Λ_b^0 production asymmetry

Finally, a value for the Λ_b^0 production asymmetry is determined in the same paper as the B^- , $\bar{B}^0$, and $\bar{B}_s^0$ production asymmetry [58]. The method is explained in more detail in Section 1.3.8, and measured a value of:

$$\begin{aligned} A_P(\Lambda_b^0) &= (-0.11 \pm 2.53 (\text{stat}) \pm 1.08 (\text{syst}))\% \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_P(\Lambda_b^0) &= (3.44 \pm 1.61 (\text{stat}) \pm 0.76 (\text{syst}))\% \quad \text{at } \sqrt{s} = 8 \text{ TeV} . \end{aligned}$$

Overview background asymmetries

Table 6.8 and Table 6.9 show for respectively $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ the background fractions, their production asymmetry, corresponding sign, and the product of the fraction and the asymmetry. Finally, adding up all the contributions,

it is found that:

$$f_{\text{secondary}}A_{\text{P}} = (0.25 \pm 1.04) \times 10^{-4} \quad \text{at} \quad \sqrt{s} = 7 \text{ TeV} ,$$

$$f_{\text{secondary}}A_{\text{P}} = (1.73 \pm 0.76) \times 10^{-4} \quad \text{at} \quad \sqrt{s} = 8 \text{ TeV} .$$

The contribution of the background may change within a kinematic bin; even a variation of a factor two is expected. In addition, the production asymmetries may also dependent on kinematics, especially for the the Λ_b^0 [58]. However, since the contribution of the B backgrounds to the production asymmetry is negligible compared to the other systematic uncertainties, these variations are neglected.

Table 6.8: Fractions of b mesons and baryons in the prompt D_s^+ signal and their production asymmetries at $\sqrt{s} = 7$ TeV.

	$f_{\text{secondary}}$ [%]	$A_{\text{P}}(B)$ [%]	$\text{sign}(A_{\text{P}})$	$f_{\text{secondary}}A_{\text{P}}(B) [\times 10^{-4}]$
B^+	0.63 ± 0.18	-0.32 ± 0.33 [57, 58]	–	0.20 ± 0.21
B^-	0.09 ± 0.04	-0.32 ± 0.33 [57, 58]	+	-0.03 ± 0.03
B^0	0.81 ± 0.26	-0.19 ± 0.16 [32, 58]	–	0.15 ± 0.14
$\bar{B}^0$	0.20 ± 0.21	-0.19 ± 0.16 [32, 58]	+	-0.04 ± 0.05
$\bar{B}_s^0$	2.01 ± 0.21	N/A	+	N/A
Λ_b^0	0.36 ± 0.09	-0.11 ± 2.75 [58]	+	-0.04 ± 1.00
Total	4.12 ± 1.23	–	–	0.25 ± 1.04

Table 6.9: Fractions of b mesons and baryons in the prompt D_s^+ signal and their production asymmetries at $\sqrt{s} = 8$ TeV.

	$f_{\text{secondary}}$ [%]	$A_{\text{P}}(B)$ [%]	$\text{sign}(A_{\text{P}})$	$f_{\text{secondary}}A_{\text{P}}(B) [\times 10^{-4}]$
B^+	0.63 ± 0.18	-0.64 ± 0.24 [57, 58]	–	0.41 ± 0.19
B^-	0.09 ± 0.04	-0.64 ± 0.24 [57, 58]	+	-0.06 ± 0.03
B^0	0.81 ± 0.26	-0.21 ± 0.14 [32, 58]	–	0.17 ± 0.13
$\bar{B}^0$	0.20 ± 0.21	-0.21 ± 0.14 [32, 58]	+	-0.04 ± 0.05
$\bar{B}_s^0$	2.01 ± 0.21	N/A	–	N/A
Λ_b^0	0.36 ± 0.09	3.44 ± 1.78 [58]	+	1.25 ± 0.07
Total	4.12 ± 1.23	–	–	1.73 ± 0.76

6.5 Signal yields

The raw asymmetries are obtained from a binned maximum likelihood fit to the D_s^+ invariant mass distribution. The D_s^+ signal peak is modelled with the double-sided Hypatia function [109], as described in Section 5.4.1. For the background, an exponential function is used, which is simpler than the Chebyshev polynomial used in the a_{sl}^s analysis. It suffices in this case because of the small background yields in the prompt D_s^+ sample. Since it is more stable than a polynomial function, the mass range between 1900 to 2035 MeV is sufficient to constrain the background shape. Consequently, there is no peak from $D^+ \rightarrow K^+ K^- \pi^-$ decays, as there is in the a_{sl}^s analysis.

6.5.1 Fitting signal shape and tail parameters

In order to get the fits with the Hypatia function to be stable and converge, the parameters λ , ζ , $a_{\text{I,II}}$ and $n_{\text{I,II}}$ are fixed. This is done using two different strategies, where the second is a simplification of the first yielding more stable fit results. This simplified strategy is only performed in the $\phi\pi$ region. Since the results of the first strategy are used throughout this thesis, both strategies are explained here.

Initial strategy

To determine the values to which the tail parameters are fixed, all data sets are combined within a kinematic bin, in two stages. In the first stage, separate fits are performed in which the data from the two data-taking years, with both magnet polarities, all Dalitz regions and D_s^+ charges are combined, but separate fits are performed in each of the 12 kinematic bins. This is done because the mass distributions vary more between kinematic bins than between Dalitz regions. From these first stage fits the parameters λ and ζ are extracted and these values are fixed for further fits. The outcomes of the fits are shown in Tables 6.10 and 6.11.

Table 6.10: Values for the variable λ in the signal fits, per kinematic bin in p_T and y .

$y \backslash p_T$	λ			
	2.5 – 4.7 GeV	4.7 – 6.5 GeV	6.5 – 8.5 GeV	8.5 – 25.0 GeV
2.0-3.0	-5.14 ± 0.09	-5.30 ± 0.19	-5.48 ± 0.07	-4.93 ± 0.10
3.0-3.5	-5.64 ± 0.16	-6.36 ± 0.11	-6.85 ± 1.04	-5.78 ± 0.07
3.5-4.5	-4.03 ± 0.08	-5.48 ± 1.27	-6.19 ± 0.11	-5.56 ± 0.31

Table 6.11: Values for the variable ζ in the signal fits, per kinematic bin in p_T and y .

$y \backslash p_T$	ζ			
	2.5 – 4.7 GeV	4.7 – 6.5 GeV	6.5 – 8.5 GeV	8.5 – 25.0 GeV
2.0-3.0	0.00 ± 0.38	0.00 ± 0.01	0.00 ± 0.45	1.11 ± 0.47
3.0-3.5	0.00 ± 1.40	0.00 ± 0.52	0.10 ± 0.16	0.00 ± 0.75
3.5-4.5	5.71 ± 0.05	2.85 ± 1.80	0.00 ± 1.86	1.13 ± 0.66

The differences between the tail parameters of the distributions seem too large between the Dalitz plot regions to use a single value for $a_{I,II}$ and $n_{I,II}$ for all fits. Therefore, the second stage of the process is to determine the tail parameters, where the fits are split up between kinematic regions and Dalitz regions. The data sets of the two data-taking years, magnet polarities and charges are still combined. The parameters λ and ζ are fixed to the values determined from the previous stage. The starting values for $a_{I,II}$ and $n_{I,II}$ are taken from the outcome of the first stage, separately for each kinematic bin. The fitted values for $a_{I,II}$ and $n_{I,II}$ are displayed in Tables 6.12 to 6.15 and these values are fixed for the final asymmetry fits.

Tables 6.12 to 6.15 show that some of the fits are not optimal and still have too many free parameters, such that their uncertainties are large. Section 6.5.3 investigates whether the values of these tail parameters have a significant influence on the extracted raw asymmetry. In addition, a second strategy fixing most of the fit parameters from the start is implemented and discussed in the next paragraph.

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Table 6.12: Values for the variable a_I in the signal fits, per Dalitz region, and per kinematic bin in p_T and y .

$y \backslash p_T$	a_I			
	2.5 – 4.7 GeV	4.7 – 6.5 GeV	6.5 – 8.5 GeV	8.5 – 25.0 GeV
$\phi\pi$				
2.0 – 3.0	2.42 ± 0.01	2.34 ± 0.01	2.27 ± 0.01	2.30 ± 0.01
3.0 – 3.5	2.16 ± 0.01	2.07 ± 0.01	1.97 ± 0.01	2.08 ± 0.01
3.5 – 4.5	1.94 ± 0.07	2.06 ± 0.03	2.15 ± 0.03	2.37 ± 0.05
K^*K				
2.0 – 3.0	2.40 ± 0.03	2.32 ± 0.02	2.20 ± 0.01	2.37 ± 0.02
3.0 – 3.5	2.09 ± 0.02	1.99 ± 0.01	1.84 ± 0.00	2.00 ± 0.01
3.5 – 4.5	2.08 ± 0.03	1.98 ± 0.02	2.10 ± 0.05	2.18 ± 0.07
NR				
2.0 – 3.0	2.26 ± 0.03	2.19 ± 0.02	2.26 ± 0.01	2.06 ± 0.01
3.0 – 3.5	2.07 ± 0.01	2.00 ± 0.00	1.91 ± 0.01	1.82 ± 0.02
3.5 – 4.5	1.81 ± 0.10	1.87 ± 0.16	2.01 ± 0.03	3.37 ± 2.10

Table 6.13: Values for the variable a_{II} in the signal fits, per Dalitz region, and per kinematic bin in p_T and y .

$y \backslash p_T$	a_{II}			
	2.5 – 4.7 GeV	4.7 – 6.5 GeV	6.5 – 8.5 GeV	8.5 – 25.0 GeV
$\phi\pi$				
2.0 – 3.0	11.91 ± 2.49	6.51 ± 2.16	11.01 ± 2.65	7.53 ± 8.01
3.0 – 3.5	7.65 ± 4.16	10.90 ± 9.38	9.32 ± 3.97	8.99 ± 9.27
3.5 – 4.5	1.90 ± 0.28	5.80 ± 7.63	9.27 ± 7.33	9.24 ± 8.23
K^*K				
2.0 – 3.0	9.27 ± 4.00	4.96 ± 7.37	2.78 ± 0.08	6.10 ± 7.01
3.0 – 3.5	9.35 ± 3.96	11.19 ± 5.93	9.68 ± 6.64	8.86 ± 6.92
3.5 – 4.5	3.32 ± 6.52	7.11 ± 4.46	11.21 ± 10.35	9.79 ± 6.54
NR				
2.0 – 3.0	2.23 ± 0.04	2.35 ± 0.06	3.96 ± 3.11	10.70 ± 10.14
3.0 – 3.5	2.16 ± 0.19	3.14 ± 0.87	7.63 ± 8.67	8.86 ± 6.74
3.5 – 4.5	1.93 ± 0.32	3.50 ± 1.93	11.21 ± 10.35	8.32 ± 9.07

Table 6.14: Values for the variable n_I in the signal fits, per Dalitz region, and per kinematic bin in p_T and y .

$y \backslash p_T$	n_I			
	2.5 – 4.7 GeV	4.7 – 6.5 GeV	6.5 – 8.5 GeV	8.5 – 25.0 GeV
$\phi\pi$				
2.0 – 3.0	2.06 ± 0.03	2.34 ± 0.06	2.83 ± 0.04	3.05 ± 0.09
3.0 – 3.5	4.06 ± 0.13	4.96 ± 0.10	6.20 ± 0.27	5.77 ± 0.21
3.5 – 4.5	8.27 ± 1.83	8.67 ± 0.72	7.17 ± 0.45	5.94 ± 0.70
K^*K				
2.0 – 3.0	2.13 ± 0.15	2.38 ± 0.11	3.17 ± 0.16	2.06 ± 0.10
3.0 – 3.5	5.89 ± 0.50	5.01 ± 0.18	7.69 ± 0.47	5.00 ± 0.28
3.5 – 4.5	8.23 ± 0.73	6.69 ± 0.72	7.98 ± 1.28	4.91 ± 1.02
NR				
2.0 – 3.0	1.77 ± 0.21	1.95 ± 0.11	1.93 ± 0.04	3.09 ± 0.13
3.0 – 3.5	1.80 ± 0.10	3.19 ± 0.02	4.00 ± 0.33	10.52 ± 1.50
3.5 – 4.5	5.23 ± 2.99	5.11 ± 2.64	4.93 ± 0.66	14.97 ± 14.10

Table 6.15: Values for the variable n_{II} in the signal fits, per Dalitz region, and per kinematic bin in p_T and y .

$y \backslash p_T$	n_{II}			
	2.5 – 4.7 GeV	4.7 – 6.5 GeV	6.5 – 8.5 GeV	8.5 – 25.0 GeV
$\phi\pi$				
2.0 – 3.0	26.30 ± 22.60	39.61 ± 18.01	20.31 ± 24.04	39.81 ± 4.54
3.0 – 3.5	11.41 ± 20.79	10.46 ± 15.49	19.87 ± 11.85	14.00 ± 8.58
3.5 – 4.5	39.99 ± 28.45	38.58 ± 1.85	14.00 ± 8.58	14.00 ± 8.58
K^*K				
2.0 – 3.0	19.96 ± 11.88	36.60 ± 5.82	10.93 ± 17.67	30.32 ± 16.08
3.0 – 3.5	20.36 ± 11.99	10.46 ± 4.36	19.01 ± 25.38	14.00 ± 8.58
3.5 – 4.5	39.73 ± 0.32	18.99 ± 11.56	14.00 ± 8.58	14.00 ± 8.58
NR				
2.0 – 3.0	10.00 ± 0.63	10.00 ± 1.11	10.01 ± 26.36	26.42 ± 21.37
3.0 – 3.5	10.42 ± 23.59	22.71 ± 19.14	10.00 ± 28.24	14.00 ± 8.58
3.5 – 4.5	38.31 ± 1.42	10.01 ± 24.57	14.00 ± 8.58	14.00 ± 8.58

6. The D_s^+ production asymmetry

Simplified strategy

Since the initial strategy with a large number of free parameters in the tails show significant variations between their fitted parameters, an alternative strategy is also tried to cross-check the results. In this simplified strategy some of the tail parameters are fixed, based on the results from the initial strategy. The results in Table 6.11 indicate that ζ can be set to zero for all fits. Technically, this means that the Hypatia function reduces to a Student's t -distribution [109]. Both a_I and a_{II} are fixed to 2.3, and n_{II} is fixed to 20.

