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Measurement of CP asymmetries in
 $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decays
analysing LHCb Run 3 data

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Abstract

Understanding the origin of the matter–antimatter asymmetry observed in the Universe is one of the major open questions in modern physics. A necessary ingredient to explain this asymmetry is the violation of the combined charge-parity (CP) symmetry. While the Standard Model (SM) of particle physics predicts CP violation through the complex phase of the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix, the amount of CP violation it provides is far too small to account for the observed imbalance between matter and antimatter. This makes the search for additional sources of CP violation a key objective of contemporary particle physics.

The violation of CP symmetry has been observed in several meson decays, including K^0 , D^0 , B^0 , B^+ and B_s^0 mesons, whereas in the baryonic sector CP violation has so far been observed only in Λ_b^0 decays. The study of baryonic decays therefore provides an important complementary probe of CP violation. In particular, the $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decay modes are of interest because they proceed through decay mechanisms analogous to those of the $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$ decays, for which CP violation has been observed. However, no evidence of CP violation has been found in the corresponding decay modes Λ_b^0 by the CDF and LHCb collaborations so far. The study of these decays with larger and more recent datasets can therefore provide further insight into CP violation in the baryonic sector.

This thesis presents a measurement of the difference between the CP asymmetries in the $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decay modes,

$$\Delta A_{CP} = A_{CP}(pK^-) - A_{CP}(p\pi^-).$$

The difference between the CP asymmetries allows many common instrumental and production asymmetries affecting the two decay modes to cancel. The analysis is performed using approximately 1.5 fb^{-1} of proton-proton collision data recorded by the LHCb experiment during Run 3 of the Large Hadron Collider at a center-of-mass energy of 13.6 TeV. The dataset is divided into two subsamples, corresponding to the two opposite dipole-magnet polarities, MagUp and MagDown, which are analysed separately. The resulting measurements are then combined to reduce residual detector-induced asymmetries.

The results obtained in this work are

$$\begin{aligned}\Delta A_{CP}^{\text{MagUp}} &= (-7.9 \pm 3.1 \pm 0.9)\%, \\ \Delta A_{CP}^{\text{MagDown}} &= (-0.7 \pm 2.4 \pm 0.4)\%, \\ \Delta A_{CP}^{\text{Avg}} &= (-2.4 \pm 1.9 \pm 0.4)\%,\end{aligned}$$

The MagUp and MagDown measurements are compatible within 2.1σ , while the weighted average is compatible with zero within 1.2σ . No evidence of CP violation is observed. This work constitutes the first measurement of ΔA_{CP} in these decay channels using Run 3 data collected by the LHCb experiment.

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Introduction

The Standard Model (SM) of particle physics provides a remarkably successful description of three of the four fundamental interactions in nature: the electromagnetic, weak, and strong interactions. Developed through decades of theoretical and experimental advances during the twentieth century, it reached a major milestone with the discovery of the Higgs boson in 2012 by the ATLAS and CMS collaborations [1, 2].

Despite its success, the SM cannot provide a complete description of nature. Several fundamental questions remain unanswered, including the origin of neutrino masses, the nature of dark matter and dark energy, and the origin of the observed baryon asymmetry, namely the predominance of matter over antimatter in the Universe. Explaining this asymmetry requires, among other ingredients, sources of charge-parity (CP) violation. Within the SM, CP violation in the quark sector is described by the irreducible complex phase of the Cabibbo–Kobayashi–Maskawa (CKM) matrix. However, the amount of CP violation currently observed in the SM is many orders of magnitude too small to account for the observed baryon asymmetry, motivating more precise measurements of CP-violating observables as a probe for physics beyond the SM.

The violation of CP symmetry has been observed in several flavour systems, including neutral kaons [3], B^0 [4, 5], B^+ [6, 7] B_s^0 [8, 9], D^0 mesons [10] and Λ_b^0 baryon [11, 12, 13]. Measurements in different systems provide complementary tests of the SM description of CP violation and offer sensitivity to possible contributions from physics beyond the SM.

Of particular interest are the baryonic decays $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$. These decay modes are closely related to the mesonic decays $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$, in which direct CP violation has been firmly established [8, 14]. However, no significant evidence for CP violation has been observed so far in the corresponding Λ_b^0 decay channels. More recently, CP violation has been observed in $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ [11], while evidences of CPV in $\Lambda_b^0 \rightarrow J/\Psi p\pi^-$ [12] and $\Lambda_b^0 \rightarrow \Lambda K^+K^-$ [13] decays, further demonstrate the potential of Λ_b^0 decays as a probe of CP-violating effects. The study of $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ therefore provides a complementary test of the description of CP violation in the quark sector and extends the search for CP-violating effects to other Λ_b^0 decay modes.

This thesis presents the first measurement of the difference between the CP asymmetries of the $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decay modes, using approximately 1.5 fb^{-1} of proton–proton collision data collected by the LHCb experiment during Run 3 of the Large Hadron Collider. Taking the difference between the two CP asymmetries allows common production and instrumental asymmetries affecting the two decay modes to cancel.

The thesis is organized as follows. Chapter 1 introduces the theoretical framework relevant to this measurement, including the discrete symmetries C, P, and CP, their violation in weak interactions, the Standard Model, the CKM matrix and the phenomenology of the decay channels under study. Chapter 2 presents the Large Hadron Collider and the LHCb detector. Chapter 3 describes the analysis strategy and the extraction of the CP-violation observable from the experimental data.

1 Theoretical framework

This chapter introduces the theoretical framework relevant to the measurement presented in this thesis. It begins with a discussion of the discrete symmetries C, P, and CP and their violation in weak interactions. The Standard Model (SM) and the Cabibbo–Kobayashi–Maskawa (CKM) matrix are then presented, followed by a brief overview of the phenomenology of the $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decay channels.

1.1 C, P and CP transformations

Charge conjugation (C) and parity (P) are two fundamental discrete transformations in particle physics. Charge conjugation exchanges particles with their corresponding antiparticles, while parity reverses the spatial coordinates. During the first half of the twentieth century, both C and P were believed to be exact symmetries of nature, as no violation of either symmetry had been observed.

However, in 1956, Lee and Yang pointed out that parity conservation in weak interactions had never been experimentally tested and proposed several experiments to investigate this possibility [15]. The challenge was taken up by Wu and collaborators, who studied the β decay of polarized ^{60}Co nuclei. The experiment observed a clear asymmetry in the angular distribution of the emitted electrons, providing the first direct evidence of parity violation in weak interactions [16]. This result demonstrated that the weak interaction distinguishes between left- and right-handed configurations.

The violation of parity was soon found to be accompanied by the violation of charge conjugation. In fact, the weak interaction maximally violates both C and P separately.

Despite the violation of C and P individually, their combination, CP, was initially believed to be conserved. This expectation was consistent with the chiral structure of the weak interaction. The Goldhaber experiment demonstrated that neutrinos are produced with left-handed helicity, while antineutrinos are right-handed [17]. Under a CP transformation, a left-handed neutrino is mapped onto a right-handed antineutrino, both of which are observed in nature. By contrast, applying C or P separately would produce states that are not observed in weak interactions.

The hypothesis of CP conservation was overturned in 1964, when Christenson, Cronin, Fitch, and Turlay observed CP violation in the decays of neutral kaons [3]. This discovery established that the weak interaction can distinguish between matter and antimatter even under the combined action of C and P.

Since then, CP violation has been observed in several flavour systems, including B^0 [4, 5], B^+ [6, 7], B_s^0 [8, 9], D^0 [10] mesons and Λ_b^0 baryon [11, 12, 13].

1.2 The Standard Model

The SM of particle physics is a quantum field theory based on the principle of local gauge invariance. Its gauge symmetry group is

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y,$$

where the $SU(3)_C$ symmetry describes the strong interaction through quantum chromodynamics (QCD), while the electroweak symmetry $SU(2)_L \otimes U(1)_Y$ unifies the weak and electromagnetic interactions in the Glashow–Weinberg–Salam (GWS) model [18, 19, 20]. Through the mechanism of spontaneous symmetry breaking (SSB), the electroweak symmetry is broken, giving rise to the observed weak and electromagnetic interactions.

SSB also underlies the Brout–Englert–Higgs mechanism [21, 22], which explains the origin of the masses of the weak gauge bosons and fermions through their interactions with the Higgs field. This mechanism was experimentally confirmed in 2012 with the discovery of the Higgs boson by the ATLAS and CMS collaborations [1, 2].

The fundamental particles of the SM are classified into two categories: fermions and bosons. The bosonic sector consists of the twelve gauge bosons, which mediate the fundamental interactions (eight gluons, the $W^\pm$ and Z^0 bosons, and the photon γ), together with the scalar Higgs boson. The fermionic sector comprises twelve elementary particles, which are grouped into quarks and leptons. Both quarks and leptons are arranged into three generations, whose members are connected by charged-current weak interactions mediated by the $W^\pm$ bosons. A schematic overview of the particle content of the SM is shown in Figure 1. Since CP violation in the SM originates from the flavour structure of the quark sector, only this sector will be discussed in detail in the following.

1.2.1 The quark sector

To understand the structure of the quark sector, it is useful to briefly review its historical development.

In 1964, Gell-Mann and independently Zweig proposed the quark model, in which hadrons are composed of three fundamental quarks: up (u), down (d), and strange (s) [23, 24]. The model successfully explained the classification of hadrons, with the strange quark carrying the previously introduced strangeness quantum number (S) [25, 26]. During the same period, experiments showed that weak processes involving a change in strangeness ($|\Delta S| = 1$) occurred with significantly

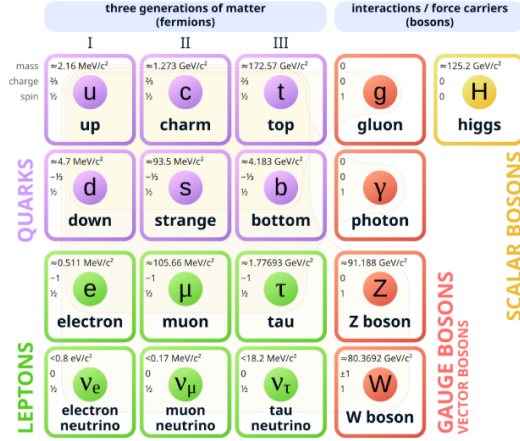


Figure 1: The particle content of the SM, including the three generations of fermions, the gauge bosons that mediate the fundamental interactions, and the Higgs boson.

lower rates than analogous strangeness-conserving processes ($\Delta S = 0$). This apparent suppression posed a challenge to the universality of the weak interaction.

In 1963, Cabibbo proposed a solution that preserved weak universality by postulating that the quark weak-interaction eigenstates do not coincide with the flavour (or mass) eigenstates [27]. Instead, the weak eigenstates are related to the flavour eigenstates through a rotation,

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos \theta_C & \sin \theta_C \\ -\sin \theta_C & \cos \theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}, \quad (1)$$

where d' and s' denote the weak eigenstates, $\theta_C \simeq 13^\circ$ is the Cabibbo angle, and the up quark remains unchanged. In this framework, the suppression of strangeness-changing weak decays arises naturally from the mixing angle, with the corresponding amplitudes being proportional to either $\cos \theta_C$ or $\sin \theta_C$, while the weak coupling constant remains universal. The Cabibbo theory was soon confirmed experimentally, although it did not provide the complete picture of quark mixing.

Although the Cabibbo theory successfully described charged-current weak interactions, it also predicted tree-level flavour-changing neutral currents (FCNCs) with a magnitude incompatible with experimental observations. This discrepancy was resolved in 1970 by the Glashow–Iliopoulos–Maiani (GIM) mechanism [28], which postulated the existence of a fourth quark, the charm (c), completing the second quark generation:

$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d \cos \theta_C + s \sin \theta_C \end{pmatrix}, \quad \begin{pmatrix} c \\ s' \end{pmatrix} = \begin{pmatrix} c \\ -d \sin \theta_C + s \cos \theta_C \end{pmatrix}.$$

The inclusion of the charm quark leads to a cancellation of the amplitudes responsible for FCNC processes at tree level, naturally explaining their strong suppression. The GIM mechanism was experimentally confirmed by the discovery of the charm quark in 1974 [29, 30].

Building upon Cabibbo's idea, Kobayashi and Maskawa generalized quark mixing to three generations in order to accommodate CP violation within the SM [31]. They showed that, with three generations of quarks, the charged-current weak interaction is described by a unitary 3×3 mixing matrix containing a single irreducible complex phase. This phase provides the only source of CP violation in the quark sector of the SM. The resulting CKM matrix plays a central role in flavour physics and will be discussed in detail in the following section.

1.3 The CKM matrix

In the SM, the charged-current weak interaction couples the left-handed up-type and down-type quarks through the CKM matrix. The weak eigenstates (d', s', b') are related to the corresponding mass eigenstates (d, s, b) by

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv \hat{V}_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \quad (2)$$

while the up-type quark fields (u, c, t) are left unchanged by this transformation. Each matrix element V_{ij} describes the strength of the charged-current transition between the up-type quark i and the down-type quark j .

The CKM matrix enters the charged-current weak-interaction Lagrangian as

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \left(\bar{u}_{i,L} \gamma^\mu V_{ij} d_{j,L} W_\mu^+ + \bar{d}_{j,L} \gamma^\mu V_{ij}^* u_{i,L} W_\mu^- \right), \quad (3)$$

where g is the weak coupling constant, γ^μ are the Dirac matrices, and the subscript L denotes left-handed fields. The interaction therefore depends explicitly on the CKM matrix, which governs flavour-changing charged-current transitions between quarks.

As a general 3×3 complex matrix, $\hat{V}_{\text{CKM}}$ contains eighteen real parameters. Imposing unitarity reduces this number to nine, while five additional phases can be absorbed through redefinitions of the quark fields. Consequently, the CKM matrix is described by only four independent physical parameters: three real mixing angles and one irreducible complex phase. If all CKM matrix elements could be made simultaneously real through field redefinitions, the charged-current weak interaction would conserve CP.

A naive way to illustrate this connection is to apply a CP transformation to $\mathcal{L}_{CC}$, which gives

$$\mathcal{L}_{CC}^{CP} = -\frac{g}{\sqrt{2}} (\bar{u}_{i,L} \gamma^\mu V_{ij}^* d_{j,L} W_\mu^+ + \bar{d}_{j,L} \gamma^\mu V_{ij} u_{i,L} W_\mu^-) \quad (4)$$

Comparing $\mathcal{L}_{CC}^{CP}$ with $\mathcal{L}_{CC}$, a necessary condition for CP violation, such that $\mathcal{L}_{CC} \neq \mathcal{L}_{CC}^{CP}$, is that $V_{ij} \neq V_{ij}^*$ for at least one CKM matrix element. Therefore, the existence of an irreducible complex phase in the CKM matrix provides the mechanism through which CP violation arises in the SM.

Several equivalent parametrizations of the CKM matrix exist. The two most commonly used are the Standard parametrization [32] and the Wolfenstein parametrization [33]. In the Standard parametrization, the matrix is expressed in terms of the three mixing angles $(\theta_{12}/\theta_C, \theta_{23}, \theta_{13})$ and the CP-violating phase δ :

$$\hat{V}_{\text{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \quad (5)$$

where

$$s_{ij} = \sin \theta_{ij}, \quad c_{ij} = \cos \theta_{ij}.$$

Although this parametrization is completely general, it does not explicitly highlight the hierarchical structure of quark mixing. Since the CKM matrix is nearly diagonal, it is often more convenient to employ the Wolfenstein parametrization,

$$\hat{V}_{\text{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4), \quad (6)$$

where the four independent parameters are (λ, A, ρ, η) . Although this representation is only approximate, it makes the hierarchy of the CKM elements explicit and is therefore particularly useful in flavour physics. To leading order, the Wolfenstein parameters are related to the Standard parametrization through

$$\lambda = s_{12}, \quad A\lambda^2 = s_{23}, \quad A\lambda^3(\rho - i\eta) = s_{13}e^{-i\delta}.$$

The Wolfenstein parametrization clearly illustrates that transitions within the same quark generation are favoured, whereas transitions between different generations are progressively suppressed. For example,

$$|V_{ud}|, |V_{cs}|, |V_{tb}| \sim \mathcal{O}(\lambda^0) \simeq 1,$$

while

$$|V_{us}| \sim \mathcal{O}(\lambda) \simeq 0.22, \quad |V_{cb}| \sim \mathcal{O}(\lambda^2) \simeq 0.04, \quad |V_{ub}| \sim \mathcal{O}(\lambda^3) \simeq 0.004.$$

This hierarchy plays a central role in heavy-flavour physics, determining the relative strengths of weak decay amplitudes.

The unitarity of the CKM matrix implies orthogonality relations between its different rows and columns, leading to six independent complex equations commonly referred to as the unitarity conditions. One of the most important is

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0, \quad (7)$$

which is particularly relevant for the study of beauty-hadron decays. Since each term is a complex number, this relation may be represented geometrically in the complex plane as the sum of three vectors whose total is zero. These vectors therefore form a closed triangle, known as the Unitarity Triangle, shown in Figure 2. The angles of this Unitarity Triangle are defined as:

$$\begin{aligned} \alpha &= \arg \left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right), \\ \beta &= \arg \left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right), \\ \gamma &= \arg \left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right). \end{aligned}$$

Independent measurements of these angles provide stringent tests of the CKM mechanism. Within the SM they satisfy

$$\alpha + \beta + \gamma = \pi$$

and any significant deviation from this relation would indicate physics beyond the SM.

Although the six unitarity conditions give rise to triangles with different shapes and orientations, they all have the same area. This common area is directly proportional to the Jarlskog invariant J [34],

$$J = \text{Im} \left(V_{ij}V_{kl}V_{il}^*V_{kj}^* \right), \quad |J| = 2A_{\Delta}. \quad (8)$$

The Jarlskog invariant is independent of the chosen CKM parametrization and therefore provides a basis-independent measure of CP violation in the SM. If all CKM matrix elements were real, then J would vanish identically, implying CP conservation in the quark sector. Current experimental measurements yield $J \sim \mathcal{O}(10^{-5})$ [35]. This relatively small value reflects the limited amount of CP violation encoded in the CKM matrix and contributes to the inability of the SM to account for the observed baryon asymmetry of the Universe.

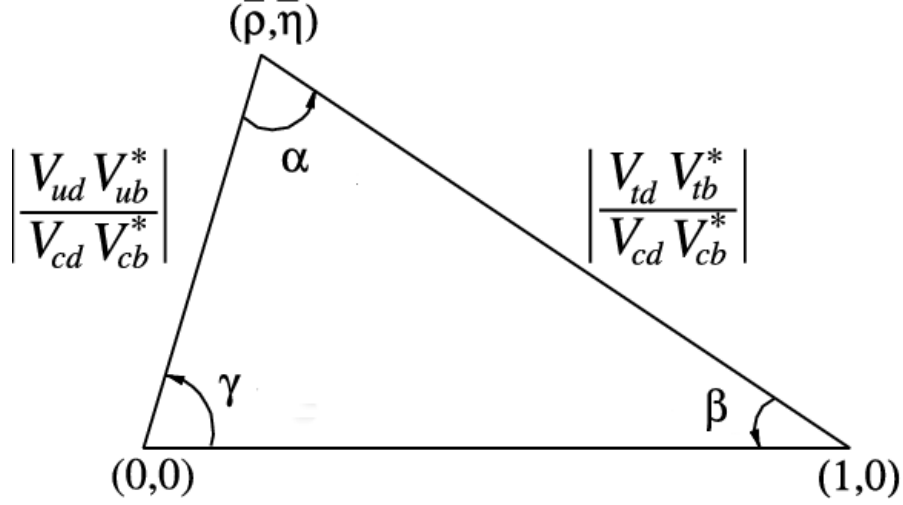


Figure 2: Geometrical representation of one of the six Unitarity Triangles arising from the unitarity of the CKM matrix.

1.3.1 Measurement of the CKM matrix elements

The numerical values of the CKM matrix elements are free parameters of the SM and must therefore be determined experimentally. Their extraction relies on a variety of weak processes involving different quark transitions.

- $|V_{ud}|$: determined with high precision from superallowed nuclear β decays, neutron β decay ($n \rightarrow p e^- \bar{\nu}_e$), and pion β decays ($\pi^+ \rightarrow \pi^0 e^+ \nu_e$).
- $|V_{us}|$: extracted primarily from semileptonic kaon decays, such as $K_L^0 \rightarrow \pi e \nu$, together with leptonic kaon and pion decays, e.g. $K^- \rightarrow \mu^- \bar{\nu}_\mu$ and $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$.
- $|V_{cd}|$: measured mainly from semileptonic and leptonic D -meson decays, for example $D^+ \rightarrow \pi^0 \ell^+ \nu_\ell$ and $D^+ \rightarrow \tau^+ \nu_\tau$.
- $|V_{cs}|$: determined from leptonic and semileptonic decays of D and D_s mesons, such as $D_s^+ \rightarrow \mu^+ \nu_\mu$ and $D^+ \rightarrow \bar{K}^0 \ell^+ \nu_\ell$, with additional constraints provided by W -boson decays.
- $|V_{cb}|$: extracted from inclusive and exclusive semileptonic decays of b hadrons, notably through $b \rightarrow c \ell \bar{\nu}_\ell$ transitions and decays such as $B^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$.
- $|V_{ub}|$: determined from inclusive and exclusive semileptonic $b \rightarrow u \ell \bar{\nu}_\ell$ decays, where dedicated phase-space selections are required to suppress the much larger $b \rightarrow c \ell \bar{\nu}_\ell$ background.

- $|V_{td}|$ and $|V_{ts}|$: inferred from loop-induced processes, since they cannot be measured directly through tree-level top-quark decays. Their determination relies primarily on neutral B -meson mixing and rare decays such as $B \rightarrow X_s \gamma$.
- $|V_{tb}|$: measured from top-quark decays and the production cross section of single top quarks.

The current world-average values of the CKM matrix elements, obtained from global fits to the available experimental data [35], are

$$|\hat{V}_{\text{CKM}}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22501 \pm 0.00068 & 0.003732^{+0.000090}_{-0.000085} \\ 0.22487 \pm 0.00068 & 0.97349 \pm 0.00016 & 0.04183^{+0.00079}_{-0.00069} \\ 0.00858^{+0.00019}_{-0.00017} & 0.04111^{+0.00077}_{-0.00068} & 0.999118^{+0.000029}_{-0.000034} \end{pmatrix}. \quad (9)$$

These values clearly illustrate the hierarchical structure of quark mixing. Transitions between quarks belonging to the same generation are strongly favoured, as indicated by the near-unity diagonal elements, whereas transitions between different generations are progressively suppressed. In particular, mixing between the first and third generations is the weakest, with $|V_{ub}|$ and $|V_{td}|$ of the order of 10^{-3} .

1.4 Phenomenology of $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decays

The decays $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ are charmless hadronic decays mediated by the weak interaction. Their decay amplitudes receive contributions from both tree-level and penguin topologies. These amplitudes are associated with different combinations of CKM matrix elements and therefore carry different weak phases. Their relative magnitudes also depend on the decay channel. In particular, the tree-level contribution is Cabibbo suppressed in $\Lambda_b^0 \rightarrow pK^-$ with respect to $\Lambda_b^0 \rightarrow p\pi^-$, since it is proportional to $V_{ub}V_{us}^*$ rather than $V_{ub}V_{ud}^*$.

In addition to the weak phases, strong interactions generate strong phases through hadronization and final-state interactions. Direct CP violation can arise when at least two amplitudes with different weak and strong phases interfere. Consequently, the interference between tree and penguin contributions could provide the necessary condition for a non-zero direct CP asymmetry in these decays.

Representative tree-level, QCD penguin, and electroweak penguin diagrams contributing to these decays are shown in Figure 3. Since the penguin amplitudes involve virtual particles propagating inside the loop, they can also receive contributions from particles beyond those of the SM. Therefore, precision measurements of CP-violating observables in these decays could provide an indirect probe of possible new-physics effects.

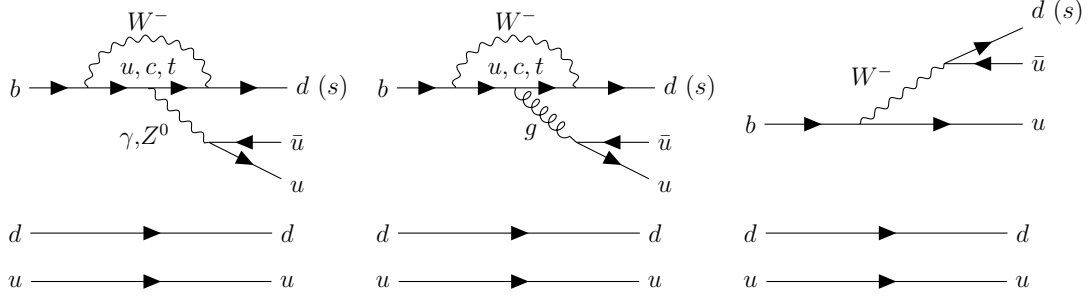


Figure 3: $\Lambda_b^0 \rightarrow p\pi^-$ and $\Lambda_b^0 \rightarrow pK^-$ examples of Feynman diagrams: electroweak penguin (left), QCD penguin (middle) and tree-level (right).

The same underlying decay topologies appear in the mesonic decays $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$, for which direct CP violation has been firmly established [8, 14]. In contrast, no statistically significant evidence of CP violation has yet been observed in the baryonic decays $\Lambda_b^0 \rightarrow p\pi^-$ and $\Lambda_b^0 \rightarrow pK^-$. Measuring their CP asymmetries is therefore of particular interest, as it provides a test of the expected CP-violating effects in the baryonic sector and may shed light on the dynamics governing these decays.