Consequently, fits are performed for the values for the parameters λ , n_I for which the data from the two data-taking years, with both magnet polarities and D_s^+ charges are combined. Since these parameters are dependent on the kinematics of the D_s^+ , these are performed per kinematic bin. The outcomes of the fits are shown for the $\phi\pi$ region in Tables 6.14 and 6.16. The simplified fits for the other two Dalitz regions are not implemented since these are not included in the final analysis, which is explained in Section 6.7.3.

Table 6.16: Values for the variable λ in the simplified signal fits, in the $\phi\pi$ Dalitz region, and per kinematic bin in p_T and y .

$y \backslash p_T$	λ			
	2.5 – 4.7 GeV	4.7 – 6.5 GeV	6.5 – 8.5 GeV	8.5 – 25.0 GeV
2.0-3.0	-5.81 ± 0.11	-5.64 ± 0.08	-5.59 ± 0.10	-4.88 ± 0.07
3.0-3.5	-5.79 ± 0.11	-6.14 ± 0.11	-6.23 ± 0.15	-5.76 ± 0.15
3.5-4.5	-5.27 ± 0.12	-6.08 ± 0.15	-6.32 ± 0.23	-5.44 ± 0.25

Table 6.17: Values for the variable n_I in the simplified signal fits, in the $\phi\pi$ Dalitz region, and per kinematic bin in p_T and y .

$y \backslash p_T$	n_I			
	2.5 – 4.7 GeV	4.7 – 6.5 GeV	6.5 – 8.5 GeV	8.5 – 25.0 GeV
$\phi\pi$				
2.0 – 3.0	2.38 ± 0.05	2.38 ± 0.04	2.54 ± 0.05	2.94 ± 0.07
3.0 – 3.5	2.90 ± 0.08	2.92 ± 0.07	2.98 ± 0.10	3.23 ± 0.14
3.5 – 4.5	4.51 ± 0.32	4.17 ± 0.21	4.48 ± 0.36	6.64 ± 0.97

6.5.2 Raw asymmetries

Finally, the positively and negatively charged $D_s^\pm$ candidates are fitted simultaneously, where the yields and the mean of the signal shapes are allowed to vary independently, as well as all the background parameters. The σ parameter is shared between the D_s^+ and D_s^- candidates. The raw asymmetry A_{raw} is included as a free parameter in the fit, and the yield of the negatively charged candidates is expressed as:

$$N_{D_s^-} = N_{D_s^+} \frac{1 - A_{\text{raw}}}{1 + A_{\text{raw}}} . \quad (6.8)$$

An overview of the fit parameters, indicating whether they are fixed or shared, is given in Tables 6.18 and 6.19. This table also includes references to the tables with all values of the parameters, where applicable. An example of a fit is shown in Figure 6.6.

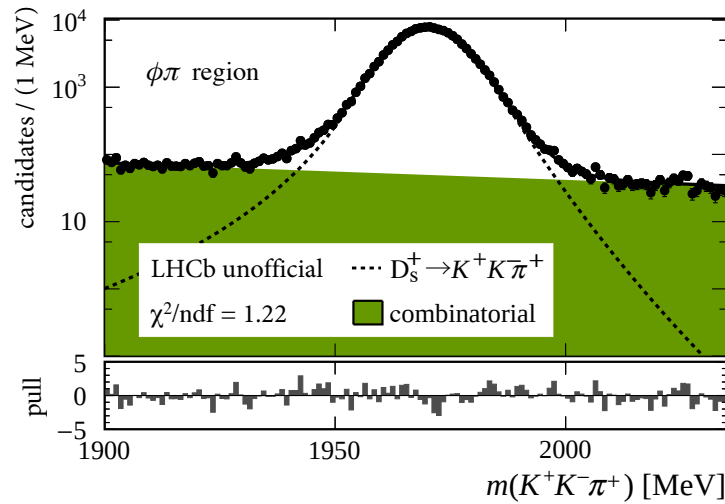


Figure 6.6: Plot of A_{raw} mass fit in $\phi\pi$ Dalitz region for D_s^+ candidates, in the kinematic range $3.5 < y < 4.5$ and $2.5 < p_T < 4.7$ GeV for the dataset recorded in 2012 with the magnet polarity down.

Comparing the strategies

The two fit strategies are in good agreement with one another. The largest difference in A_{raw} found is 0.02% in a single bin with a statistical uncertainty of 0.62%, while in 77% of the bins the difference is less than 0.01%. Therefore, it is concluded that the poorly converging fits to determine the tail parameters have no significant influence on the result of A_{raw} . The simplified fit strategy will be adapted in the future for this analysis, while the initial strategy is used throughout this thesis.

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Table 6.18: Overview of the fit parameters and where they can be found for the initial strategy. Shared refers to whether the parameter is shared between the D_s^+ and D_s^- fit.

parameter	fixed/free	shared	Tables
μ	free	not shared	
σ	free	shared	
N_{sig}	free	not shared	
N_{bkg}	free	not shared	
λ	fixed per kinematic bin	shared	6.10
ζ	fixed per kinematic bin	shared	6.11
a_{I}	fixed per kinematic and Dalitz bin	shared	6.12
a_{II}	fixed per kinematic and Dalitz bin	shared	6.13
n_{I}	fixed per kinematic and Dalitz bin	shared	6.14
n_{II}	fixed per kinematic and Dalitz bin	shared	6.15
exp	free	not shared	

Table 6.19: Overview of the fit parameters and where they can be found for the simplified strategy. Shared refers to whether the parameter is shared between the D_s^+ and D_s^- fit.

parameter	fixed/free	shared	Tables
μ	free	not shared	
σ	free	shared	
N_{sig}	free	not shared	
N_{bkg}	free	not shared	
λ	fixed per kinematic bin	shared	6.16
ζ	fixed to 0	shared	
a_{I}	fixed to 2.3	shared	
a_{II}	fixed to 2.3	shared	
n_{I}	fixed per kinematic	shared	6.17
n_{II}	fixed to 20	shared	
exp	free	not shared	

6.5.3 Systematic uncertainties

The focus of the systematic studies for the signal fit lies on the variation of the Hypatia tail parameters. These are assessed by generating simplified simulations: signal distributions with a known signal asymmetry. The distributions are generated

with the Hypatia function for which the tail parameters are varied by a Gaussian distribution with their nominal value as a mean, and the fit uncertainty from the tail parameters as standard deviation.

For each kinematic and Dalitz region, 1000 simulations are performed and fitted to the signal PDF. Their pulls are calculated and fitted to a Gaussian distribution. The NR region is the region with the lowest signal purity and is thus most prone to any biases, which was confirmed by the studies for the a_{sl}^s analysis, see Section 5.4.2. Therefore, this is the region that is chosen to show in Figure 6.7. No significant bias nor incorrect uncertainty estimation is found in any of the regions.

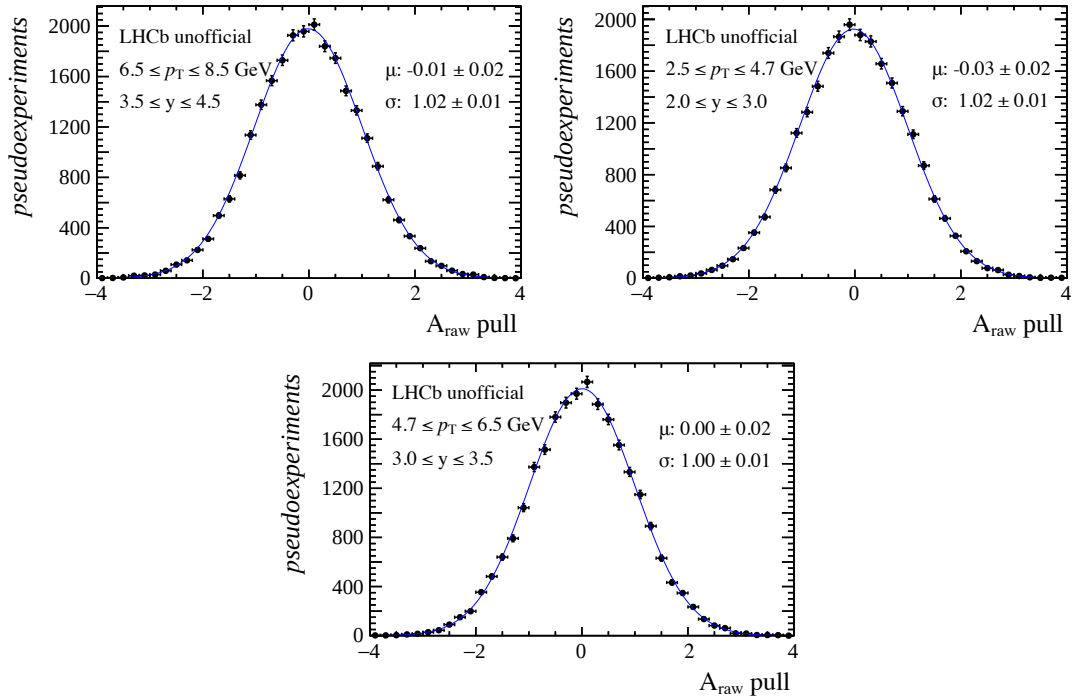


Figure 6.7: Pull distributions from the pseudo-experiments using variations of the tail parameters.

For the a_{sl}^s analysis, a systematic bias from the signal PDF was studied. For this analysis, both the signal purity is higher, and the background shape is simpler. Therefore, it is safe to assume that any systematic uncertainty coming from the signal shape is smaller than in the a_{sl}^s analysis. Since this systematic uncertainty is small compared to the other systematic uncertainties in this analysis, no further studies are conducted and a conservative systematic uncertainty of 0.02% is assigned to every region. This corresponds to the largest deviation in A_{raw} found in studies of the tail parameters for the a_{sl}^s analysis and thus provides a safe upper limit.

6.6 Detection asymmetries

The raw asymmetries must be corrected for various sources of detection asymmetries, which can come from the trigger, reconstruction, material interactions, and particle identification. The detection asymmetries that are taken into account are the tracking asymmetries coming from the pion: $A_{(\text{track})}^{\pi^+}$, and two kaons: $A_{(\text{track})}^{K^+K^-}$; the PID asymmetries: $A_{(\text{PID}|\text{track})}^{K^+K^-\pi^+}$; the asymmetry caused by the HLT1: $A_{(\text{HLT1}|\text{track}+\text{PID}+\text{L0})}^{K^+K^-\pi^+}$; and asymmetries from the L0 trigger $A_{(\text{L0}|\text{HLT1}+\text{track})}$, such that:

$$A_D = A_{(\text{track})}^{\pi^+} + A_{(\text{track})}^{K^+K^-} + A_{(\text{PID}|\text{track})}^{K^+K^-\pi^+} + A_{(\text{HLT1}|\text{track}+\text{PID}+\text{L0})}^{K^+K^-\pi^+} + A_{(\text{L0}|\text{HLT1}+\text{track})}. \quad (6.9)$$

This section explains the methods used to determine each of these detection asymmetries. The L0 detection asymmetries are explained in Section 6.6.1, followed by the HLT1 asymmetries in Section 6.6.2. The asymmetries coming from the HLT2 trigger can be neglected, as explained in Section 6.6.3. Section 6.6.4. Section 6.6.5 discuss the tracking asymmetries coming from respectively the pion and kaons. Finally, the contribution from the PID asymmetries is explained in Section 6.6.6.

To only correct the raw asymmetry, and not the combinatorial background, the detection asymmetries are evaluated for the sWeighted [107] signal sample, which are explained in Section 4.1.3. These sWeights are determined per event, by fitting the data per kinematic bin to a Hypatia function for the signal, and an exponential for the background, the same as the nominal fit procedure for the raw asymmetries which is described in Section 6.5.

Since detection asymmetries are dependent on the kinematics of the tracks, the variation of the detection asymmetries between the D_s^+ p_T - η bins is expected. This is indicated by the kinematic distributions of the pions and kaons in these D_s^+ p_T - η bins. An overview of these kinematic distributions is given in Figures 6.8 to 6.10. Figure 6.8 shows the p_T (left) and η (right) distributions of the pion. Figure 6.9 displays the p_T distributions of the same-sign kaon and the opposite-sign kaon. Figure 6.10 shows the pseudorapidity distributions of the kaons. Each of these figures shows all three Dalitz regions. The p_T distributions are integrated over the D_s^+ y bins, while the η distributions are integrated over the D_s^+ p_T bins.