From a theoretical perspective, baryonic decays are generally more challenging to describe than mesonic decays. The presence of two spectator quarks in the initial-state baryon leads to a more complicated hadronization process and enhances the role of non-perturbative QCD effects, resulting in larger theoretical uncertainties. Therefore, precise experimental measurements are also essential for constraining theoretical models and improving our understanding of heavy-flavour baryon dynamics.

2 The LHCb experiment

LHCb is one of the four major experiments located at the Large Hadron Collider (LHC) accelerator complex at CERN in Geneva. This chapter begins with a brief overview of the LHC, followed by a description of the main components of the LHCb detector.

2.1 The Large Hadron Collider

The LHC is a two-ring hadron accelerator and collider installed in the existing 26.7 km tunnel that previously housed the Large Electron–Positron collider. It is located approximately 100 m underground, spanning the Swiss–French border [36]. The LHC hosts four of the world’s largest particle physics experiments: ATLAS, ALICE, CMS, and LHCb.

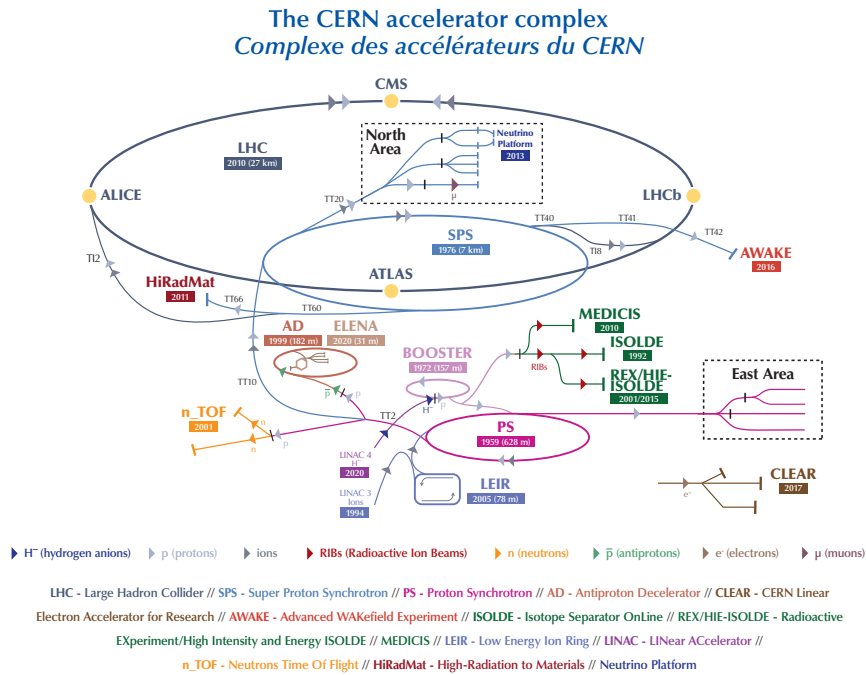


Figure 4: General layout of the CERN accelerator complex [37].

The LHC primarily collides proton-proton (pp) beams and, during dedicated operation periods, also proton-ion and ion-ion beams. Protons are produced by stripping the electron from hydrogen atoms and are subsequently accelerated through a sequence of linear and circular accelerators, shown in Figure 4, before

being injected into the LHC ring. At design performance, each beam reaches an energy of approximately 7 TeV. During Run 3, however, the collider operated with beam energies of 6.8 TeV, corresponding to a centre-of-mass energy of 13.6 TeV for pp collision. The protons are grouped into bunches containing approximately 10^{11} particles, with a bunch spacing of 25 ns. Since the LHC is a particle–particle collider, two separate rings are required to circulate counter-rotating beams, unlike particle–antiparticle colliders, where both beams can share the same ring. The beams are brought into collision at four interaction points, where the four major experiments are located.

A crucial parameter in collider-based particle physics experiments is the instantaneous luminosity, as it directly determines the rate of particle interactions. ATLAS and CMS are general-purpose detectors and operate at an instantaneous luminosity of approximately $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. In contrast, ALICE and LHCb are dedicated to heavy-ion and heavy-flavour physics, respectively. To limit the effects of multiple proton–proton interactions per bunch crossing (pile-up), they operate at lower instantaneous luminosities, typically ranging from 10^{27} to $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, depending on the experiment and the colliding particle species.

During the most recent data-taking period, Run 3, a major upgrade enabled the LHCb detector to operate at an instantaneous luminosity approximately five times higher than in previous runs, substantially increasing the size of the recorded datasets available for physics analyses [38].

2.2 The LHCb detector

The LHCb experiment is dedicated to heavy-flavour physics. Its primary goal is to search for indirect evidence of physics beyond the Standard Model through precision measurements of CP violation and rare decays of beauty and charm hadrons [39]. Although the detector was originally designed for heavy-flavour physics, it has also demonstrated excellent performance in a wide range of other areas, including electroweak, heavy-ion, and fixed-target physics.

To achieve this broad physics programme, the detector must provide excellent vertexing and tracking performance, together with precise particle identification (PID) efficiencies. These capabilities are complemented by a highly efficient trigger system capable of selecting a broad range of signal signatures from the large number of pp collisions delivered by the LHC.

The LHCb detector [38] is a single-arm forward spectrometer. Its configuration for Run 3 is shown in Figure 5. The detector can be broadly divided into three main subsystems. The tracking system consists of the Vertex Locator (VELO), the Upstream Tracker (UT), the Scintillating Fibre (SciFi) Tracker, and a dipole magnet. Particle identification is provided by two Ring-Imaging Cherenkov (RICH) detectors, the electromagnetic and hadronic calorimeters (ECAL and HCAL, re-

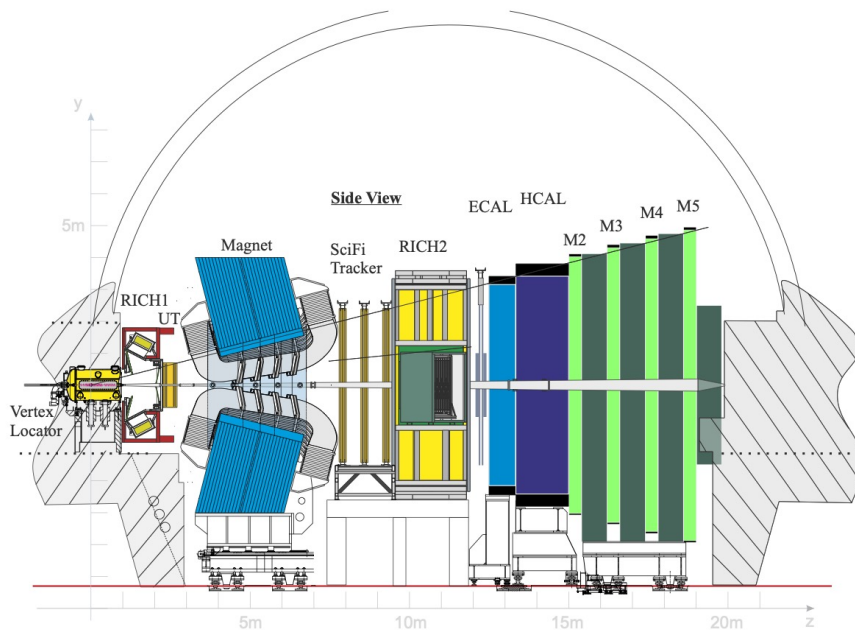


Figure 5: Run 3 layout of the LHCb detector [38].

spectively), and the muon system. Finally, events of interest are selected by a trigger system that, since Run 3, has been implemented entirely in software.

The main detector components in the Run 3 configuration are described in greater detail in the following sections.

2.3 Tracking system

The tracking system is responsible for identifying the interaction vertices, reconstructing the trajectories of charged particles, and measuring their momenta by exploiting the magnetic field of the dipole magnet to bend their trajectories.

The interaction vertices are reconstructed by the VELO, while the charged-particle trajectories are measured by the UT and the SciFi Tracker, located upstream and downstream of the dipole magnet, respectively.

2.3.1 Vertex Locator

The primary role of the VELO is to reconstruct pp interaction vertices, identify displaced decay vertices of long-lived particles, and measure the distances between them by detecting charged particles produced close to the interaction region [40].

The VELO is based on pixelated hybrid silicon detector technology. It consists of 52 identical modules arranged perpendicular to the beamline, each cooled by a silicon microchannel cooling system. Every module contains 12 VeloPix readout ASICs, each comprising a matrix of 256×256 pixels with an individual pixel size of $(55 \times 55) \mu\text{m}^2$. Since each pixel is equipped with an independent readout channel, the detector features more than 40 million readout channels in total. This fine granularity provides the excellent spatial resolution required for precise vertex reconstruction. The detector employs 200 μm -thick silicon sensors, which are cooled by an evaporative CO_2 system to mitigate radiation damage [40].

The layout of the VELO is shown in Figure 6. The coordinate system is defined with its origin at the nominal pp interaction point. The z axis is aligned with the beam direction and points towards the muon system, the y axis points vertically upwards, and the x axis completes the right-handed coordinate system.

The detector is divided into two mechanically independent halves that can move horizontally; one of them is shown in Figure 7. During beam injection, when the beams are not yet stable, the two halves are retracted by approximately 3 cm from the beamline. They are moved into their operating position only once stable beam conditions have been established. In the closed configuration, the innermost sensitive pixels are located just 5.1 mm from the LHC beam axis. The detector operates under vacuum and is separated from the LHC beam vacuum by a thin aluminium-alloy radio-frequency foil, which shields the front-end electronics from beam-induced electromagnetic fields while maintaining vacuum separation.

A key metric for assessing the performance of a vertex detector is the impact parameter (IP) resolution, σ_{IP} . The IP is defined as the perpendicular distance between a particle trajectory and a given point. This metric is a function of the transverse-momentum of the track, p_T ; the average axial distance of the material before the second measurement, r_1 ; the distances from the point to the first and second measurements, Δ_i ($i = 1, 2$); and the position uncertainties of those measurements, σ_i . In the VELO case, it can be approximated as:

$$\sigma_{\text{IP}}^2 \approx \underbrace{\left(\frac{r_1}{p_T [\text{GeV}/c]} \right)^2 \left(0.0136 \text{ GeV}/c \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln \frac{x}{X_0} \right) \right)^2}_{\text{multiple scattering}} + \underbrace{\frac{\Delta_2^2 \sigma_1^2 + \Delta_1^2 \sigma_2^2}{\Delta_{12}^2}}_{\text{extrapolation}}; \quad (10)$$

where x/X_0 is the fraction of radiation length traversed before the second measurement. The first term describes the degradation induced by multiple scattering. The second term is the extrapolation error, which is dominated by detector geometry. The measured IP resolutions in the two transverse projections are

$$\sigma_{\text{IP}_x} = \left(12.34 + \frac{13.27}{p_T} \right) \mu\text{m}, \quad \sigma_{\text{IP}_y} = \left(12.06 + \frac{13.11}{p_T} \right) \mu\text{m}, \quad (11)$$

where p_T is expressed in GeV/c [38]. These values demonstrate the excellent spatial precision of the VELO and its ability to provide the accurate vertex and decay-point reconstruction required for heavy-flavour physics.

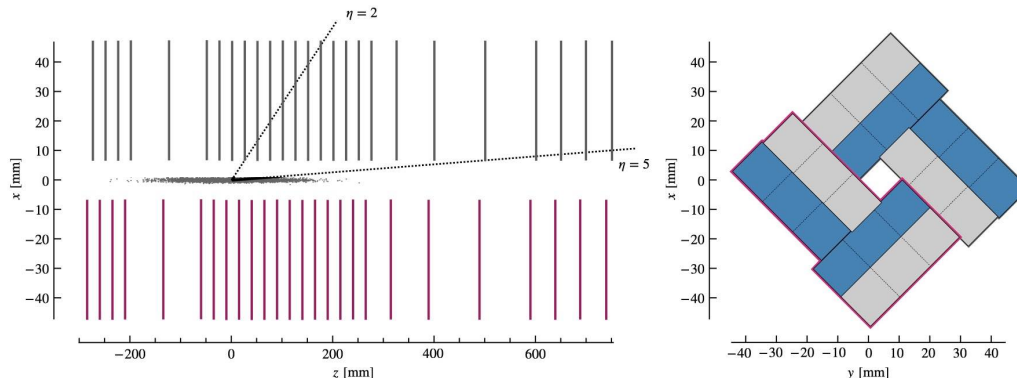


Figure 6: Left: schematic cross-section at $y = 0$ illustrating the z -extent of the luminous region and the nominal LHCb acceptance. Right: nominal layout of the VeloPix ASICs around the z axis in the closed VELO configuration [38].