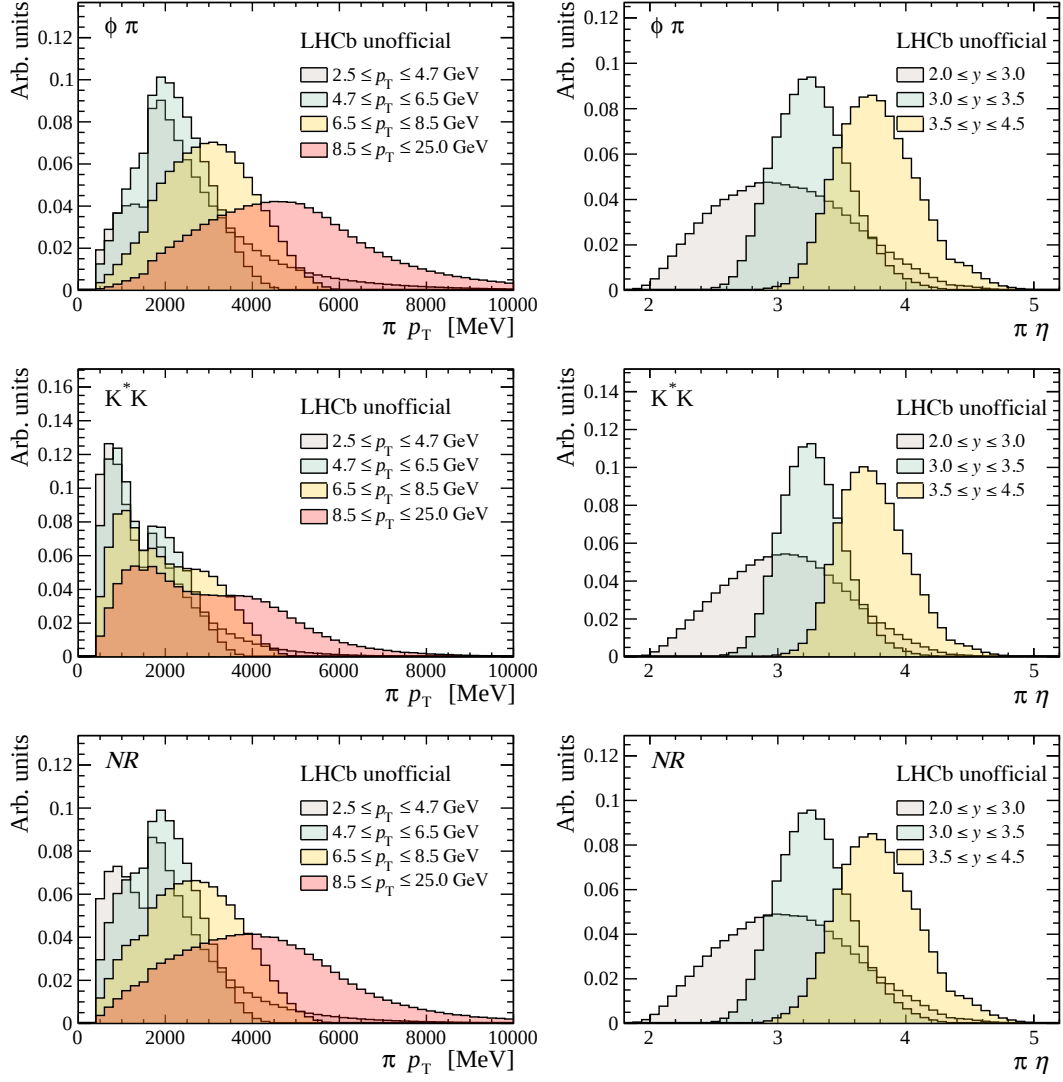


Figure 6.8: Transverse momentum (left) and pseudorapidity (right) spectra for the pions in the 2012 data set, after offline selection. Each plot shows distributions which are split in bins of D_s^+ kinematics. From top to bottom the plots show candidates in the Dalitz regions $\phi\pi$, K^*K , NR .

6.6.1 L0 asymmetry

As explained in Section 6.3.1, the L0 trigger requirement is chosen to be independent of the final state particles arising from the signal decay (TIS), to prevent a bias from the L0 trigger on the measurement. However, it was found that the L0 calorimeter triggers are not quite independent of the signal particle deposits, as explained in Section 4.2.3.

6. The D_s^+ production asymmetry

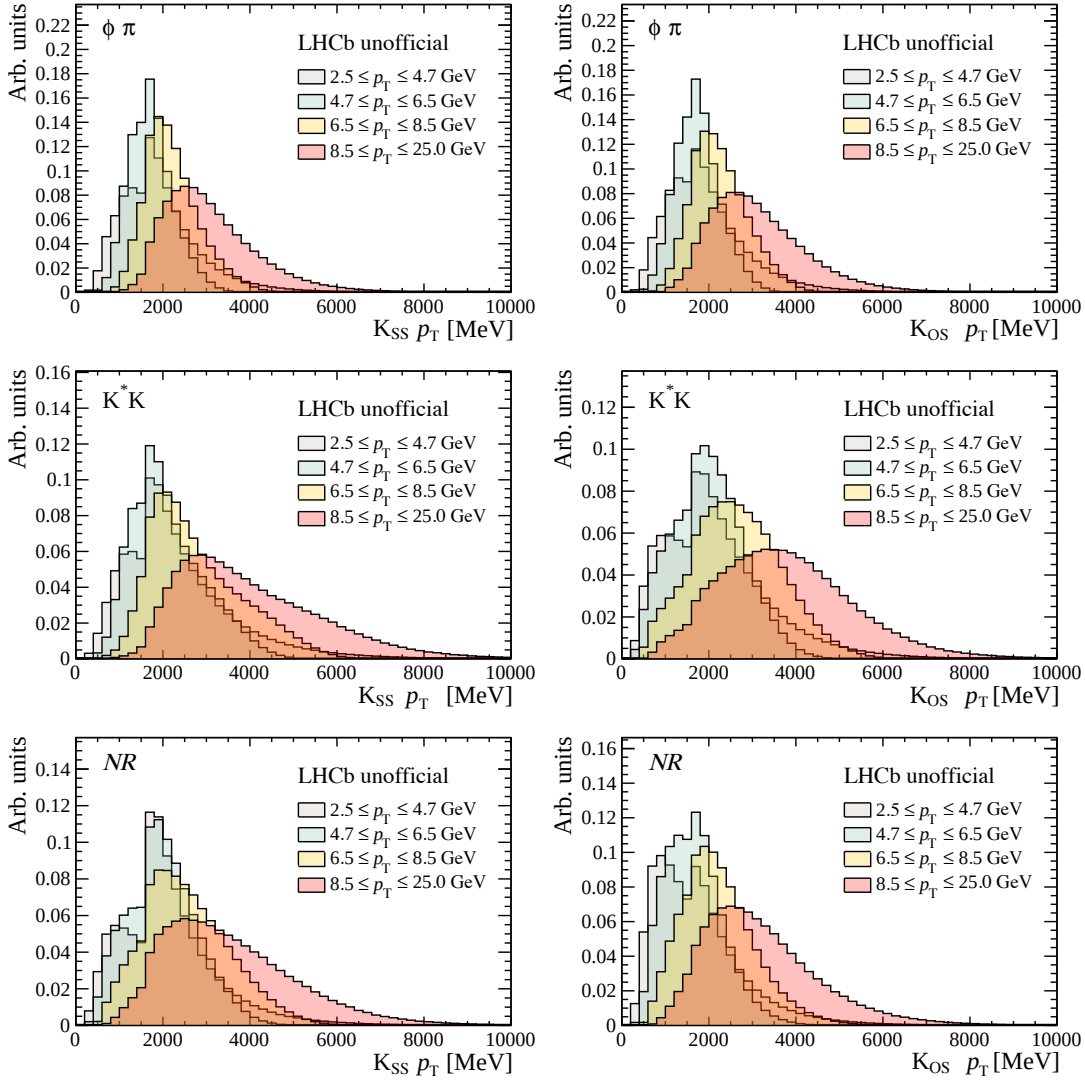


Figure 6.9: Transverse momentum spectra for same-sign (left) and opposite-sign kaons (right) in the 2012 data set, after offline selection. Each plot shows distributions which are split in bins of D_s^+ kinematics. From top to bottom the plots show candidates in the Dalitz regions $\phi\pi$, K^*K , NR .

The resulting L0 TIS asymmetry is determined using the $\phi\pi$ resonant region of the signal sample, as explained in Section 4.2.3. This is done by determining the TIS efficiency from events that are triggered on the signal particles (TOS). Like the measurement, it is performed in bins of $D_s^+ p_T$ and y . The correction between kinematic bins is thus uncorrelated. As the kinematic dependence of the asymmetry is captured by the binning, the correction in each bin will also apply to the other Dalitz regions, i.e. the results are assumed to be 100% correlated between Dalitz regions. Because the signal sample is used to determine the L0 TIS asymmetry, the correlation between A_{raw} and the L0 correction is 100% in the $\phi\pi$

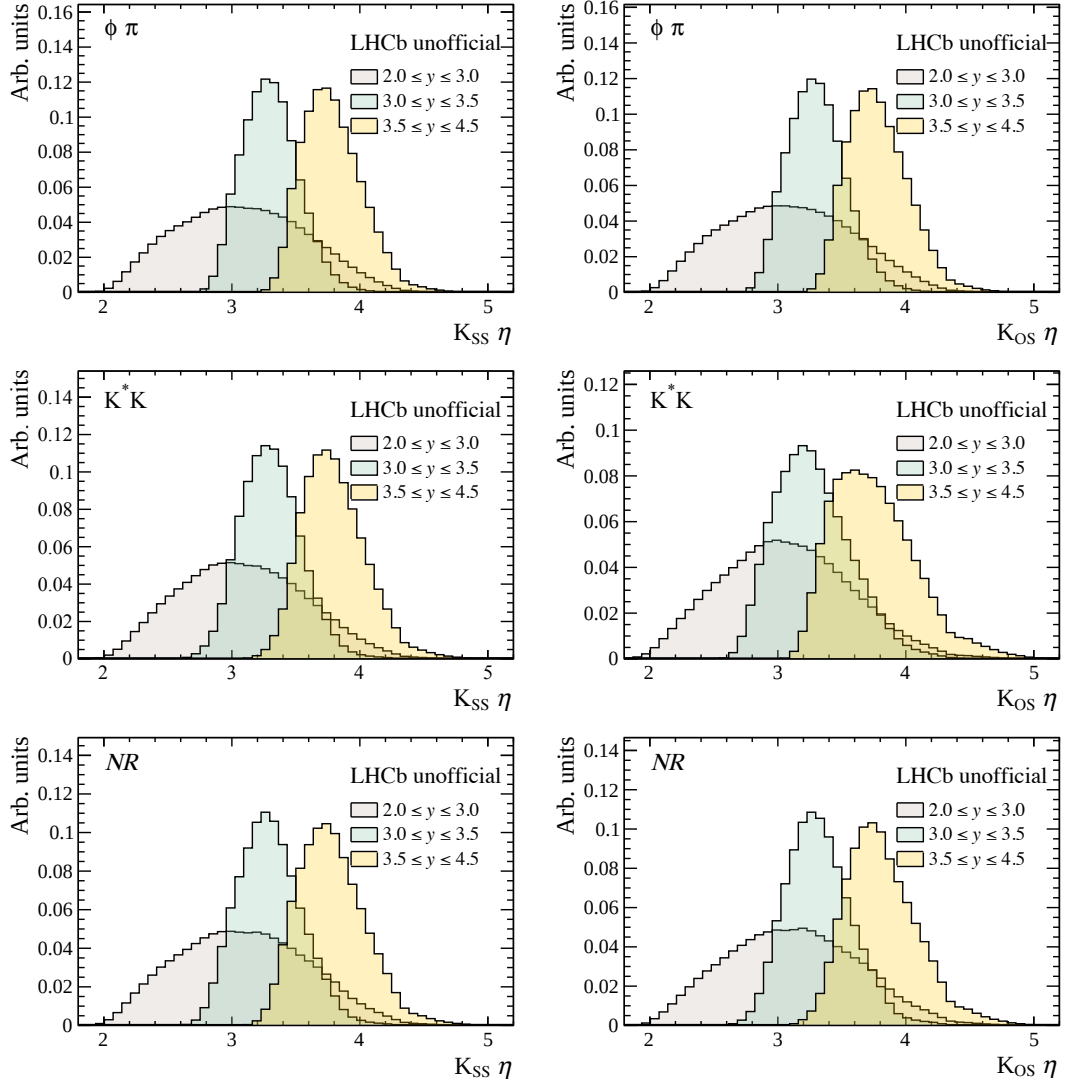


Figure 6.10: Pseudorapidity spectra for same-sign (left) and opposite-sign kaons in the 2012 data set, after offline selection. Each plot shows distributions which are split in bins of D_s^+ kinematics. From top to bottom the plots show candidates in the Dalitz regions $\phi\pi$, K^*K , NR .

Dalitz region. However, this is less than 10% of the signal in A_{raw} , such that this can safely be neglected when determining the statistical uncertainty on the D_s^+ production asymmetry.

To determine the systematic uncertainty on the L0 TIS asymmetries, a sample of $D^+ \rightarrow \pi^+\pi^-K^+$ is used, which has much higher signal yields than the $D_s^+ \rightarrow K^+K^-\pi^+$ sample. With this D^+ sample, the dependency of the L0 TIS trigger on the signal particles is tested. In the nominal method to determine the TIS efficiency, the L0 trigger is also required to trigger on the signal (TOS), which are the final state particles that are combined to make the D_s^+ or D^+ candidate.

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TIS efficiencies from the D^+ sample are determined also using samples where one of the pion or kaon tracks in the signal decay are TOS. The resulting L0 TIS asymmetries are shown in Figure 6.11. If the TIS efficiency were truly independent of signal, it would be the same for each of the tracks or the combination of the three tracks TOS. This is not the case and there appears to be a tendency that the two same sign pions have more similar asymmetries. Consequently a systematic effect is assigned to cover the breakdown of the assumption that the TIS is independent of TOS. Half of the maximum difference between the three separate evaluations of the TIS asymmetry, using the samples that are TOS on each of the signal kaons and pions, is assigned as a systematic uncertainty per kinematic bin. This is done using the arithmetic mean of the data taken with both magnet polarities, since the final result is computed in this manner for the signal.