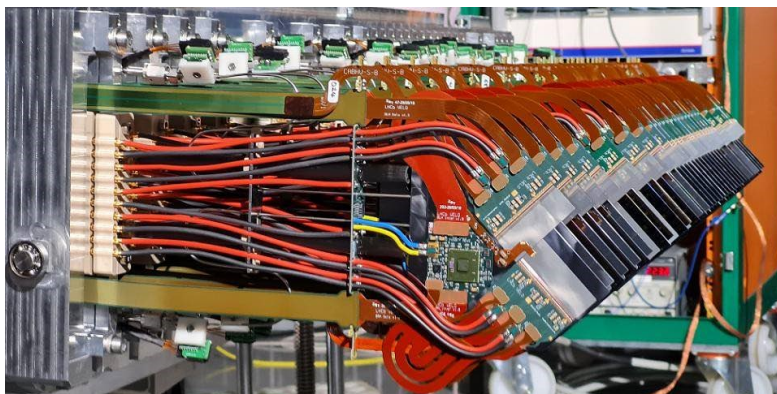


Figure 7: One half of the VELO detector, comprising 26 modules [38].

2.3.2 Upstream Tracker

The UT [38] is located between the RICH1 detector and the dipole magnet. It is used for charged-particle tracking and plays a key role in the first stage of the software trigger. By combining UT hits with tracks reconstructed in the VELO and exploiting the residual magnetic field between the interaction region and the UT, the trigger performs a first estimate of the particle momentum.

The UT consists of four planes of silicon strip detectors arranged in two stations, as shown in Figure 8. The silicon sensors, represented by the coloured boxes in the figure, are mounted on vertical support structures called staves. Each staff provides the mechanical support for the sensors and front-end electronics, while also incorporating an active cooling system. In particular, the staves are constructed from a carbon-fibre sandwich structure containing a titanium tube that forms part of the evaporative CO₂ cooling system.

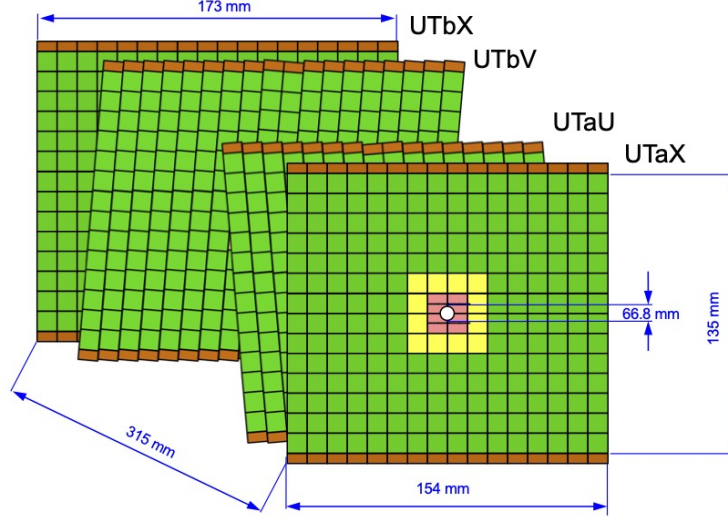


Figure 8: Layout of the Upstream Tracker [38].

Each station consists of two detector layers. The first station comprises an x -measuring layer (UTaX), with vertical strips, and a stereo layer (UTaU), whose strips are inclined by 5° . Both layers contain 16 staves. The second station has a similar layout, consisting of a stereo layer (UTbV) with strips inclined by -5° , followed by an x -measuring layer (UTbX) with vertical strips. Each of these layers contains 18 staves.

The UT layout was driven by a combination of physics requirements and environmental constraints. The detector was designed to provide full coverage of the nominal LHCb acceptance without inactive regions, a hit efficiency exceeding 99% for charged particles traversing the detector acceptance, high hit purity, an occupancy below a few percent, a low material budget, and sufficient radiation tolerance to withstand doses of the order of 1 kGy.

2.3.3 Scintillating Fibre Tracker

The SciFi Tracker [38] is located downstream of the LHCb dipole magnet and upstream of the RICH2 detector. It is responsible for charged-particle tracking

and momentum measurement. Covering an area of approximately $(6 \times 5) \text{ m}^2$ in the xy plane, it provides full coverage of the LHCb acceptance.

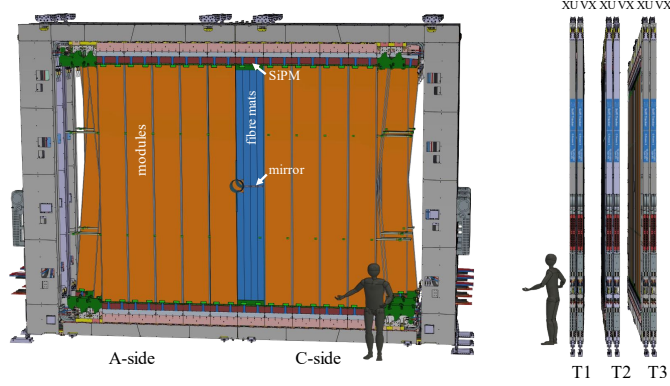


Figure 9: Front and side views of the 3D model of the SciFi Tracker [38].

The detector employs scintillating fibres arranged in multilayer fibre mats as its active material. It consists of 12 detection planes grouped into three tracking stations (T1, T2, and T3), each comprising four layers in an X–U–V–X configuration, as shown in Figure 9. The fibres in the X layers are oriented vertically and are used to measure the deflection of charged-particle trajectories induced by the magnetic field. The two inner stereo layers, U and V, have fibres inclined by $\pm 5^\circ$ with respect to the vertical, allowing the vertical coordinate of the hit to be reconstructed.

Each station is assembled from identical SciFi modules approximately 52 cm wide and spanning the full detector height, except for a few shortened modules located close to the beam pipe. Each module consists of a carbon-fibre honeycomb sandwich structure containing eight SciFi mats, each made of six staggered layers of scintillating fibres. A thin mirror is attached to one end of the fibres to reflect light back towards the readout electronics, thereby increasing the collected signal. The scintillation light is detected by 128-channel arrays of silicon photomultipliers (SiPMs).

At the beginning of operation, the SciFi Tracker provides an average light yield of approximately 18–20 photoelectrons for particles traversing the detector perpendicularly near the mirrored end of the fibres. Radiation damage gradually reduces the light yield, and a loss of about 40% is expected in the most heavily irradiated regions by the end of the detector’s lifetime. Nevertheless, the average signal is expected to remain above 10 photoelectrons, ensuring a single-hit detection efficiency above 99% and a single-hit spatial resolution of about $70 \mu\text{m}$. These performances are sufficient to provide efficient reconstruction of charged-particle tracks downstream of the LHCb magnet.

2.3.4 Magnet

The magnet is a key component of the LHCb detector, as it enables the determination of the charge and momentum of charged particles from the curvature of their trajectories. LHCb employs a warm (i.e. non-superconducting) dipole magnet consisting of two identical saddle-shaped coils mounted symmetrically inside a window-frame yoke, as shown in Figure 10. Each coil is formed by five triplets of aluminium pancakes and is supported by cast aluminium clamps attached to the yoke. The magnet is located between the UT and the SciFi Tracker and provides a vertical magnetic field with an integrated bending power of approximately 4 Tm.

During data taking, the magnet polarity is regularly reversed so that approximately equal data samples are collected in the two field configurations [38]. This procedure reduces detector-induced charge asymmetries, such as left–right asymmetries in the detector response, which could otherwise bias measurements of CP violation. Consequently, the analysis presented in this thesis is performed separately for the two magnet polarities, and the final result is obtained by combining the two independent measurements.

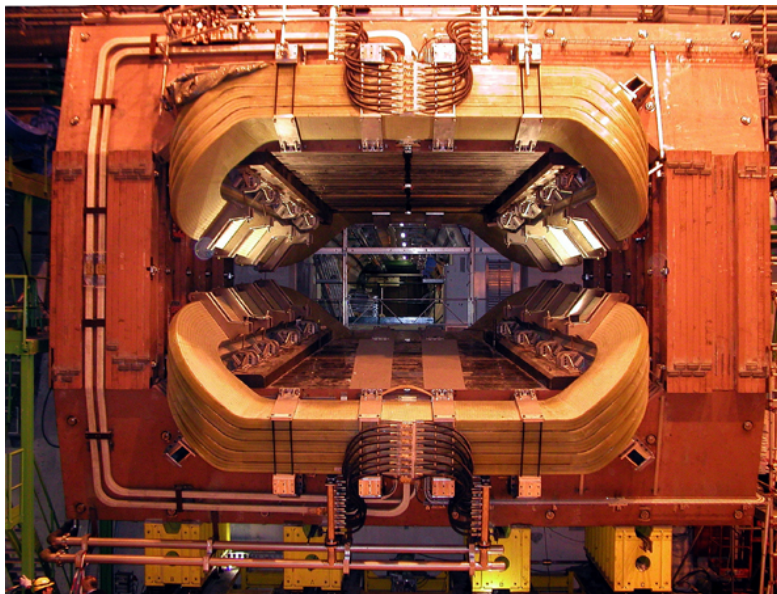


Figure 10: Front view of the LHCb dipole magnet [41].

2.4 Particle identification system

The PID system consists of two RICH detectors (RICH1 and RICH2), two calorimeters, and four muon stations. By combining the information provided by these sub-detectors, it enables the identification of charged particles, such as pions, kaons,

protons, electrons, and muons. This capability is essential for most analyses performed at LHCb, including the one presented in this thesis. The individual PID subdetectors are described in greater detail in the following sections.

2.4.1 RICH detectors

The RICH detectors exploit the Cherenkov effect to provide hadron identification. Cherenkov radiation is emitted when a charged particle traverses a dielectric medium with a velocity greater than the phase velocity of light in that medium. The emitted light forms a cone around the particle trajectory with an opening angle θ_{Ch} satisfying

$$\cos \theta_{\text{Ch}} = \frac{1}{n\beta},$$

where n is the refractive index of the radiator and β is the particle velocity expressed in units of the speed of light in vacuum. Since the Cherenkov angle (θ_{Ch}) depends on the particle velocity, combining its measurement with the momentum provided by the tracking system allows different particle species to be distinguished.

The LHCb RICH system, shown in Figure 11, consists of two detectors, RICH1 and RICH2, which together provide hadron identification over a momentum range from approximately 2.6 to 100 GeV/ c [38].

- RICH1 is located upstream of the dipole magnet and covers an angular acceptance from 25 to 300 mrad in the bending plane and from 25 to 250 mrad in the vertical direction. Its photon detector planes are positioned above and below the beam pipe, where the residual magnetic field is minimal. The detector employs a C_4F_{10} gas radiator with a refractive index of $n = 1.0014$ for Cherenkov light of wavelength $\lambda = 400$ nm at standard temperature and pressure (STP), providing particle identification in the momentum range from 2.6 to 60 GeV/ c .
- RICH2 is located downstream of the dipole magnet and covers an angular acceptance from 15 to 120 mrad in the bending plane and from 15 to 100 mrad in the vertical direction. Its photon detector planes are mounted on either side of the detector. RICH2 is designed to identify higher-momentum particles, between 15 and 100 GeV/ c , using a CF_4 gas radiator with a refractive index of $n = 1.0005$ for Cherenkov light of wavelength $\lambda = 400$ nm at STP.

In both detectors, the Cherenkov photons produced in the fluorocarbon gas radiators are reflected by a system of spherical and planar mirrors, which focus the ring images onto the photon detector planes located outside the LHCb acceptance. Both RICH1 and RICH2 employ Multi-Anode Photomultiplier Tubes as their photon detection technology.

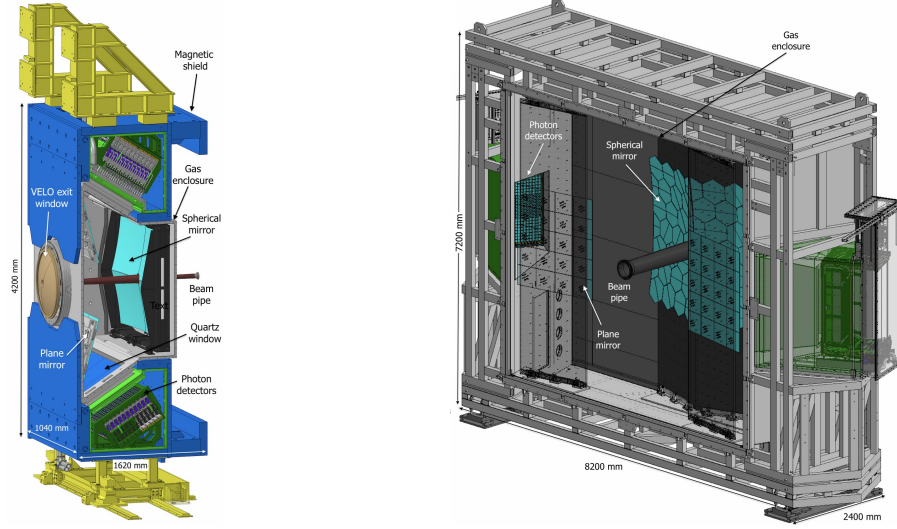


Figure 11: Schematic views of the RICH1 (left) and RICH2 (right) detectors [42].