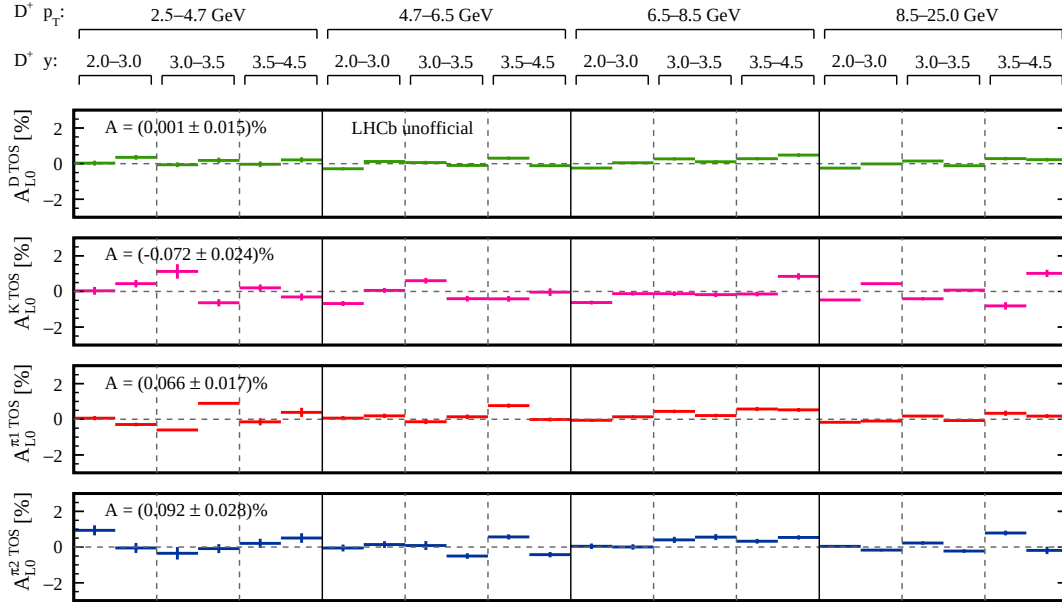


Figure 6.11: L0 TIS asymmetry determined from the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay determined on data recorded in 2012, using various TOS requirements. From top to bottom the TOS requirement is applied either on the D^+ candidate, the kaon, the first pion, or the second pion. The different columns show different kinematic regions of the D^+ , as indicated at the top of the plot. Within each kinematic bin, the left data point is for data taken with the magnet polarity up, and the right for data taken with the magnet polarity down. The quoted asymmetries and uncertainties are the result from fitting a constant, not including any systematic uncertainties.

The assumption that, after splitting by kinematic bin, the L0 TIS asymmetry is the same in each of the Dalitz regions is also tested. The control channel is divided into two Dalitz regions: the $K^*\pi$ resonant region, and the non-resonant region. As shown in Figure 6.12, it is found that there is only a small difference between these two regions per kinematic bin, and half of the difference is used as a additional systematic uncertainty. Again, this is the difference per kinematic bin of the arithmetic average of the data taken with both magnet polarities. This systematic uncertainty is assigned only to the K^*K and NR region.

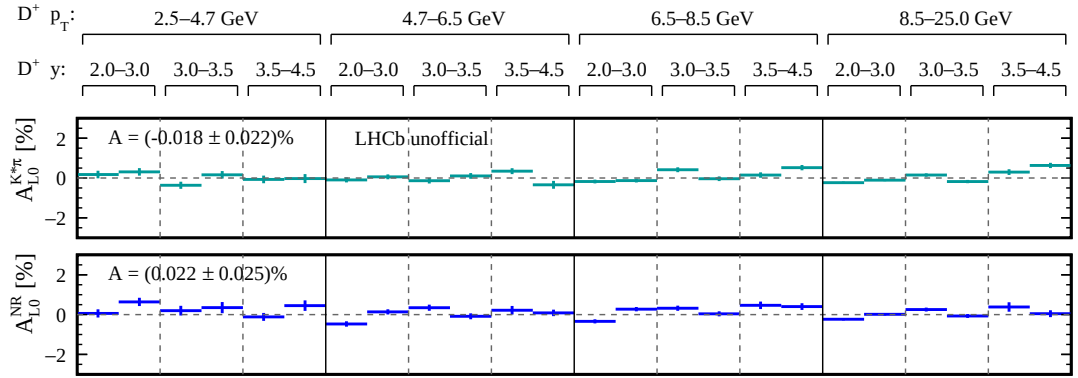


Figure 6.12: L0 TIS asymmetry determined from the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay using data recorded in 2012, determined on different regions in the Dalitz space, following the selection shown in Figure 4.11. The different columns show different kinematic regions of the D^+ , as indicated at the top of the plot. Within each kinematic bin, the left data point is for data taken with the magnet polarity up, and the right for data taken with the magnet polarity down. The quoted asymmetries and uncertainties are the result from fitting a constant, not including any systematic uncertainties.

An additional check was performed to rule out any dependence on the number of SPD hits. Every L0 trigger has a requirement on the maximum number of SPD hits in the event of 600. This removes extremely busy events that may take too long in the event processing. However, the requirement is different for the DiMuon trigger line. This could result in a different distribution of the number of tracks in the TIS and TISTOS sample, and, if there is a dependence of the L0 TIS asymmetry on the number of tracks, or hits, this could bias the measurement. It was found that only 0.5% of the events in the $D_s^+ \rightarrow K^+ K^- \pi^+$ signal sample has a number of SPD hits larger than 600. Even if all these events would have a large asymmetry of 2%, this would contribute to a change of 0.01% on the overall L0 TIS asymmetry, which is negligible compared to the statistical and systematic uncertainty of the measurement.

6. The D_s^+ production asymmetry

6.6.2 HLT1 asymmetry

The selection of the D_s^+ production asymmetry requires the HLT1 Hlt1TrackAllL0 trigger to have fired on one track of a charge-neutral combination of the D_s^+ daughters. This means that for a D_s^+ decay the HLT1 trigger requirement is either on the K^- or π^+ candidate, for odd events, or the trigger is on the K^- or K^+ candidate, for even events, as described in Section 6.3.2.

The per-track asymmetries that are determined using the method described in Section 4.2.2 are translated to the per-event asymmetries as follows: the per-track efficiencies of the pions and kaons are added up, while the overlap is subtracted to prevent double counting. This is equivalent to Equation (5.21), and is defined as:

$$\varepsilon_{\text{HLT1}} = \frac{1}{\sum w_i} \sum_i^{N_{\text{evts}}} w_i \left(\varepsilon_{K^-}^i + \varepsilon_+^i - \varepsilon_{K^-}^i \varepsilon_+^i \right), \quad (6.10)$$

where

$$\varepsilon_+ = \begin{cases} \varepsilon_{K^+}, & \text{for even events,} \\ \varepsilon_{\pi^+}, & \text{for odd events.} \end{cases} \quad (6.11)$$

Here, ε_j^i , with $j = (K^+, K^-, \pi^+)$ are the per-track efficiencies for the Hlt1TrackAllL0 to fire, and w_i are the sWeights of the signal sample. Different efficiencies are applied for kaons and pions, since the studies in Section 4.2.2 show slight differences between their per-track asymmetries.

The per-track efficiencies depend on kinematics; therefore, the mean efficiency and asymmetry are determined in bins of the transverse momentum and pseudo-rapidity of the tracks. These bins are chosen such that the efficiency does not vary much within the bin.

To determine the statistical uncertainty, the value of the per-track mean efficiency and asymmetry in each of the bins is varied by taking a random number from a Gaussian distribution taking as mean the central value in that bin and as standard deviation the uncertainty in the bin, independently bin-by-bin. Using these varied values, the HLT1 asymmetry is calculated. This procedure is repeated 50 times and the statistical uncertainty is taken as the RMS of these asymmetries. The statistical uncertainties are between 0.02% and 0.12%.

The systematic uncertainties related to the method are probed by varying the per-track efficiencies. The online p_T variable in the trigger is different from the offline reconstructed one that is used in this analysis. In the analysis, only tracks with a $p_T > 1.7$ (1.6) GeV are assigned a trigger efficiency for 2011 (2012).

However, the p_T of tracks with `Hlt1TrackAllL0` is smeared, such that the offline p_T distributions do not have a sharp cut-off at 1.7 (1.6) GeV, but instead more smooth turn-on from 1.65 (1.55) GeV. Therefore, as a check, requirements of 1.65 (1.65) GeV were applied to study this effect.

To study the influence of binning in p_T and η , the binning is changed to p and η . Finally, for the nominal method, the pion and kaon efficiencies were calculated separately. This was done because a small difference in the asymmetries was seen, as described in Section 4.2.2. However, no difference in behaviour is expected for `Hlt1TrackAllL0`, since this just selects on tracks, and not on PID. Hence, another check was performed by combining the kaons and pions to calculate their efficiencies.

In each kinematic bin, the largest difference between the default value and the other three is taken as a systematic uncertainty. The systematic uncertainties are of the order of a permille, with the largest being 0.04%. As expected, the effect of the p_T requirement is very small. Depending on the bin, either the p - η binning or the combination of $K\pi$ gives the largest systematic deviation.

6.6.3 HLT2 asymmetry

The asymmetry of the HLT2 muon topological lines `Hlt2TopoMu(2|3|4)BodyBBDT` has been limited to a few times 10^{-4} [134]. While this analysis does not use the muon topological lines, the argument from Section 5.5.3 can be repeated: the asymmetry relevant for this measurement is due to the difference in online HLT2 and offline tracking reconstruction. Since the tracking algorithms are the same for the various HLT2 lines, this upper limit of 2×10^{-4} can safely be used as a systematic uncertainty, which is negligible compared to the other detection asymmetries.

6.6.4 Pion tracking asymmetry

The tracking asymmetry coming from the pion daughter cannot be paired with another particle and is thus expected to be much larger than the combined $\mu\pi$ tracking asymmetry for the a_{sl}^s analysis. It is determined by combining the $J/\psi \rightarrow \mu^+\mu^-$ tag-and-probe method, described in Section 4.2.1, and the partially reconstructed D^* method, which is detailed in Section 4.3. Their systematic uncertainties are taken from varying the kinematic binning from p_T - η to p - η .

6. The D_s^+ production asymmetry

Unfortunately, the partially reconstructed D^* method only works for tracks with momenta up to 100 GeV, which is not sufficient for the high rapidity bins, especially in the $\phi\pi$ Dalitz region, as indicated in Figure 6.13. For momenta higher than that, there is significant background and the signal shape is difficult to fit for the partially reconstructed decays. To assess a value of the pion asymmetry for events with a pion $p > 100$ GeV, the value for the highest p bin is used, with a 100% uncertainty. When taking the weighted average between the two methods, this practically means that only the tag-and-probe measurement is used in kinematic bins with a large number of high momentum pions.

The $J/\psi \rightarrow \mu^+\mu^-$ method is corrected for the pion nuclear interaction asymmetry and the acceptance using simulations which are described in Section 4.4.1. The simulated corrections are determined with respect to the $J/\psi \rightarrow \mu^+\mu^-$ tag-and-probe method and added to this method, before the weighted average of the two tracking asymmetry methods is taken. The systematic uncertainty of the simulated corrections is taken as half of the central value of the corrections.

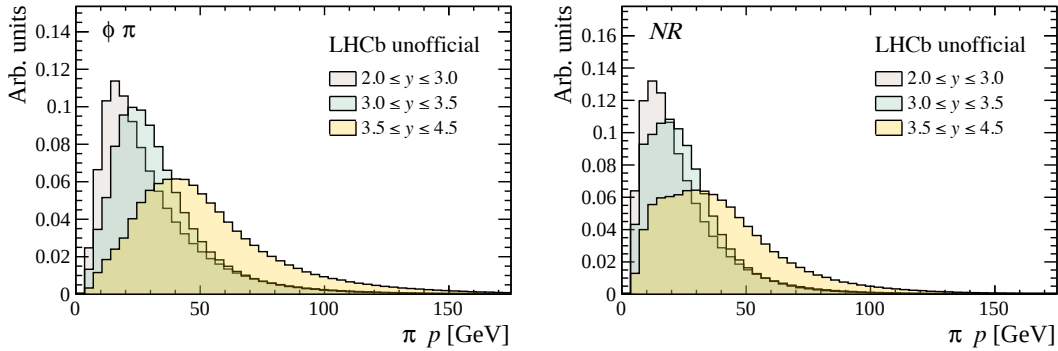


Figure 6.13: Pion momentum distributions in the $\phi\pi$ (left) and NR (right) region, from the data sample recorded in 2012. In the K^*K region the number of events with a pion $p > 100$ GeV is even more limited than in the NR region.

6.6.5 Kaon asymmetry

The HLT1 trigger requirement on a charge-neutral combination of tracks, is asymmetric on the kaons. Hence, while this requirement reduces the HLT1 asymmetry, it increases the kaon asymmetry; this is illustrated in Figure 6.14. The momentum distribution for the kaons are shown before and after the HLT1 requirement is applied. After this requirement, the overlap between the momentum distributions of the two kaons has visibly decreased.

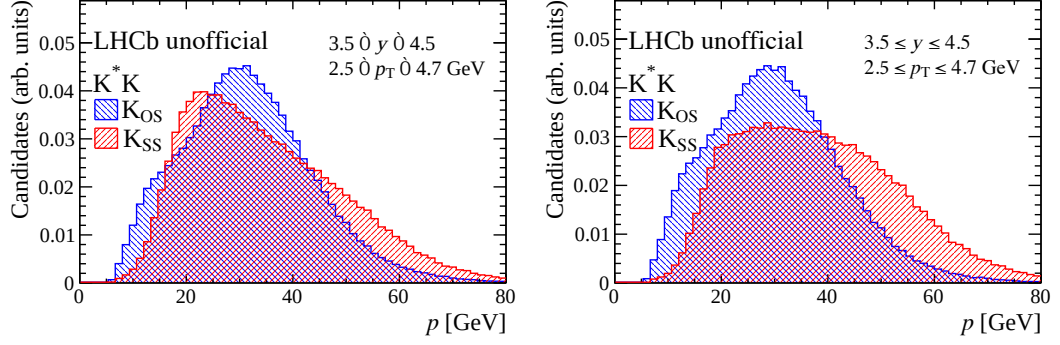


Figure 6.14: Momentum distributions of the two kaons: on the left are the kaon distributions before applying the HLT1 requirement, on the right after this requirement. These plots show the distributions from the data collected in 2012, in the K^*K Dalitz region, in the D_s^+ kinematic bin $3.5 < y < 4.5$ and $2.5 < p_T < 4.7$ GeV.

The kaon asymmetry is calculated using the method described in Section 4.5.1. This method determines kaon-pion asymmetries, instead of kaon-kaon asymmetries. In order to determine the kaon-kaon asymmetries, the kaon-pion asymmetry is determined twice. Once reweighted to the kaon with the same charge as the D_s^+ (same-sign), $A_D(K_{SS}^-\pi_c^+)$, and once to the opposite-sign kaon, $A_D(K_{OS}^-\pi_c^+)$. These are combined as follows:

$$A_D(K_{SS}^-\pi_c^+) - A_D(K_{OS}^-\pi_c^+) = A_{(\text{track})}^{K^+K^-} + A_D(\pi_c^+) - A_D(\pi_c^+). \quad (6.12)$$

The variables $A_D(\pi_c^+)$ and $A_D(\pi_c^+)$ are the detection asymmetries of the pions in the control channel. In addition, this method measures the PID asymmetry corresponding to the PID requirements from the RICH detector ($DLL_{K\pi} > 7$), which is the same for the signal sample and for the control samples.

The kinematic distributions of the control channel pions are reweighted to one another, such that their detection asymmetries cancel out. Figure 6.15 shows the p_T (left) and η (right) distributions of the control channel pions after reweighting and illustrates a good overlap, such that it is safe to assume that $A_D(\pi_c^+) \approx A_D(\pi_c^+)$.

Any asymmetries coming from the neutral kaon nuclear interaction are estimated using the numbers from Reference [114], similarly to what is done for the α_{sl}^s analysis in Section 5.5.5. These numbers are used as corrections on the values of $A_{(\text{track})}^{K^+K^-}$. The largest systematic uncertainty for the kaon detection asymmetries comes from varying the kinematic binning from the default p - η binning to p_T - η . The difference between the values measured in both binning schemes is taken as a systematic uncertainty.

6. The D_s^+ production asymmetry

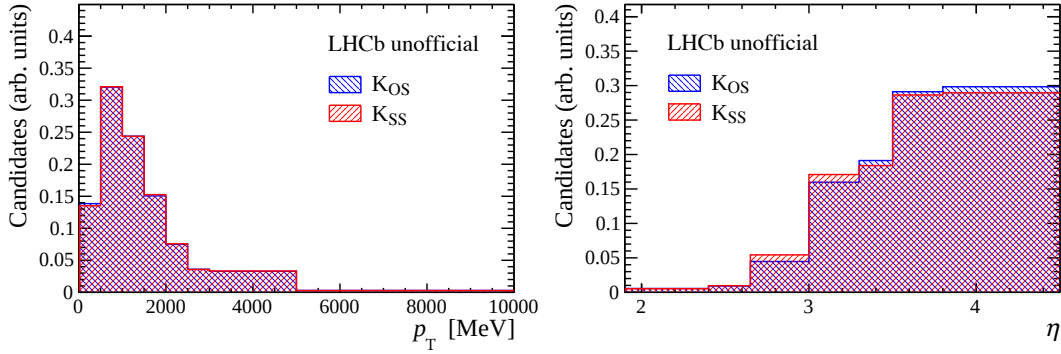


Figure 6.15: Overlap in the transverse momentum (left) and pseudorapidity (right) distributions for the pions π_c and $\pi_{c'}$ from the control channels after reweighting. These plots show the sample recorded in 2012, with the magnet polarity up, in the K^*K Dalitz region, for the D_s^+ kinematic bins $8.5 < p_T < 25.0$ GeV, $3.5 < y < 4.5$.

6.6.6 PID asymmetry

To determine detection asymmetries coming from the PID requirements applied in the selection, large samples of $D^0 \rightarrow K^- \pi^+$ decays are used, as is described in Section 4.2.4. While the global requirement on the kaon PID based on the RICH information is already taken into account by the kaon asymmetries, there are PID asymmetries coming from the PROBNNK variable that is used to select a clean sample of kaons. In addition, the background vetoes introduce more PID asymmetries.

The PID asymmetries are determined separately for global requirements and for every background veto. The overlap between the D^+ and Λ_c^+ signal windows is taken into account. The statistical uncertainties are determined by varying the efficiency histograms using a Gaussian distribution with the nominal value as mean, and the uncertainty as standard deviation. This sampling is performed a 100 times to determine the statistical uncertainty.

The calibration samples are reweighted to the sWeighted signal sample before and after applying the PID selection, and systematic uncertainties are assigned based on the variation of the PID asymmetries determined on different binning schemes: the nominal binning is done in p - η , and variations are performed in p_T - η , and p_T - η - ϕ . An extra systematic uncertainty is added to cover for the fact that sWeights are determined using the signal sample after PID requirements, which is taken to be 20% of the statistical uncertainty, based on the studies performed for the a_{sl}^s analysis. The final source of systematic uncertainty comes from the usage of sWeights determined on the full signal sample. This uncertainty is evaluated by making sWeight signal fits in kinematic bins for the main PID requirements.

6.6.7 Summary of detection asymmetries

An overview of all raw asymmetry measurements and each of the detection asymmetries per kinematic bin, split by polarity and Dalitz region is shown in Figure 6.16, for the dataset recorded in 2012. Their uncertainties are a combination of the statistical and systematic uncertainties. Through each of the asymmetries, a horizontal line was fit to give an indication of the size of the asymmetry and its uncertainty. This uncertainty does not take into account the correlation between the different kinematic bins.

For the tracking asymmetry, there are three rows, one for the tracking asymmetry from the J/ψ tag-and-probe method, without corrections, one from the partially reconstructed D^* , and one for the weighted average of the two corrected methods. The bottom row of the plot shows the production asymmetry, including the correction for the background asymmetry, $f_{\text{secondary}}A_{\text{secondary}}$. This is subtracted and the result is multiplied by $1/(1 - f_{\text{secondary}})$.

6. The D_s^+ production asymmetry

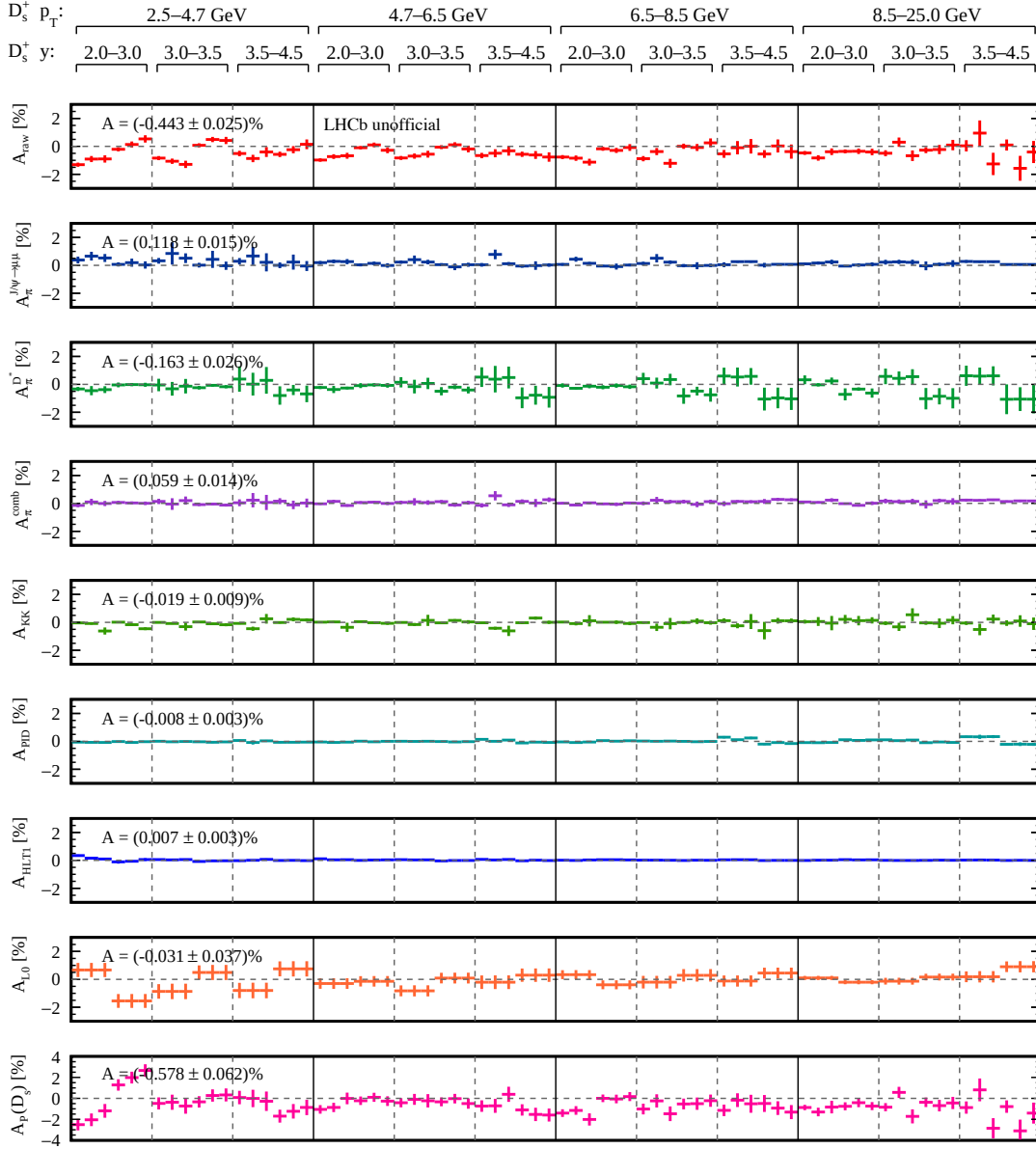


Figure 6.16: Overview of the various contributions to the production asymmetries for the dataset recorded in 2012. From top to bottom these are A_{raw} , $A_{\pi}^{J/\psi \rightarrow \mu^+ \mu^-}$ (the pion tracking asymmetry determined by the tag-and-probe method), $A_{\pi}^{D^*}$ (the pion tracking asymmetry determined from partially reconstructed D^* decays), A_{π}^{comb} (the combined pion tracking asymmetry including correction), A_{KK} , A_{PID} , A_{HLT1} , A_{LO} , and $A_P(D_s^+)$, which also includes the background corrections. All are expressed in percentages and the plot range is from -3% to +3%, except for the $A_P(D_s^+)$, which has a range from -4% to +4%. The bins from left to right are the D_s^+ kinematic bins as indicated at the top. Within each kinematic bin, from left to right are the data recorded with the magnet polarity up: ($\phi\pi$, K^*K , NR), followed by the magnet polarity down: ($\phi\pi$, K^*K , NR). The quoted asymmetries and uncertainties come from fitting a constant through all datapoints, not taking into account the correlations between the bins.

6.7 Results

The final results for the $A_P(D_s^+)$ measurement can be calculated using:

$$A_P(D_s^+) = \frac{1}{1 - f_{\text{secondary}}}(A_{\text{raw}} - A_D - f_{\text{secondary}}A_P(B)), \quad (6.13)$$

where $f_{\text{secondary}}$ is the fraction of secondary D_s^+ candidates in the signal sample, $A_P(B)$ the corresponding production asymmetries and

$$A_D = A_{(\text{track})}^{\pi^+} + A_{(\text{track})}^{K^+K^-} + A_{(\text{PID}|\text{track})}^{K^+K^-\pi^+} + A_{(\text{HLT1}|\text{track}+\text{PID}+\text{L0})}^{K^+K^-\pi^+} + A_{(\text{L0}|\text{HLT1}+\text{track})}. \quad (6.14)$$

After taking the arithmetic mean of the data taken with both magnet polarities, this yields 12 (kinematic bins) $\times 3$ (Dalitz regions) $\times 2$ (data-taking years) = 72 values for $A_P(D_s^+)$. These are shown in Table 6.20 for the 2011 data-taking year and in Table 6.21 for the 2012 data-taking year.

Table 6.20: Values of the D_s^+ production asymmetry per D_s^+ kinematic bin for the $\phi\pi$, K^*K and NR Dalitz regions. These data are the arithmetic average of both magnet polarities of the 2011 data-taking year.