2.4.2 Calorimeters

The primary purpose of a calorimeter is to measure the energy of particles traversing it. This is achieved by inducing the particles to interact with the detector material, producing cascades of secondary particles, known as showers, through which the particles gradually deposit their energy. Since electromagnetic and hadronic particles develop different types of showers, different detector geometries and absorber materials are required to optimise the measurement of each.

The LHCb calorimeter system consists of an electromagnetic calorimeter followed by a hadronic calorimeter. Both detectors are based on the same read-out principle: scintillation light produced in plastic scintillators is collected by wavelength-shifting fibres and guided to photomultiplier tubes for detection [38].

The ECAL is approximately 25 radiation lengths thick, ensuring almost complete containment of electromagnetic showers produced by high-energy electrons and photons, thereby providing excellent particle identification and energy resolution. To accommodate the varying particle flux across the detector acceptance, the ECAL is divided into three lateral regions: inner, middle, and outer; with progressively larger cell sizes moving away from the beam pipe. This segmentation keeps the particle occupancy per cell approximately uniform. Each cell has a shashlik structure consisting of alternating layers of 4 mm thick plastic scintillator and 2 mm thick lead absorbers, as shown in Figure 12. The energy resolution of a given cell, measured with a test electron beam, is parametrized as:

$$\frac{\sigma(E)}{E} = \frac{(9.0 \pm 0.5)\%}{\sqrt{E}} \oplus (0.8 \pm 0.2)\% \oplus \frac{0.003}{E \sin \theta}; \quad (12)$$

where E is the particle energy in GeV, θ is the angle between the beam axis and the line from the LHCb interaction point to the centre of the ECAL cell. The second contribution is a constant term taking into account mis-calibrations, nonlinearities, energy leakage out of the cell and other effects, while the third term is due to the noise of the electronics.

Due to the limited space available, the HCAL has a thickness of 5.6 interaction lengths. It is a sampling calorimeter composed of alternating iron absorber plates and plastic scintillator tiles arranged parallel to the beam axis to maximise light collection. The detector is divided into inner and outer regions and segmented into square cells, as illustrated in Figure 12. The energy resolution, as measured in beam tests with pions, is parametrised as follows:

$$\frac{\sigma(E)}{E} = \frac{(67 \pm 5)\%}{\sqrt{E}} \oplus (9 \pm 2)\% \quad (13)$$

where E is the deposited energy in GeV.

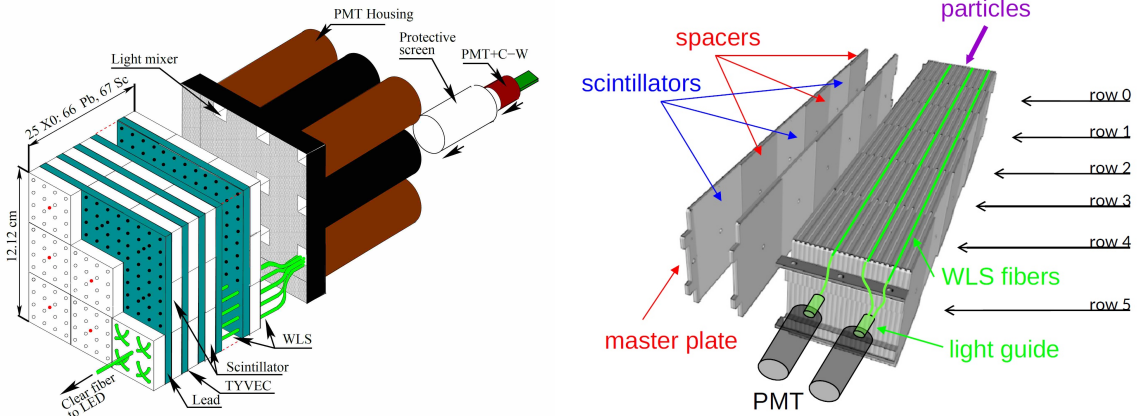


Figure 12: Schematic views of an ECAL cell (left) and an HCAL cell (right) [38].

2.4.3 Muon detector

The muon detector [43] consists of four rectangular stations, M2–M5, located downstream of the calorimeter system. The stations are arranged sequentially along the beam axis and are interleaved with 80 cm-thick iron absorbers, which filter out hadrons and other non-penetrating particles, allowing muons to be efficiently identified. Each station is instrumented with Multiwire Proportional Chambers (MWPCs), which consist of four independent gas gaps, each containing an anode wire plane enclosed between two cathode planes, as illustrated in Figure 13.

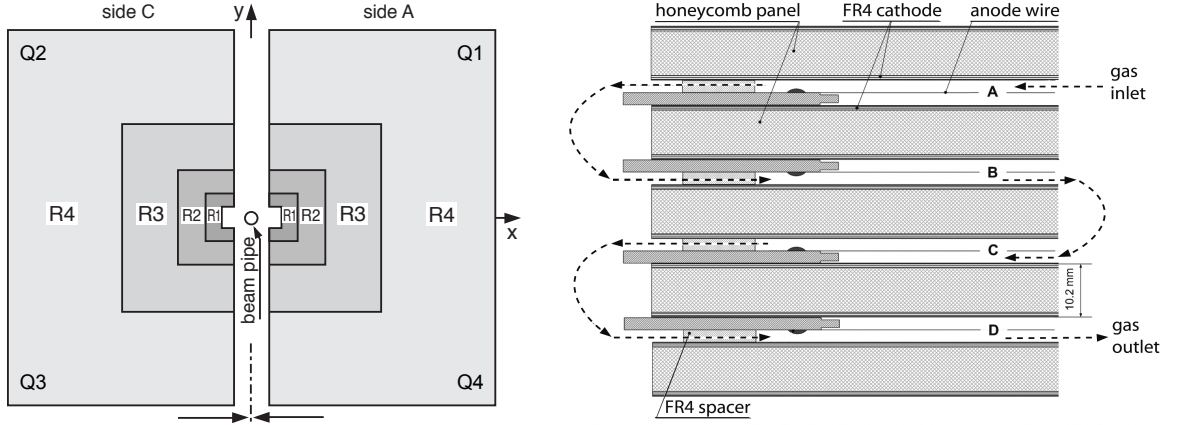


Figure 13: Left: front view of a muon station showing its quadrant and region segmentation. The four quadrants (Q1–Q4) are indicated in region R4. Right: cross-section of a MWPC consisting of four identical 5 mm-thick gas gaps, each containing an anode wire plane (labelled A, B, C, and D) [43].

Each station is composed of two mechanically independent halves that can be opened to allow access to the detector. Every half is divided into two quadrants, resulting in four quadrants (Q1–Q4) per station. Each quadrant is further segmented into four regions (R1–R4), with the readout granularity decreasing with increasing distance from the beam pipe, as shown in Figure 13. This segmentation ensures an approximately uniform particle flux and channel occupancy across the detector.

Two of the main metrics used to assess the performance of the muon detector are the muon hit detection efficiency and the muon identification performance. The former exceeds 99% across all detector regions. The muon identification performance depends on the track kinematics; for tracks with momenta above 10 GeV/c, a working point with a muon identification efficiency of around 90% can be achieved while keeping the hadron misidentification probability at the per-mille level.

2.5 Trigger

The main purpose of the trigger system is to reduce the data rate from approximately 4 TB/s, corresponding to the nominal instantaneous luminosity in pp collisions, to around 10 GB/s, which can be permanently stored for offline analysis.

During Run 3, the LHCb detector adopted a fully software-based trigger system with a triggerless readout architecture, transmitting the raw detector hits from all 30 MHz of LHC bunch crossings to a dedicated data processing centre. The

first stage of this processing consists of the event building, where raw data fragments from the individual subdetectors are combined into complete events. These events are then processed by grouping detector hits into higher-level physics objects through the reconstruction stage and by determining whether they contain signatures of sufficient interest to be retained for further analysis. This processing stage is collectively referred to as the High Level Trigger (HLT) in LHCb.

Events accepted by the HLT are permanently stored and transferred to the GRID infrastructure for further processing and distribution to analysts [44]. A schematic representation of this data flow is shown in Figure 14.

The HLT sequence is divided into two stages, conventionally referred to as HLT1 and HLT2, separated by a disk buffer. This buffer stores events between the two stages, allowing the detector to be aligned and calibrated in near real time with a precision comparable to that achieved in offline processing. In the following, a brief description of the task performed by each trigger state is provided.

The HLT1, running entirely on GPUs, first applies a Global Event Cut, which removes a fraction of events with a very large number of tracks. Such events require a disproportionate amount of computing time to reconstruct while generally providing poorer detector performance. The subsequent reconstruction focuses on identifying the trajectories of charged particles originating within the LHCb vertex detector and traversing the remainder of the tracking system, namely the UT and SciFi Tracker, as well as the muon chambers. The reconstruction aims to measure the particle momenta with percent-level precision, associate each particle with the corresponding pp collision, determine its displacement from the collision point, and identify whether it is a muon. Following reconstruction, HLT1 applies a limited number of selection algorithms ($\mathcal{O}(100)$). These cover the primary inclusive selections for the bulk of the LHCb physics programme, selections for calibration samples, specific physics signatures not covered by the inclusive triggers, and technical triggers for luminosity determination, monitoring, calibration, and alignment. Overall, HLT1 reduces the data rate by approximately a factor of 20, allowing the events to be temporarily stored in the buffer disk.

The HLT2, running on CPUs, performs the full detector reconstruction online at offline quality, including alignment and calibration, and selects high-level physics objects relevant to the different LHCb analyses for permanent storage. As in HLT1, the processing follows a reconstruction–selection chain. HLT2, however, relies on approximately one thousand selection algorithms, each optimised for a specific signal topology and/or physics analysis. The overall procedure, in which the detector data are reconstructed and selected in real time, is known as real-time analysis.

Real-time analysis is essential for the LHCb experiment since many of the interesting physics channels cannot be efficiently selected using only a small set of

generic event features, as is commonly done in other experiments. Instead, the full detector information must be exploited online to perform precise reconstruction and selection of the relevant decay signatures.

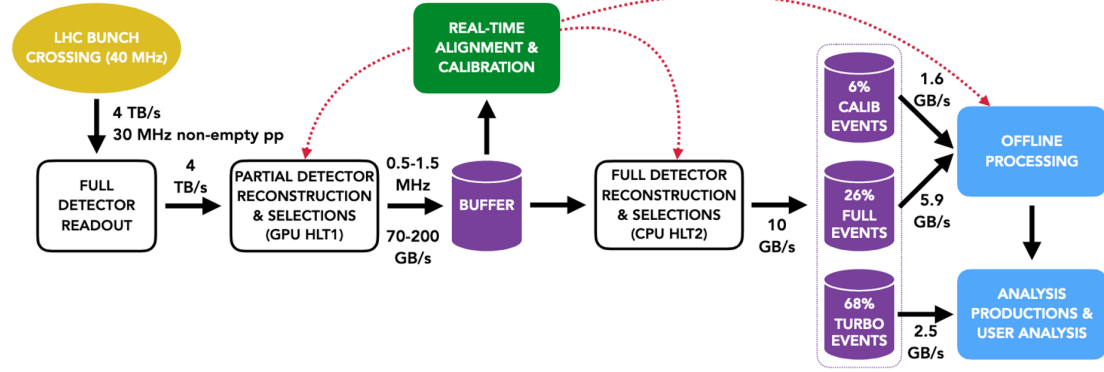


Figure 14: Schematic representation of the LHCb data flow [45].

3 Determination of ΔA_{CP}

This chapter presents the main result of this thesis: the measurement of the difference between the CP asymmetries of the $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decay channels,

$$\Delta A_{CP} \equiv A_{CP}(pK^-) - A_{CP}(p\pi^-).$$

Section 3.1 introduces the analysis strategy by defining the quantities required to determine ΔA_{CP} and explaining the motivation for measuring the asymmetry difference rather than the individual CP asymmetries.

Section 3.2 summarizes the requirements applied to select the data used in the analysis.

Section 3.3 describes the extraction of the raw asymmetries from the observed signal yields of the decay channels under study. Section 3.4 discusses the correction for detection asymmetries arising from differences in the detection efficiencies of a final state and its CP-conjugate counterpart (e.g. $p\pi^-$ and $\bar{p}\pi^+$). Section 3.5 presents the evaluation of the asymmetries introduced by the PID requirements, while Section 3.6 describes the determination of the asymmetries associated with the trigger selection.

Finally, Section 3.8 combines all the measured contributions to obtain the final value of ΔA_{CP} .

3.1 Analysis strategy

The CP asymmetries associated with the $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decay modes are defined as:

$$A_{CP}(pK^-) \equiv \frac{\Gamma(\Lambda_b^0 \rightarrow pK^-) - \Gamma(\bar{\Lambda}_b^0 \rightarrow \bar{p}K^+)}{\Gamma(\Lambda_b^0 \rightarrow pK^-) + \Gamma(\bar{\Lambda}_b^0 \rightarrow \bar{p}K^+)}, \quad (14)$$

$$A_{CP}(p\pi^-) \equiv \frac{\Gamma(\Lambda_b^0 \rightarrow p\pi^-) - \Gamma(\bar{\Lambda}_b^0 \rightarrow \bar{p}\pi^+)}{\Gamma(\Lambda_b^0 \rightarrow p\pi^-) + \Gamma(\bar{\Lambda}_b^0 \rightarrow \bar{p}\pi^+)}, \quad (15)$$

where Γ denotes the decay rate of the corresponding CP-conjugated processes. Experimentally, the CP asymmetries can be written as:

$$A_{CP}(pK^-) = A_{\text{raw}}(pK^-) - A_{\text{det}}(p) - A_{\text{det}}(K^-) - A_{\text{PID}}(pK^-) - A_{\text{prod}}(\Lambda_b^0) - A_{\text{trig}}(pK^-), \quad (16)$$

$$A_{CP}(p\pi^-) = A_{\text{raw}}(p\pi^-) - A_{\text{det}}(p) - A_{\text{det}}(\pi^-) - A_{\text{PID}}(p\pi^-) - A_{\text{prod}}(\Lambda_b^0) - A_{\text{trig}}(p\pi^-). \quad (17)$$

The raw asymmetry, $A_{\text{raw}}(ph^-)$, where $h = K, \pi$, is the asymmetry between the observed signal yields (N) of the $\Lambda_b^0 \rightarrow ph^-$ and $\bar{\Lambda}_b^0 \rightarrow \bar{p}h^+$ decay channels:

$$A_{\text{raw}}(ph^-) \equiv \frac{N(\Lambda_b^0 \rightarrow ph^-) - N(\bar{\Lambda}_b^0 \rightarrow \bar{p}h^+)}{N(\Lambda_b^0 \rightarrow ph^-) + N(\bar{\Lambda}_b^0 \rightarrow \bar{p}h^+)}. \quad (18)$$

The detection asymmetry, $A_{\text{det}}(\tilde{h})$, where $\tilde{h} = p, K, \pi$, arises from differences in the detection efficiencies (ε_{det}) of particles and antiparticles, primarily due to their different interaction probabilities with the detector material. The detection efficiency can be understood as the fraction of particles traversing a given detector that are successfully detected. If this fraction differs between particles and antiparticles, their observed signal yields can exhibit an apparent asymmetry even when they are produced in equal numbers. It is defined as:

$$A_{\text{det}}(\tilde{h}^+) \equiv \frac{\varepsilon_{\text{det}}(\tilde{h}^+) - \varepsilon_{\text{det}}(\tilde{h}^-)}{\varepsilon_{\text{det}}(\tilde{h}^+) + \varepsilon_{\text{det}}(\tilde{h}^-)}. \quad (19)$$

The particle-identification asymmetry, $A_{\text{PID}}(ph^-)$, arises from the PID requirements imposed on the final-state particles. Although identical PID selection criteria are imposed on particles and antiparticles, their efficiencies (ε_{PID}) can differ. The PID efficiency can be understood as the fraction of particles of a given species that satisfy the corresponding PID requirements. Consequently, even when particles and antiparticles are produced in equal numbers, different PID efficiencies can result in different numbers of particles passing the selection, thereby inducing an instrumental asymmetry that could mimic CP violation. This contribution can be written as:

$$A_{\text{PID}}(ph^-) \equiv A_{\text{PID}}(p) + A_{\text{PID}}(h^-) \quad (20)$$

$$= \frac{\varepsilon_{\text{PID}}(p) - \varepsilon_{\text{PID}}(\bar{p})}{\varepsilon_{\text{PID}}(p) + \varepsilon_{\text{PID}}(\bar{p})} + \frac{\varepsilon_{\text{PID}}(h^-) - \varepsilon_{\text{PID}}(h^+)}{\varepsilon_{\text{PID}}(h^-) + \varepsilon_{\text{PID}}(h^+)}. \quad (21)$$

The Λ_b^0 production asymmetry, $A_{\text{prod}}(\Lambda_b^0)$, accounts for the different production rates of Λ_b^0 and $\bar{\Lambda}_b^0$ baryons in pp collisions [46, 47]. This asymmetry originates from the fact that the initial pp state is not symmetric in terms of valence quarks and antiquarks, since no antiquarks are present, and this enhances the production of baryons over anti-baryons.

Finally, $A_{\text{trig}}(ph^-)$ represents the asymmetry introduced by the trigger selection. Although $\Lambda_b^0 \rightarrow ph^-$ and $\bar{\Lambda}_b^0 \rightarrow \bar{p}h^+$ are subject to the same trigger requirements, their trigger efficiencies ($\varepsilon_{\text{trig}}$) can differ due to the slightly different kinematics of the final-state particles. The trigger efficiency can be understood as the fraction of events that satisfy the trigger requirements out of the total number of events entering the trigger. Consequently, different trigger efficiencies

for the two CP-conjugate decays can lead to different numbers of selected events, producing a nuisance asymmetry. This contribution is defined as:

$$A_{\text{trig}}(ph^-) \equiv \frac{\varepsilon_{\text{trig}}(\Lambda_b^0) - \varepsilon_{\text{trig}}(\bar{\Lambda}_b^0)}{\varepsilon_{\text{trig}}(\Lambda_b^0) + \varepsilon_{\text{trig}}(\bar{\Lambda}_b^0)}. \quad (22)$$

It is important to note that Eq. (16) can be written as a sum of different contributions only if second-order terms can be neglected. This is the case since all the terms in Eq. (16) are of the order of few percents, making the second-order terms of $\mathcal{O}(10^{-4})$, about a factor 10 smaller than the uncertainties expected in this measurement.

Among all the quantities introduced above, the determination of $A_{\text{det}}(p)$ and $A_{\text{prod}}(\Lambda_b^0)$ is particularly challenging and lies beyond the scope of this project. However, assuming that the kinematic distributions of the two decay modes are sufficiently similar, taking the difference between the two CP asymmetries yields to:

$$\Delta A_{CP} = A_{CP}(pK^-) - A_{CP}(p\pi^-) \quad (23)$$

$$\begin{aligned} &= A_{\text{raw}}(pK^-) - A_{\text{raw}}(p\pi^-) - A_{\text{det}}(K^-) + A_{\text{det}}(\pi^-) \\ &\quad - A_{\text{PID}}(pK^-) + A_{\text{PID}}(p\pi^-) - A_{\text{trig}}(pK^-) + A_{\text{trig}}(p\pi^-) \\ &\quad - \cancel{A_{\text{det}}(p)} + \cancel{A_{\text{det}}(p)} - \cancel{A_{\text{prod}}(\Lambda_b^0)} + \cancel{A_{\text{prod}}(\Lambda_b^0)}. \end{aligned} \quad (24)$$

The proton detection asymmetry and the Λ_b^0 production asymmetry therefore cancel in the difference. The validity of the assumption underlying these cancellations is assessed in Section 3.7. Furthermore

$$A_{\text{det}}(K^-) - A_{\text{det}}(\pi^-) = A_{\text{det}}(K^-) + A_{\text{det}}(\pi^+) = A_{\text{det}}(K^-\pi^+);$$

where $A_{\text{det}}(\pi^-) = -A_{\text{det}}(\pi^+)$ follows directly from the definition in Eq. (19). Hence, the difference between the kaon and pion detection asymmetries is equal to the detection asymmetry of the $K^-\pi^+$ final state, $A_{\text{det}}(K^-\pi^+)$, which is the quantity measured in Section 3.4.

Therefore, the determination of ΔA_{CP} requires the determination of the raw asymmetries together with the remaining correction terms introduced above. As mentioned in Section 2.3.4, the analysis is performed independently for the two opposite polarities of the LHCb dipole magnet, referred to as MagDown and MagUp. The corresponding ΔA_{CP} measurements are then averaged, which largely cancels residual left-right detector asymmetries.

3.2 Event selection

The data set analyzed in this thesis, collected by the LHCb experiment in 2024 during Run 3, corresponds to an integrated luminosity of approximately 1.5 fb^{-1} .

The events in the dataset are required to pass the `Hlt1TrackMVA_TOS` and `Hlt2BnoC_BdToPipPim_NoPID_Full` trigger lines. At the first trigger level (HLT1), the `Hlt1TrackMVA` line is designed to inclusively select high-quality charged tracks originating from displaced vertices, a characteristic signature of b -hadron (H_b) decays. Tracks are first required to satisfy stringent quality criteria, including upper limits on the track-fit χ^2 per degree of freedom (χ^2/ndf) and the ghost probability¹(GhostProb). A dynamic kinematic requirement is then applied in the $(p_T, \chi_{\text{IP}}^2)$ plane: tracks with lower transverse momentum (p_T) are required to have a larger Impact-Parameter χ^2 (χ_{IP}^2) with respect to the Primary Vertex (PV). This requirement preferentially selects displaced tracks while suppressing prompt combinatorial background. The TOS (Trigger On Signal) requirement ensures that at least one of the two signal daughter tracks satisfies the previously mentioned trigger requirements and therefore fires the trigger line.

At the HLT2 stage, the `Hlt2BnoC_BdToPipPim_NoPID_Full` line performs the full topological reconstruction of the H_b two-body decay into oppositely charged particles, without relying on any particle identification information. The selection starts by filtering individual charged tracks, imposing minimum thresholds on both total momentum (p) and transverse momentum (p_T). Additionally, a more stringent minimum χ_{IP}^2 requirement is applied to ensure that the tracks are significantly detached from the PV. Oppositely charged tracks are then combined to form a H_b candidate. Prior to the full vertex fit, the track pair must satisfy loose criteria: the scalar sum of their p_T must be above a minimum threshold, an invariant mass, calculated under the $\pi^+\pi^-$ final-state hypothesis ($m_{\pi^+\pi^-}$), within a wide window around the nominal B^0 mass value, and an upper limit on the Distance of Closest Approach χ^2 (χ_{DOCA}^2) to require the two tracks to be spatially compatible. After fitting the decay vertex of the H_b candidate, further kinematic and geometric requirements are imposed. The H_b candidate must possess sufficient p_T and a large Flight Distance χ^2 (χ_{FD}^2), to select candidates with a significantly displaced decay vertex. To ensure that the H_b candidate is consistent with originating from the PV, its momentum vector is required to point towards the PV. This is enforced by a stringent upper limit on its χ_{IP}^2 and by requiring the cosine of the angle between the momentum direction and the direction from the PV to the decay vertex (DIRA) to be close to unity.

Table 1 summarizes the selection requirements described above.

¹The ghost probability estimates the likelihood that a reconstructed track is not associated with a true charged-particle trajectory but instead results from an incorrect combination of detector hits.

Variable	Requirement
Track χ^2/ndf	< 2.5
Track GhostProb	< 0.5
Track p [GeV/ c]	> 1.0
Track p_T [GeV/ c]	> 1.0
Track χ_{IP}^2	> 16
$p_T^+ + p_T^-$ [GeV/ c]	> 4.5
χ_{DOCA}^2	< 9
$p_T(H_b)$ [GeV/ c]	> 1.2
$\chi_{IP}^2(H_b)$	< 9
$\chi_{FD}^2(H_b)$	> 100
DIRA(H_b)	> 0.99
$m_{\pi^+\pi^-}$ [GeV/ c^2]	$\in [4.7, 6.2]$

Table 1: Summary of the selection criteria applied to reconstruct H_b two-body decays into oppositely charged particles. At least one of the two daughter tracks must satisfy each of the first two requirements, while all remaining single-track requirements are applied to both tracks.

3.3 Determination of $A_{\text{raw}}(pK^-)$ and $A_{\text{raw}}(p\pi^-)$

The first step of the analysis is the determination of the raw asymmetries. This is achieved by performing a simultaneous maximum-likelihood fit to the invariant-mass distributions of eight mutually exclusive final-state samples: $\pi^+\pi^-$, π^+K^- , $K^+\pi^-$, K^+K^- , pK^- , $K^+\bar{p}$, $p\pi^-$, and $\pi^+\bar{p}$. Together, these correspond to all relevant combinations of the π , K , and p final-state particles.

Several preparatory steps are required before performing the simultaneous fit:

- Determination of the PID efficiencies, used to estimate the ratio between the yields of correctly identified and misidentified final states;
- Modeling of the contributions arising from the misidentification of one or both final-state particles (referred to as cross-feed backgrounds);
- Extraction of the signal-shape parameters from fits to the invariant-mass distributions of fully simulated signal samples.

These ingredients are described in detail in the following sections.