$y \backslash p_T$	$A_P(D_s^+) [\%]$			
	2.5 – 4.7 GeV	4.7 – 6.5 GeV	6.5 – 8.5 GeV	8.5 – 25.0 GeV
$\phi\pi$				
2.0 – 3.0	$0.14 \pm 0.68 \pm 0.22$	$-0.86 \pm 0.43 \pm 0.24$	$-1.23 \pm 0.39 \pm 0.23$	$-0.22 \pm 0.34 \pm 0.10$
3.0 – 3.5	$-1.03 \pm 0.62 \pm 0.27$	$-0.21 \pm 0.46 \pm 0.18$	$-0.23 \pm 0.47 \pm 0.34$	$0.05 \pm 0.44 \pm 0.16$
3.5 – 4.5	$-0.31 \pm 0.70 \pm 0.28$	$-0.90 \pm 0.51 \pm 0.33$	$-0.55 \pm 0.60 \pm 0.23$	$-1.39 \pm 0.69 \pm 0.17$
K^*K				
2.0 – 3.0	$0.88 \pm 0.72 \pm 0.26$	$-1.06 \pm 0.48 \pm 0.25$	$-1.19 \pm 0.46 \pm 0.25$	$-0.97 \pm 0.45 \pm 0.20$
3.0 – 3.5	$-0.48 \pm 0.65 \pm 0.51$	$-0.16 \pm 0.51 \pm 0.27$	$-1.21 \pm 0.57 \pm 0.42$	$-0.68 \pm 0.60 \pm 0.17$
3.5 – 4.5	$-0.40 \pm 0.76 \pm 0.53$	$-1.01 \pm 0.62 \pm 0.40$	$1.33 \pm 0.78 \pm 0.15$	$1.74 \pm 1.22 \pm 0.23$
NR				
2.0 – 3.0	$0.16 \pm 0.76 \pm 0.25$	$-0.19 \pm 0.51 \pm 0.29$	$-1.47 \pm 0.50 \pm 0.26$	$-0.46 \pm 0.48 \pm 0.17$
3.0 – 3.5	$-0.56 \pm 0.70 \pm 0.40$	$-0.37 \pm 0.54 \pm 0.36$	$-1.17 \pm 0.59 \pm 0.34$	$-0.67 \pm 0.61 \pm 0.15$
3.5 – 4.5	$-0.59 \pm 0.81 \pm 0.60$	$-1.40 \pm 0.63 \pm 0.35$	$-0.40 \pm 0.80 \pm 0.33$	$1.17 \pm 1.14 \pm 0.30$

The results are combined to find values for the D_s^+ production asymmetry as a function of transverse momentum and rapidity. In addition, a single integrated value is determined. In order to do that, the results must be in agreement between the Dalitz regions, which is shown in Section 6.7.1. In addition, consistency between data taken using opposite magnet polarities is checked in Section 6.7.2. Then, results can be integrated over p_T , y , or both. This is done while taking into account the correlations between the systematic and statistical uncertainties.

6. The D_s^+ production asymmetry

Table 6.21: Values of the D_s^+ production asymmetry per D_s^+ kinematic bin for the $\phi\pi$, K^*K and NR Dalitz regions. These data are the arithmetic average of both magnet polarities of the 2012 data-taking year.

y \ P_T	$A_P(D_s^+) [\%]$			
	2.5 – 4.7 GeV	4.7 – 6.5 GeV	6.5 – 8.5 GeV	8.5 – 25.0 GeV
$\phi\pi$				
2.0 – 3.0	$-0.39 \pm 0.37 \pm 0.22$	$-0.44 \pm 0.25 \pm 0.24$	$-0.52 \pm 0.22 \pm 0.23$	$-0.62 \pm 0.18 \pm 0.10$
3.0 – 3.5	$-0.24 \pm 0.37 \pm 0.27$	$-0.19 \pm 0.29 \pm 0.18$	$-0.59 \pm 0.29 \pm 0.34$	$-0.44 \pm 0.26 \pm 0.16$
3.5 – 4.5	$-0.60 \pm 0.42 \pm 0.28$	$-0.72 \pm 0.32 \pm 0.33$	$-0.64 \pm 0.38 \pm 0.23$	$-0.72 \pm 0.42 \pm 0.17$
K^*K				
2.0 – 3.0	$0.12 \pm 0.40 \pm 0.26$	$-0.22 \pm 0.27 \pm 0.25$	$-0.44 \pm 0.25 \pm 0.25$	$-0.65 \pm 0.27 \pm 0.20$
3.0 – 3.5	$0.07 \pm 0.38 \pm 0.51$	$0.08 \pm 0.32 \pm 0.27$	$-0.25 \pm 0.35 \pm 0.42$	$0.02 \pm 0.38 \pm 0.17$
3.5 – 4.5	$-0.44 \pm 0.46 \pm 0.53$	$-0.88 \pm 0.39 \pm 0.40$	$-0.42 \pm 0.47 \pm 0.15$	$-0.98 \pm 0.78 \pm 0.23$
NR				
2.0 – 3.0	$0.78 \pm 0.43 \pm 0.25$	$-0.00 \pm 0.32 \pm 0.29$	$-0.71 \pm 0.33 \pm 0.26$	$-0.59 \pm 0.36 \pm 0.17$
3.0 – 3.5	$-0.06 \pm 0.43 \pm 0.40$	$-0.18 \pm 0.36 \pm 0.36$	$-0.65 \pm 0.41 \pm 0.34$	$-0.86 \pm 0.44 \pm 0.15$
3.5 – 4.5	$-0.42 \pm 0.51 \pm 0.60$	$-0.44 \pm 0.43 \pm 0.35$	$-0.74 \pm 0.54 \pm 0.33$	$-1.83 \pm 0.67 \pm 0.30$

6.7.1 Consistency between the Dalitz regions

The consistency between the Dalitz regions is checked by comparing the difference within each kinematic bin, using the combination of the data sets recorded in the two data-taking years, with both magnet polarities. The χ^2/ndf is calculated by comparing the K^*K with the $\phi\pi$, and NR with $\phi\pi$ measurements of the D_s^+ production asymmetry. The statistical and systematic uncertainties from the detection asymmetries are highly correlated between the Dalitz regions. The correlation between the Dalitz regions for the statistical uncertainties is estimated to be $\rho = 0.8$ for this cross-check, based on experience with the a_{sl}^s datasets. The statistical uncertainty on the A_{raw} measurements are uncorrelated.

The systematic uncertainties on the differences between the Dalitz regions are determined for the dominating systematic uncertainties in the $A_P(D_s^+)$ measurement, which are the tracking asymmetries. Both for the kaon and pion tracking asymmetries, the systematic uncertainties are determined by changing the binning schemes in which the events are reweighted. The detection asymmetry for the tracking asymmetries is determined on the difference between the Dalitz regions, once using the nominal binning scheme, and once using a different one. The difference between the outcomes is assigned as an additional systematic uncertainty for this cross-check. In addition, the systematic uncertainty on the L0 asymmetry comes from the small differences in the L0 asymmetry between the Dalitz regions, see Figure 6.12.

The difference between the $\phi\pi$ and K^*K region per kinematic bin is shown on the top of Figure 6.17, and between the $\phi\pi$ and NR region is shown on the bottom. The χ^2/ndf of 0.74 and 1.25 indicate that the regions are in good agreement, confirming the understanding of the backgrounds and detection asymmetry methods that are used in the analyses of $A_P(D_s^+)$ and a_{sl}^s .

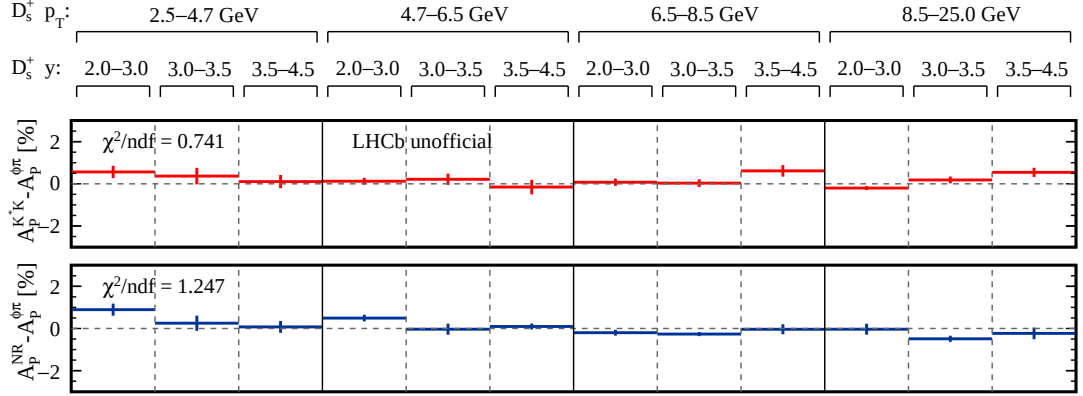


Figure 6.17: Differences between the $A_P(D_s^+)$ measurements in the Dalitz $\phi\pi$ and K^*K region (top) and between the $\phi\pi$ and NR region (bottom), per kinematic bin.

6.7.2 Consistency between magnet polarities

The consistency between the magnet polarities is determined on the $\phi\pi$ Dalitz region only, and integrated over both data-taking years. The difference between the production asymmetry measurements determined on data recorded with the different magnet polarities is shown in Figure 6.18 per kinematic bin. The statistical uncertainties are uncorrelated between the data recorded using the different polarities, while for the systematic uncertainty, the anticorrelation between the uncertainties is taken into account. The agreement is generally good, except in the low- p_T -low- y bin. Overall the agreement has χ^2/ndf of 2.29, which reduces to 1.08 when excluding the first bin. When excluding this bin from the measurement of $A_P(D_s^+)$, the average asymmetry changes by 0.02% which is well within the systematic uncertainty of 0.10%. Hence, the discrepancy between the magnet polarities in this bin does not have a significant influence on the result and this bin is retained in the measurement results that are presented here.

6. The D_s^+ production asymmetry

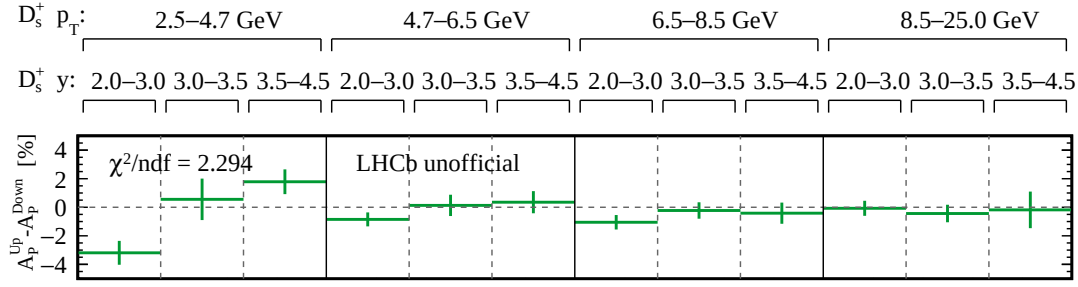


Figure 6.18: Differences between the $A_p(D_s^+)$ measurements in data recorded with the magnet polarity up and down in the Dalitz $\phi\pi$ region.

6.7.3 Combining the Dalitz regions

Tables 6.20 and 6.21 show that both the statistical and systematic uncertainties are smallest in the $\phi\pi$ resonant Dalitz region. This can be explained by the fact that this is the region with most events, least amount of background, and the nearly 100% kinematic overlap between the two kaons.

When combining the three Dalitz regions, the correlation between the statistical and systematic uncertainties from the detection asymmetries need to be taken into account, because the same control samples were used in all three regions. In fact, since this overlap is so large, and because the systematic uncertainties in the K^*K and NR regions are larger than in the $\phi\pi$ region, the overall systematic uncertainty of the measurement increases when combining the three regions.

This can be avoided by optimising the combination as was done in the a_{sl}^s analysis, independently per kinematic bin. However, when doing that the $\phi\pi$ region has a weight of nearly one in every kinematic bin, which means the uncertainties barely improve, while the analysis becomes more complicated by adding the other Dalitz regions. It is therefore decided that only the $\phi\pi$ region is used for the final measurement, and the other regions are used purely for consistency cross-checks as reported above.

6.7.4 Systematic uncertainties

Figure 6.19 shows the systematic uncertainties on the various inputs, in the different kinematic bins. The systematic uncertainties are determined for the 2012 data sample and are taken to be fully correlated with those of the 2011 data sample. Table 6.22 lists the systematic and statistical uncertainties on $A_p(D_s^+)$ for 2011 and 2012 data-taking years from the various sources of detection asymmetries. Since

the systematic uncertainties are fully correlated, they are the same for both data-taking years.

The correlations between the kinematic bins are determined based on the overlap of the kinematic distributions of the control samples between these bins. This is a valid approximation for the statistical uncertainties and is also used for the correlations between the systematic uncertainties. The actual correlations for the systematic uncertainties may be smaller, such that the overall systematic uncertainty is larger.