3.3.1 PID calibration

The RICH detectors are the primary subdetectors used for hadronic particle identification at LHCb. Their performances depend mainly on the particle momentum,

which determines the Cherenkov emission angle, on the pseudorapidity, due to the fact that the two RICHes have different acceptances, and on the detector occupancy, since higher occupancy leads to a larger number of overlapping Cherenkov rings and hence degraded detector performances. The RICHes response is used to construct a likelihood function, $\mathcal{L}$, for each particle species. The discrimination between two particle hypotheses, h_1 and h_2 , is then quantified by

$$\Delta \log(\mathcal{L}_{h_1-h_2}) = \log \left(\frac{\mathcal{L}_{h_1}}{\mathcal{L}_{h_2}} \right). \quad (25)$$

The PID discriminant used in this analysis, $\Delta \log(\mathcal{L})$, therefore exhibits a dependence on the particle momentum, pseudorapidity, and detector occupancy.

An accurate determination of the PID efficiencies is essential for this analysis. All the $[H_b \rightarrow h^+ h'^-]^2$ decay modes constitute one of the main background sources for one another, since their invariant-mass distributions obtained when one or both final-state particles are misidentified peak in the same mass region as the correctly identified final states.

Particle identification efficiencies are determined using calibration samples of $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ decays for pions and kaons, and $\Lambda^0 \rightarrow p\pi^-$ decays for protons. The decay topology of these channels allows the identity of the final-state particles to be established without relying on any PID information. A fiducial selection in the (p, η) plane is applied both to the calibration samples and to the signal candidates in order to reject H_b candidates whose final-state particles populate regions of phase space not covered by the calibration samples, as illustrated in Figure 15. The fiducial region is defined as the area enclosed by the following lines in the (p, η) plane (with momentum expressed in GeV/c):

$$\begin{aligned} \ell_1 : \eta &> 2 \\ \ell_2 : \eta &< 4.2 \\ \ell_3 : \eta &> 0.0184p + 1.639 \\ \ell_4 : \eta &> 0.150p - 14.25 \end{aligned} \quad (26)$$

A kinematic and geometrical selection based on a Boosted Decision Tree (BDT) algorithm [48] is also applied to all decay channels in order to suppress combinatorial background arising from randomly associated oppositely charged hadrons that do not originate from the same decay. The BDT training is explained in greater detail in Section 3.3.5.

² H_b denotes a generic b hadron, namely B^0 , $\bar{B}^0$, B_s^0 , $\bar{B}_s^0$, Λ_b^0 , or $\bar{\Lambda}_b^0$, while $h^+ h'^-$ denotes one of the eight final-state hypotheses considered. Depending on the parent hadron, only a subset of these final states corresponds to a physical decay mode.

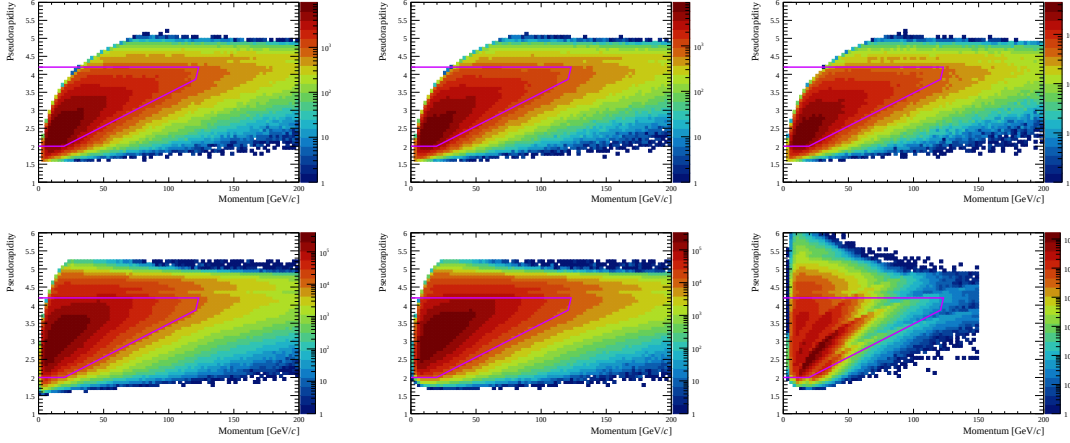


Figure 15: (p, η) distributions of the fully simulated samples (top row) and PID calibration samples (bottom row). The left, middle, and right columns correspond to pions, kaons, and protons, respectively. The violet line indicates the boundary of the fiducial region.

Since the PID performances depend on the kinematic and occupancy variables discussed above, three-dimensional PID efficiency maps as a function of momentum (p), pseudorapidity (η), and detector occupancy (Θ) were constructed. In each bin, the efficiency is defined as the ratio between the number of calibration events passing a given PID requirement and the total number of calibration events. The occupancy variable used throughout this chapter is $nLongTracks$, where a *LongTrack* corresponds to a charged particle traversing the entire tracking system, with hits in both the VELO, the SciFi and, optionally, in the UT detectors [49].

The binning scheme used to divide the phase space is:

- Momentum:
 - 2 uniform bins between 0 and 10 GeV/ c ;
 - 45 uniform bins between 10 and 100 GeV/ c ;
 - 20 uniform bins between 100 and 150 GeV/ c ;
 - 4 uniform bins between 150 and 500 GeV/ c ;
- Pseudorapidity:
 - 10 uniform bins between 1 and 6;
- Occupancy:
 - 4 uniform bins between 0 and 400;

– 1 bin between 400 and 600.

This binning choice, as well as the fiducial requirement, have been taken from a similar analysis outlined in Refs. [50, 51]. The PID requirements used in this analysis are:

- Pion: $[\Delta \log(\mathcal{L}_{K-\pi}) < -3] \cup [\Delta \log(\mathcal{L}_{p-\pi}) < 5]$;
- Kaon: $[\Delta \log(\mathcal{L}_{K-\pi}) > 3] \cup [\Delta \log(\mathcal{L}_{p-K}) < -5]$;
- Proton: $[\Delta \log(\mathcal{L}_{p-K}) > 9] \cup [\Delta \log(\mathcal{L}_{p-\pi}) > 9]$;

where two conditions are required for each particle species to discriminate among the three possible hadron hypotheses.

In principle, the next step would be to extract, on an event-by-event basis, the three PID efficiencies (one corresponding to the correct identification and two to possible misidentifications) for each final-state hadron using fully simulated Monte Carlo (MC) samples as a proxy for the particles kinematics and event occupancy. This is not possible in practice because the simulated samples do not accurately reproduce the detector occupancy observed in the data. Figure 16 illustrates the comparison between the MC and PID calibration samples occupancy distributions. To overcome this limitation, the occupancy dependence of

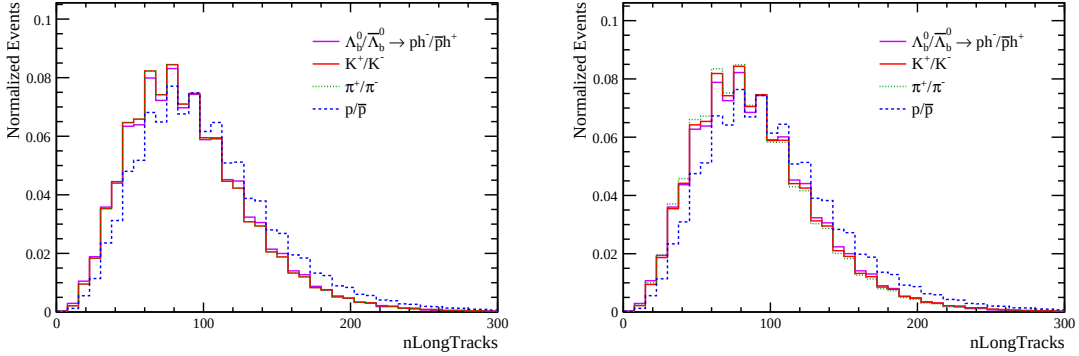


Figure 16: Normalized distributions of nLongTracks for background-subtracted PID-calibration events for kaons (red solid line), pions (green dotted line) and protons (blue dashed line) and $\Lambda_b^0/\bar{\Lambda}_b^0 \rightarrow ph^-/\bar{p}h^+$ simulated samples (violet solid line). The MagDown and MagUp samples are shown in the left and right plots, respectively.

the three-dimensional efficiency maps is averaged using occupancy distributions extracted from background-subtracted data where no PID requirements are applied. Specifically, for each (p, η) bin, 10^6 occupancy values are sampled from the

background-subtracted occupancy distribution from data and used to compute the occupancy-integrated PID efficiency:

$$\bar{\varepsilon}(p_i, \eta_j) = \frac{1}{N} \sum_{k=1}^N \varepsilon(p_i, \eta_j, \Theta_k). \quad (27)$$

The background-subtraction operation is performed using the sPlot technique [52]. The invariant mass is fitted under the $\pi^+\pi^-$ hypothesis ($m_{\pi^+\pi^-}$) for events passing the fiducial and BDT requirements but without any PID requirement. The signal components are parameterised using a Kernel Density Estimation (KDE) method [53] applied to the $m_{\pi^+\pi^-}$ distributions of fully simulated events. The resulting non-parametric distributions are then convolved with a Gaussian resolution model with free mean and width to account for the detector resolution. The relative fractions of the various $H_b \rightarrow h^+h'^-$ decay modes are fixed to their relative abundances as measured by the LHCb collaboration in Ref. [54]. For Λ_b^0 decays, the world averages of the absolute branching fractions provided by the Heavy Flavour Averaging Group (HFLAV) [55] are used. The combinatorial background is parameterised with an exponential function, while the partially reconstructed three-body component is described by an ARGUS function [56] convolved with the same Gaussian resolution model used for the signal shapes. The fit results are shown in Figure 17.

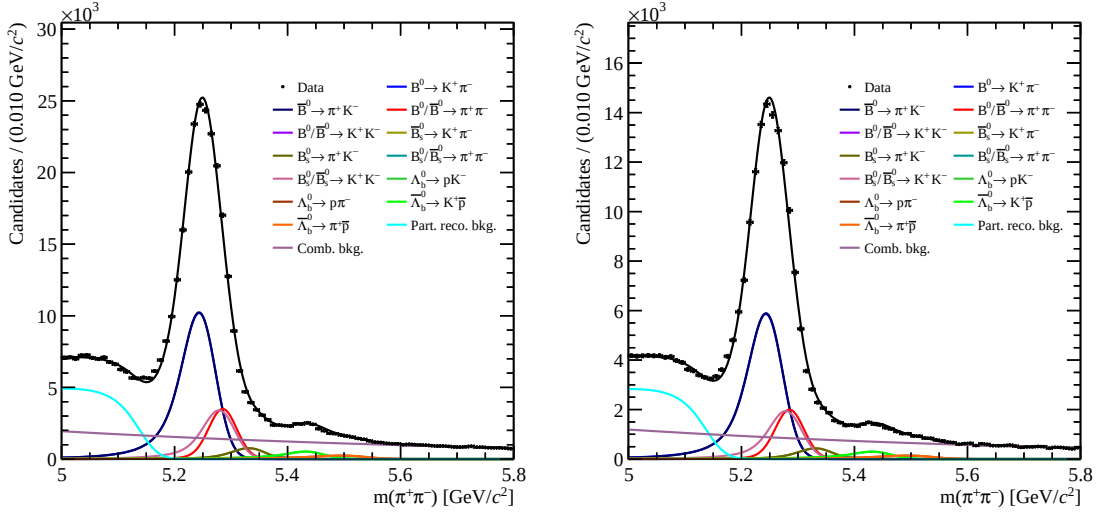


Figure 17: Fits to the invariant mass distributions of $H_b \rightarrow h^+h'^-$ candidates under the $\pi^+\pi^-$ hypothesis, with no PID requirements applied. The MagDown and MagUp samples are shown in the left and right plots, respectively.