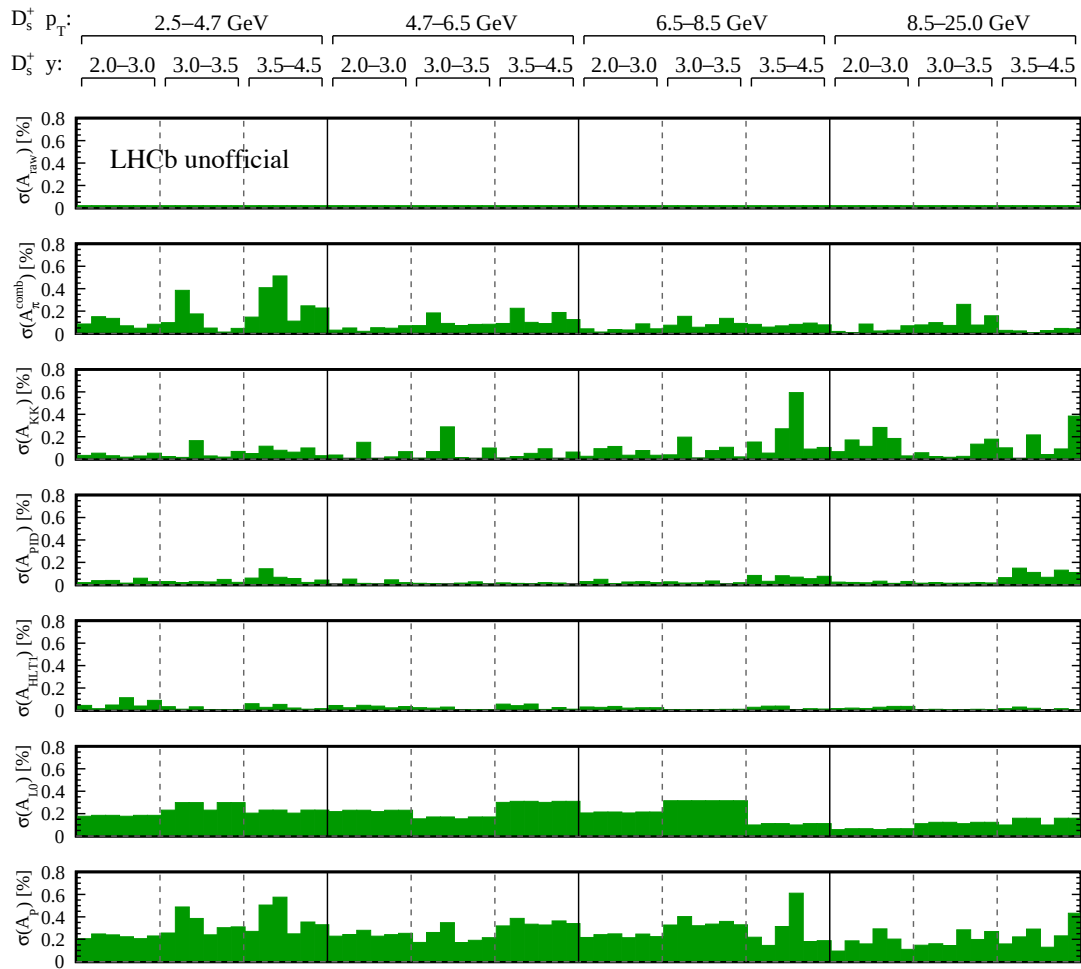


Figure 6.19: Overview of the various contributions to the systematic uncertainties for the D_s^+ production asymmetries of the dataset recorded in 2012. From top to bottom these are A_{raw} , A_{π}^{comb} (the combined pion tracking asymmetry including correction), A_{KK} , A_{PID} , A_{HLT1} , A_{L0} , $A_P(D_s^+)$. All are expressed in percentages. The bins from left to right are the D_s^+ kinematic bins as indicated at the top. Within each kinematic bin, from left to right are the data recorded with the magnet polarity up: $(\phi\pi, K^*K, NR)$, followed by the magnet polarity down: $(\phi\pi, K^*K, NR)$.

6. The D_s^+ production asymmetry

Table 6.22: Overview of the statistical (first number) and systematic (second number) uncertainties coming from the signal fit and the detection asymmetries.

source	contribution [%]		reference
	2011	2012	
fit model	$\pm 0.063 \pm 0.003$	$\pm 0.035 \pm 0.003$	Section 6.5
$A_{(\text{track})}^{\pi^+}$	$\pm 0.111 \pm 0.070$	$\pm 0.070 \pm 0.070$	Section 6.6.4
$A_{(\text{track})}^{K^+K^-}$	$\pm 0.060 \pm 0.031$	$\pm 0.027 \pm 0.031$	Section 6.6.5
$A_{(\text{PID} \text{track})}^{K^+K^-\pi^+}$	$\pm 0.007 \pm 0.014$	$\pm 0.004 \pm 0.014$	Section 6.6.6
$A_{(\text{HLT1} \text{track}+\text{PID}+\text{L0})}^{K^+K^-\pi^+}$	$\pm 0.036 \pm 0.019$	$\pm 0.022 \pm 0.019$	Section 6.6.2
$A_{(\text{L0} \text{HLT1}+\text{track})}$	$\pm 0.131 \pm 0.052$	$\pm 0.081 \pm 0.052$	Section 6.6.1
A_{HLT2}	$\pm 0.000 \pm 0.020$	$\pm 0.000 \pm 0.020$	Section 6.6.3
$A_P(D_s^+)$	$\pm 0.194 \pm 0.100$	$\pm 0.117 \pm 0.100$	

6.7.5 Combining the results

It is found that the production asymmetry measured in the K^*K and NR Dalitz regions are in agreement with the values found in the $\phi\pi$ Dalitz region, but do not add to the precision of the measurement. Therefore, only the $\phi\pi$ Dalitz region is used to determine the final values. The resulting values per kinematic bin are averaged over the magnet polarities using the arithmetic mean. They are integrated over bins of rapidity and transverse momentum using a weighted average based on the statistical uncertainty of A_{raw} . This average takes into account the correlations between the statistical uncertainties of the control samples.

The correlations between the systematic uncertainties are harder to determine and are chosen to be equal to those of the statistical uncertainties. In order to take account of the correlations between the kinematic bins when integrating over p_T , y , or both, the measurement will be performed again for the publication using the integrated data sets, only in the $\phi\pi$ Dalitz region. Here, the results using the assumption that the systematic uncertainty correlations are the same as those of the statistical uncertainties are presented.

6.7.6 Comparison with PYTHIA estimates

The result of this measurement of the D_s^+ production asymmetry shows no dependence as a function of transverse momentum nor rapidity. However, the D_s^+ production asymmetries generated by PYTHIA 8.2, see Section 6.2, show a clear dependence on D_s^+ kinematics, especially on p_T . Figure 6.20 shows the production

asymmetry as predicted by PYTHIA in the LHCb acceptance and the measured production asymmetries. The values of the integrated production asymmetries in PYTHIA agree with the measured values, see Section 6.8. However, this appears to be largely coincidental since the kinematic dependence of the production asymmetry in PYTHIA, in particular the p_T distribution, does not agree with the data.

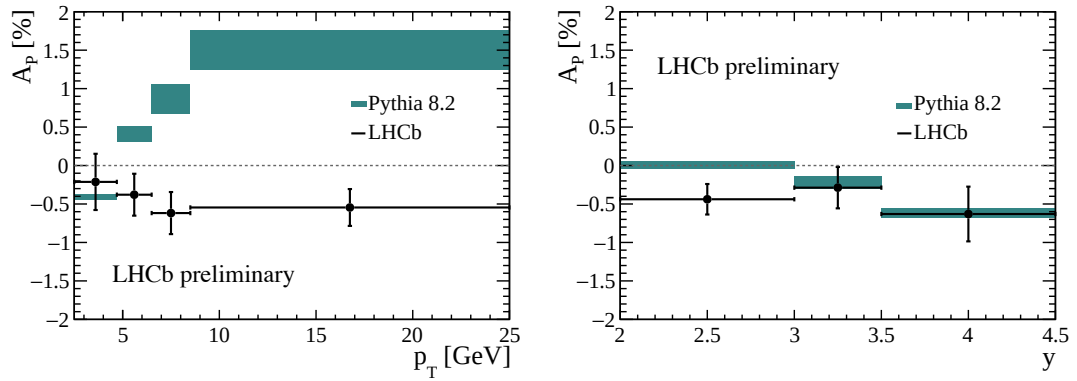


Figure 6.20: D_s^+ production asymmetry as a function of p_T (left) and y (right) distributions, from the combined 2011 and 2012 data-taking years, shown in black. In turquoise are the expectations of $A_p(D_s^+)$ from by PYTHIA 8.2 for $\sqrt{s} = 8$ TeV.

6.7.7 Comparison with previous measurement

A comparison with the previous measurement of $A_p(D_s^+)$ [55] using the dataset recorded in 2011 is made. This measurement only used the $\phi\pi$ Dalitz region, similar to the final measurement of the current analysis. While the previous measurement was restricted to events with a pion $p < 100$ GeV, the current measurement is not thanks to new methods to measure the tracking asymmetry. Figure 6.21 shows the outcome of the previous measurement compared to the current measurement, in bins of D_s^+ p_T (left) and y (right). The new analysis has an extra bin at low p_T .

The corrections from the pion tracking asymmetry between both measurements are in agreement, as well as the final values of $A_p(D_s^+)$. The largest difference is found in the low rapidity bin, where the difference between -0.52% (current analysis) and 0.05% (previous analysis) corresponds to a 2.2σ discrepancy. The analyses are concluded to be in good agreement. The current analysis has a smaller statistical uncertainty and has a more thorough evaluation of sources of detection asymmetries.

6. The D_s^+ production asymmetry

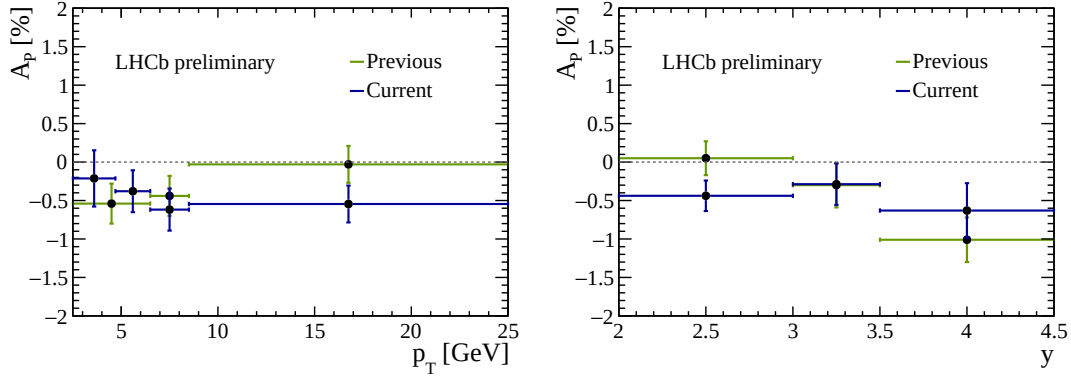


Figure 6.21: D_s^+ production asymmetry as a function of p_T (left) and y (right), from the combined 2011 and 2012 data-taking years in green. In purple are the results from the previous $A_p(D_s^+)$ measurement, which used only the 2011 data-taking year.

6.8 Conclusion

In conclusion, using the data corresponding to an integrated luminosity of 1 fb^{-1} collected in 2011, and to the 2 fb^{-1} collected in 2012, the following values for the integrated D_s^+ production asymmetry in the kinematic region $2.5 < p_T < 25.0 \text{ GeV}$ and $2.0 < y < 4.5$ are found using LHCb data:

$$A_p(D_s^+) = (-0.55 \pm 0.19 (\text{stat}) \pm 0.10 (\text{syst}))\% \quad \text{at} \quad \sqrt{s} = 7 \text{ TeV} ,$$

$$A_p(D_s^+) = (-0.46 \pm 0.12 (\text{stat}) \pm 0.10 (\text{syst}))\% \quad \text{at} \quad \sqrt{s} = 8 \text{ TeV} .$$

No significant difference is expected between production asymmetries at $\sqrt{s} = 7$ and $\sqrt{s} = 8 \text{ TeV}$, as described in Section 1.3.5, and none is observed. Combining these two results, a combined value for the full Run I data sample can be found:

$$A_p(D_s^+) = (-0.48 \pm 0.10 (\text{stat}) \pm 0.10 (\text{syst}))\% .$$

This is in agreement with the previous LHCb measurement of $A_p(D_s^+)$ using only the dataset recorded in 2011 [55].

The measurement of the production asymmetry is performed in three regions of the D_s^+ decay phase space and the values are consistent between these regions. This thus provides a cross-check on the understanding of the backgrounds in each of these regions, also for the a_{sl}^s analysis. Only the $\phi\pi$ resonant region is used for the final measurement. The analysis is performed in three bins of transverse momentum and four bins of rapidity. No significant dependence on the D_s^+ kinematics is found.

7 Conclusion and outlook

This thesis describes the analysis of three topics. First, it reports the studies for the choice of adhesives for the LHCb upgrade detector. Second, it presents an analysis of CP violation in the mixing of B_s^0 mesons. Third, it describes an investigation of the D_s^+ production asymmetries in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV. For these three studies, the conclusions and outlook are described in this chapter.

7.1 Adhesives for the VELO upgrade

Three types of adhesives are tested for attaching the sensors of the VELO upgrade module to its cooling system, see Chapter 3. These are two liquid glues, Araldite 2011 and Stycast 2850FT, and one double-sided adhesive tape, 3M 9461P. The three adhesives are tested using a shear testing apparatus for their strength, and in a thermal setup for their thermal conductivity. The tests are performed after the samples are irradiated to receive a dose similar to what the VELO upgrade sensors will receive during their operation time. The outcomes are reported in an LHCb Public Note, co-written by the author [1].

It is found that all three adhesives show no displacement under a shear force of 10N, which is far more than expected for the VELO upgrade. However, the Stycast samples show some fragility if the sample production is not carefully controlled. In addition, the Stycast glue is approximately five times, and the Araldite two times, more thermally conductive than the 3M tape. Taking into account that the tape can cover a larger area than the glues without trapping air bubbles, the Stycast glue still has a better thermal conductivity.

The proposed strategy is to attach the VELO sensors to the micro-channel cooling system using the Stycast glue, potentially with dots of the Araldite in the corners of the sensors. Following this study, Stycast is the glue that is currently used in the production of the mechanical prototypes of the VELO upgrade modules.

7.2 Measurement of CP violation in $B_s^0 - \bar{B}_s^0$ mixing

Chapter 5 reports the study of the flavour-specific CP asymmetry in the mixing of B_s^0 mesons at LHCb, called a_{sl}^s . A value of

$$a_{sl}^s = (0.39 \pm 0.26 \text{ (stat)} \pm 0.20 \text{ (syst)})\%,$$

is found and published in Reference [138], co-written by the author. This is the world's most precise measurement of a_{sl}^s , and is in agreement with the Standard Model prediction of $a_{sl}^s = (-4.7 \pm 0.6) \times 10^{-4}$ [11]. One of the motivations for performing this measurement is the anomalous inclusive measurement of the D0 experiment, which measured a combination of a_{sl}^s and a_{sl}^d that is three standard deviations away from the Standard Model values [31]. The measurement presented in this thesis is still marginally consistent with the D0 dimuon measurement.

An overview of measurements of a_{sl}^s and a_{sl}^d made by LHCb [32, 138], D0 [27, 28], BaBar [21, 22], and Belle [20], is shown in Figure 7.1. In this figure, the red data point corresponds to the a_{sl}^s measurement described in this thesis, and the black data points are from measurements of either a_{sl}^s or a_{sl}^d . The green bands represent the averages made by the Heavy Flavor Averaging Group [150] of the pure a_{sl} measurements, which are

$$\begin{aligned} a_{sl}^d &= (0.01 \pm 0.20)\%, \\ a_{sl}^s &= (0.16 \pm 0.30)\%, \end{aligned}$$

which have a small correlation of 0.07 due to the LHCb measurements. This includes the measurement presented in this thesis and not the D0 dimuon measurement [31], shown in the yellow ellipse.

The pure measurements of a_{sl}^s and a_{sl}^d cannot confirm the D0 anomaly. Moreover, the recently published Reference [12] claims that current LHCb data can even constrain the value of a_{sl}^s to $(0.004 \pm 0.075)\%$. To explain the anomalous D0 result, other possible explanations are sought. The contribution from $\Delta\Gamma_d$ is described in Section 1.2.4 and could explain the deviation that is observed [24]. Another way of explaining the anomaly considers contributions from inclusive direct CP violation in b - and c -quark decays [151], which need to be at least 0.3% in semileptonic B decays, or 1% in semileptonic D decays. A proposal by Reference [152] for studying this hypothesis using t -quark decays has been carried out by the ATLAS experiment [153]. This analysis studies same-sign and opposite-sign asymmetries.

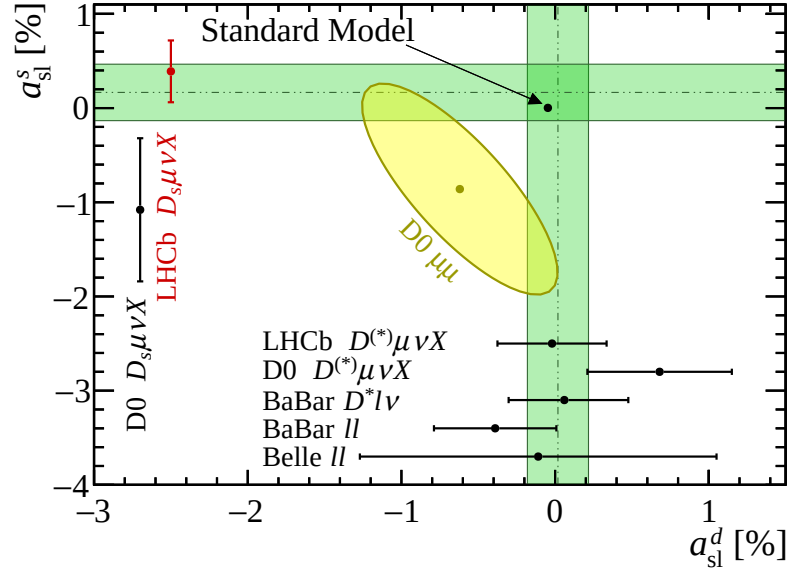


Figure 7.1: Overview of the current a_{sl}^s and a_{sl}^d measurements. The yellow ellipse shows the result of the D0 dimuon measurement [31], while the data points with error bars show the individual measurements of a_{sl}^s or a_{sl}^d from LHCb [32, 138], BaBar [21, 22], Belle [20], and D0 [27, 28]. The green bands are the averages of a_{sl}^s and a_{sl}^d , not including the D0 dimuon measurement.

Currently, this measurement is not sensitive enough to confirm or exclude the hypothesis of direct CP violation, but it is expected that using their full Run II dataset, ATLAS can make a conclusive statement.

In addition, the measurements of a_{sl}^s and a_{sl}^d will be repeated at LHCb using the dataset recorded in Run II. Several new ideas to improve its sensitivity with respect to the current measurement are already being developed. First of all, there is a significant increase in data. This is due to major improvements in the alignment and reconstruction at the trigger level, which allows to perform the selection that is now applied during the stripping, already in the trigger. Hence, more data can be stored, and one step of the selection is removed.

To reduce the uncertainties coming from non-peaking background and the corresponding production asymmetries, a new fitting strategy is proposed. This is a two-dimensional fit, in invariant and corrected mass, and fits for these backgrounds, such that A_{raw} only includes D_s^- decays from B_s^0 decays. This strategy is already employed in the measurement of the B_s^0 and D_s^- lifetimes [154]. In addition, new methods for measuring detection asymmetries using other control channels are being developed and may reduce the systematic uncertainties from detection asymmetries.

7. Conclusion and outlook

Using the full Run II dataset, and the proposed improvement for the a_{sl}^s analysis, the estimated precision with which both a_{sl}^s and a_{sl}^d can be measured is expected to be smaller than 10^{-3} , to see if the LHCb measurements continue to favour the SM values rather than the anomalous D0 dimuon value. Around 2035, after the Phase II upgrade, LHCb is expected to have collected around 300 fb^{-1} of data. Extrapolating to this amount of data, the precision of measurements of a_{sl}^s and a_{sl}^d is expected to be of the order of 10^{-4} , which would allow to distinguish between zero and the Standard Model predictions.

7.3 Measurement of the D_s^+ production asymmetry

A measurement of the D_s^+ production asymmetry is performed at a centre-of-mass energy of $\sqrt{s} = 7$ and $\sqrt{s} = 8 \text{ TeV}$. This is carried out in bins of transverse momentum and pseudorapidity in the kinematic region $2.5 < p_T < 25.0 \text{ GeV}$ and $2.0 < y < 4.5$, using the $D_s^+ \rightarrow K^+ K^- \pi^+$ decay, where the $K^+ K^-$ pair goes through the ϕ resonance in the majority of the events. The analysis is described in Chapter 6 and led by the author. An LHCb publication is expected to be forthcoming and results of the analysis are summarised here.

The following values for the D_s^+ production asymmetry are obtained:

$$\begin{aligned} A_P(D_s^+) &= (-0.55 \pm 0.19 (\text{stat}) \pm 0.10 (\text{syst}))\% \quad \text{at } \sqrt{s} = 7 \text{ TeV} , \\ A_P(D_s^+) &= (-0.46 \pm 0.12 (\text{stat}) \pm 0.10 (\text{syst}))\% \quad \text{at } \sqrt{s} = 8 \text{ TeV} . \end{aligned}$$

Averaging these two results, a combined value for the full Run I data sample is

$$A_P(D_s^+) = (-0.48 \pm 0.10 (\text{stat}) \pm 0.10 (\text{syst}))\% .$$

This is in agreement with the previous result from LHCb [55] which used only the data recorded at $\sqrt{s} = 7 \text{ TeV}$ and measured a value of

$$A_P(D_s^+) = (-0.33 \pm 0.22 (\text{stat}) \pm 0.10 (\text{syst}))\% .$$

However, unlike the previous measurement, the new measurement establishes a non-zero value for the production asymmetry, differing from zero at three standard deviations. The statistical uncertainty of the new measurement is improved by a factor two compared with the previous LHCb determination, and a more thorough evaluation of sources of detection asymmetries has been carried out.

7.3. Measurement of the D_s^+ production asymmetry

The outcome of the current measurement, as a function of transverse momentum and pseudorapidity is presented in Figure 7.2 and shows no dependence on kinematics. The same lack of kinematic dependence is observed in all other LHCb analyses measuring production asymmetries, with the exception of Reference [32]. The outcome can be used as an input to tune fragmentation models in different Monte Carlo generators. This is necessary for at least the PYTHIA tuning that is described in Section 6.2, which does not show good agreement with data.

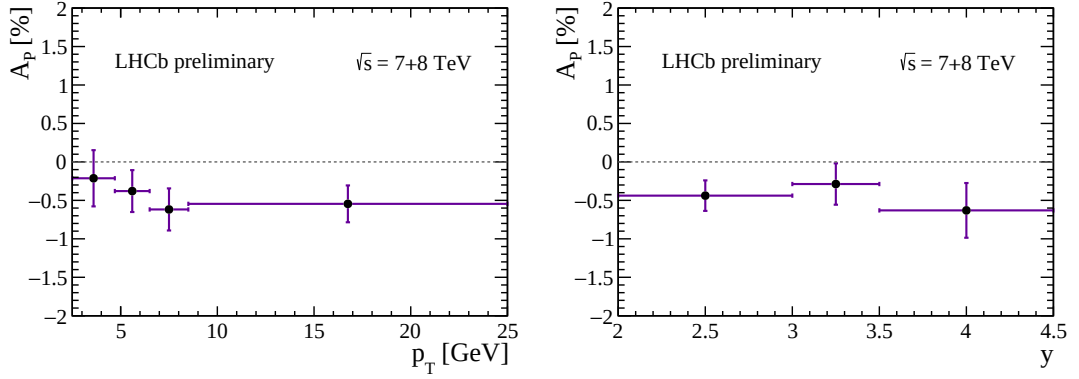


Figure 7.2: D_s^+ production asymmetry as a function of p_T (left) and y (right), from the combined 2011 and 2012 data-taking years.

The measurement will be further refined prior to publication, with a finalisation of the signal fit. In addition, the detection asymmetries will be re-evaluated over the integrated dataset to simplify the determination of correlations between the detection asymmetries in different kinematic regions. The internal LHCb analysis review will then be finalised and after this it is anticipated that the result will be submitted to a peer-reviewed journal.

A comparison can be made with other measurements of charm production asymmetries, and two are currently available from LHCb. These are the measurement of the D^+ [40] and D^0 [41] production asymmetries, which are

$$A_p(D^+) = (-0.96 \pm 0.26 \text{ (stat)} \pm 0.18 \text{ (syst)})\%,$$

$$A_p(D^0) = (-1.08 \pm 0.32 \text{ (stat)} \pm 0.12 \text{ (syst)})\%.$$

These measurements are performed at a centre-of-mass energy of $\sqrt{s} = 7$ TeV and have a more negative value than that of $A_p(D_s^+)$. This can be expected from the fact that charm quarks recombine with light quarks from the protons in the beam, which have an asymmetric quark content. The effect of that on D^+ and D^0 production asymmetries is direct, while for $A_p(D_s^+)$ it is indirect.

7. Conclusion and outlook

An overview of the current and previous LHCb measurements of production asymmetries is shown in Figure 7.3. This shows values for the production asymmetries of D^0 [41], D^+ [40], D_s^+ (this work), B^+ [57, 58], B^0 [32, 58], and B_s^0 [58] mesons, and Λ_b^0 baryons [58]. For this overview, the measurements listed in Section 1.3 are used. These are combined in a weighted average based on the statistical uncertainties, between the two data-taking years, and when applicable, between different measurements. This is done in the cases that different decay modes are used for different measurements. Any correlations between the systematic uncertainties are not taken into account.

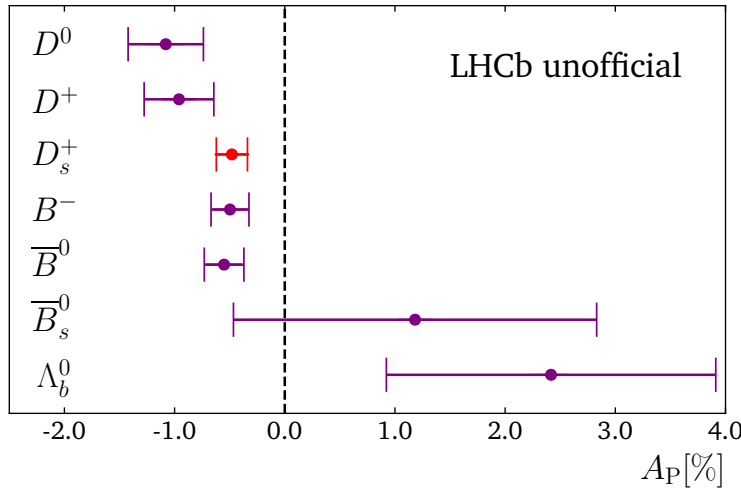


Figure 7.3: Overview of the production asymmetry measurements made by LHCb, wherever possible averaged over the 2011 and 2012 data-taking years. The values are obtained by a weighted average based on their statistical uncertainties, from several measurements. The figure shows the measured production asymmetries of D^0 [41], D^+ [40], D_s^+ (this work), B^+ [57, 58], B^0 [32, 58], and B_s^0 [58], mesons, and the inferred one for Λ_b^0 baryons. Any correlations between systematic uncertainties are not taken into account.

Eventually, it would be interesting to compare the measurement of the D_s^+ production asymmetry to theoretical predictions, such as was done for the measurement of the D^+ production asymmetry in Reference [33]. At the moment, no such predictions exist for $A_P(D_s^+)$.

Other production asymmetry measurements at LHCb are currently in preparation, for Λ_b^0 and Λ_c^+ baryons. For both of these, predictions exist [155]. The measurements of $A_P(D_s^+)$ and $A_P(D^+)$ indicate that D_s^+ , D^+ , and D^0 mesons are preferentially created with $\bar{c}$ over c quarks. The left-over c quarks are expected to cause a significant production asymmetry in Λ_c^+ baryons, which should be observed.

7.3. Measurement of the D_s^+ production asymmetry

Because production asymmetries are dependent on centre-of-mass energy, and crucial inputs to CP violation measurements, it is necessary to repeat them using the Run II dataset with $\sqrt{s} = 13$ TeV. When doing that, new detection asymmetry methods could be exploited for this measurement. More importantly, the larger recorded dataset in Run II allows to replace the L0 trigger selection by a trigger that fires on a muon in the event, such that the L0 trigger can be truly independent of signal and the currently dominating systematic uncertainty corresponding to the L0 TIS asymmetry can be omitted. This can significantly improve the precision of future production asymmetry measurements.

7. Conclusion and outlook

References

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