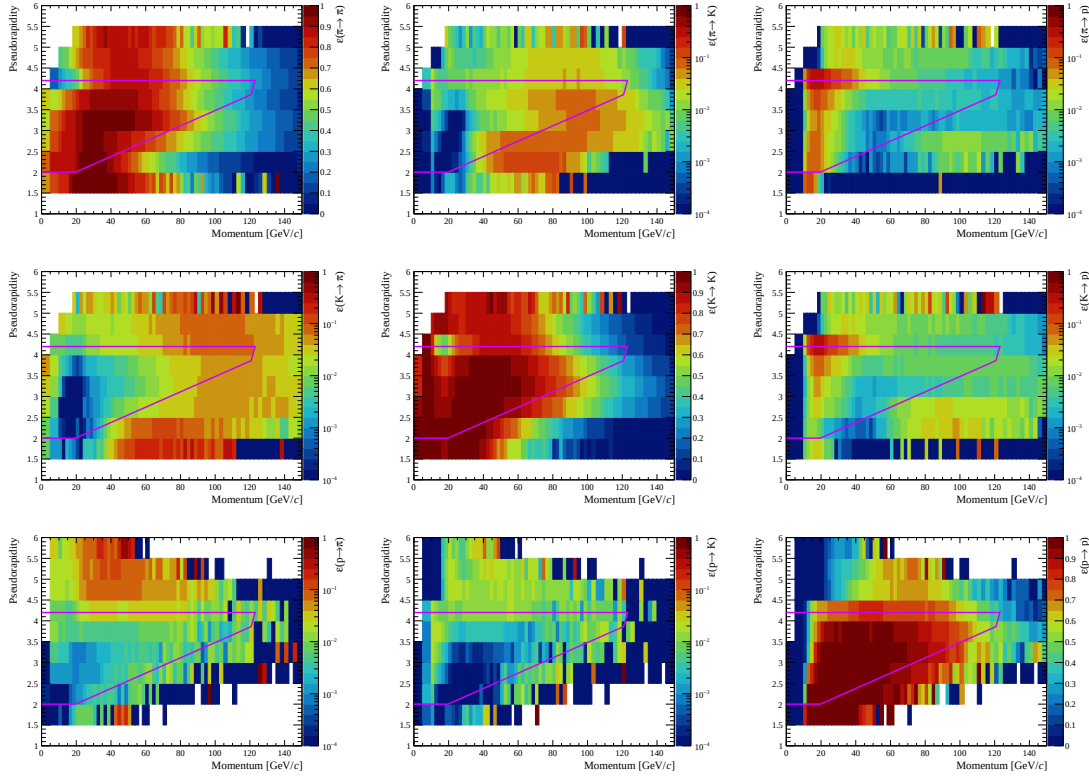


Figure 18: Occupancy-integrated two-dimensional PID efficiency maps for the MagDown polarity. The maps show $\varepsilon_{\text{PID}}(h \text{ reconstructed as } h')$, with the true particle species $h = \pi, K, p$ arranged from left to right and the reconstructed particle hypothesis $h' = \pi, K, p$ arranged from top to bottom. The violet line indicates the boundary of the fiducial region.

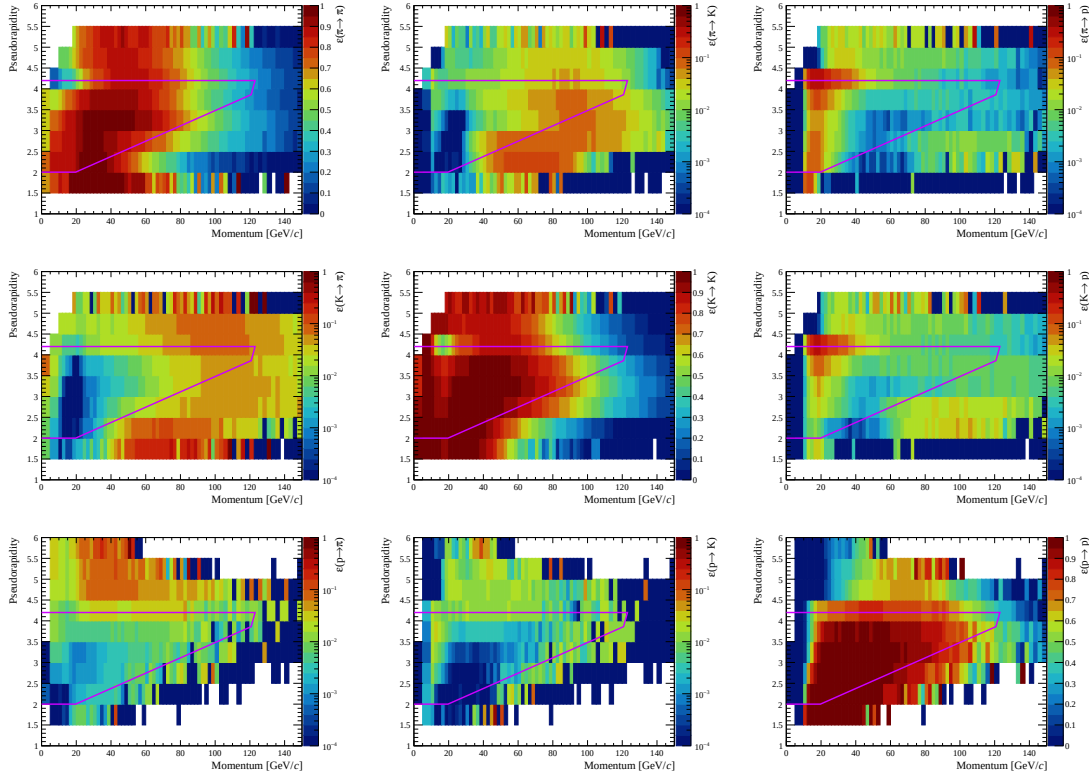


Figure 19: Occupancy-integrated two-dimensional PID efficiency maps for the MagUp polarity. The maps show $\epsilon_{\text{PID}}(h \text{ reconstructed as } h')$, with the true particle species $h = \pi, K, p$ arranged from left to right and the reconstructed particle hypothesis $h' = \pi, K, p$ arranged from top to bottom. The violet line indicates the boundary of the fiducial region.

Using the occupancy-integrated two-dimensional PID efficiency maps shown in Figures 18 and 19, the three PID efficiencies corresponding to each hadron hypothesis are assigned to every final-state particle in the simulated samples. The event-by-event two-particle PID efficiencies for each of the eight final-state samples are then computed as:

$$\varepsilon_{h^+h'^-} = \frac{1}{N} \sum_{i=1}^N \bar{\varepsilon}_{h^+}(p_i^+, \eta_i^+) \bar{\varepsilon}_{h'^-}(p_i^-, \eta_i^-); \quad (28)$$

where N is the total number of events in the corresponding MC sample. The resulting sample-averaged PID efficiencies are shown in Figure 20.

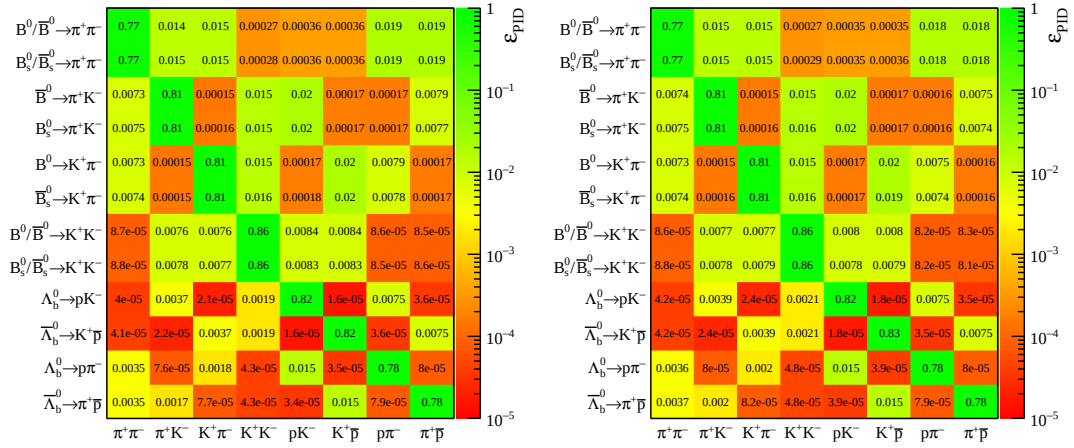


Figure 20: PID efficiencies for all the possible final states for the MagDown (left) and MagUp (right) polarities. The rows correspond to the simulated decay mode, while the columns represent the reconstructed final-state hypothesis.

The event-by-event PID efficiencies are also used as weights in the modeling of the cross-feed backgrounds and in the determination of the signal-shape parameters from simulated events, while the sample-averaged PID efficiencies enter the simultaneous fit as multiplicative factors relating the yields of the eight possible final-state hypotheses.

3.3.2 Invariant-mass models

The invariant-mass distributions of the eight possible final states contain several contributions, which are modeled using different probability density functions (PDFs). Four main components are identified for each final state:

- **Signal:** $H_b \rightarrow h^+ h'^-$ decays in which the final-state hadrons are correctly identified.
- **Cross-feed background:** $H_b \rightarrow h^+ h'^-$ decays in which one or both final-state hadrons are misidentified. This contribution is particularly important as the corresponding distributions peak very close to the signal shapes.
- **Partially reconstructed background:** $H_b \rightarrow h^+ h'^- X$ decays in which one or more particles (X) are not reconstructed. As a consequence, the reconstructed invariant mass lies at lower masses with respect to the signal peak, producing a threshold-shaped distribution with an endpoint at $m = \mu - m_{\pi^0}$, since the π^0 is the lightest particle that can escape reconstruction. This component is modeled using an ARGUS function [56] convolved with a Gaussian resolution model.
- **Combinatorial background:** candidates formed by the random association of two oppositely charged hadrons that do not originate from the same parent particle. This component is modeled using an exponential function.

The modeling of signal and cross-feed components is described in greater detail in Sections 3.3.3 and 3.3.4, respectively.

3.3.3 Signal

The invariant-mass signal shape is determined from fits to fully simulated MC samples, with applied per-event weights corresponding to PID efficiencies (as evaluated in Section 3.3.1). The resulting distribution is approximately Gaussian; however, it is necessary to account for the energy loss caused by the emission of soft photons from the final-state charged hadrons. This process, known as final-state radiation (FSR), produces a low-mass tail in the invariant-mass distribution. To model this effect, a Johnson S_U function [57] is added to the Gaussian core. Its analytical expression is given by:

$$J(m; \mu, \sigma_1, \gamma, \delta) = \frac{\delta}{\sigma_1 \sqrt{2\pi}} \frac{1}{\sqrt{1 + \left(\frac{m-\mu}{\sigma_1}\right)^2}} \exp \left[-\frac{1}{2} \left(\gamma + \delta \sinh^{-1} \left(\frac{m-\mu}{\sigma_1} \right) \right)^2 \right]. \quad (29)$$

The signal PDF that provides the best description of the simulated samples is

$$\text{PDF} = f_{G1} \cdot G1(m; \mu, \sigma_1) + f_{G2} \cdot G2(m; \mu, \sigma_2) + (1 - f_{G1} - f_{G2}) \cdot J(m; \mu, \sigma_1, \gamma, \delta). \quad (30)$$

where $G1$, $G2$, and J denote two Gaussian functions and a Johnson S_U function, respectively, while f_{G1} , f_{G2} , and $(1 - f_{G1} - f_{G2})$ are the corresponding relative

fractions. Here, m is the invariant mass, μ is the common mean of the three components, and σ_1 and σ_2 are the widths of the two Gaussian functions. Finally, δ and γ are the Johnson S_U shape parameters, which determine its asymmetry and tail.

The fits to the simulated samples of $\Lambda_b^0 \rightarrow pK^-$, $\Lambda_b^0 \rightarrow p\pi^-$, $\bar{\Lambda}_b^0 \rightarrow \bar{p}K^+$, and $\bar{\Lambda}_b^0 \rightarrow \bar{p}\pi^+$ are shown in Figures 21 and 22; the remaining fits are reported in Appendix A. The shape parameters obtained from these fits are subsequently fixed in the simultaneous fit to data, with the exception of the Gaussian widths $\sigma_{1,2}$ in the K^+K^- , pK^- , $\bar{p}K^+$, $p\pi^-$, and $\bar{p}\pi^+$ samples, which are left free to provide additional flexibility in describing the data. For the remaining samples, the ratios of their Gaussian widths to those of the K^+K^- sample are fixed to the values obtained from the fits to the simulated samples.

3.3.4 Cross-feed background

The cross-feed background constitutes one of the most challenging background sources in this analysis, since their reconstructed invariant-mass distributions peak very close to that of the correctly identified decay modes. This contribution is modeled using fully simulated MC samples. For each $H_b \rightarrow h^+h'^-$ decay mode, the invariant mass is recalculated under each of the eight possible final-state hypotheses according to

$$m(h^+h'^-) = \sqrt{m_{h^+}^2 + m_{h'^-}^2 + 2 \left[\sqrt{(m_{h^+}^2 + p_+^2)(m_{h'^-}^2 + p_-^2)} - \vec{p}_+ \cdot \vec{p}_- \right]}; \quad (31)$$

where m_{h^+} and $m_{h'^-}$ are the particle masses corresponding to the assumed final-state hypothesis, $\vec{p}_{+(-)}$ denotes the momentum of the positive (negative) particle obtained from the simulation, and $p_{+(-)}$ is the magnitude of $\vec{p}_{+(-)}$. This procedure reproduces the invariant-mass distributions that would be observed if the final-state particles were reconstructed under an incorrect mass hypothesis, but with a perfect momentum resolution.

A KDE technique [53] is then used to construct, for each simulated decay mode, a non-parametric PDF under each of the eight mass hypotheses. The corresponding event-by-event PID efficiencies are used as weights when building the templates. This weighting is necessary since the PID requirements distort the momentum distributions of the final-state particles and therefore modify the corresponding invariant-mass distributions. The effect is illustrated for the dominant cross-feed contributions in Figure 23.

The resulting non-parametric PDFs are used as templates for the cross-feed background components in the simultaneous fit.

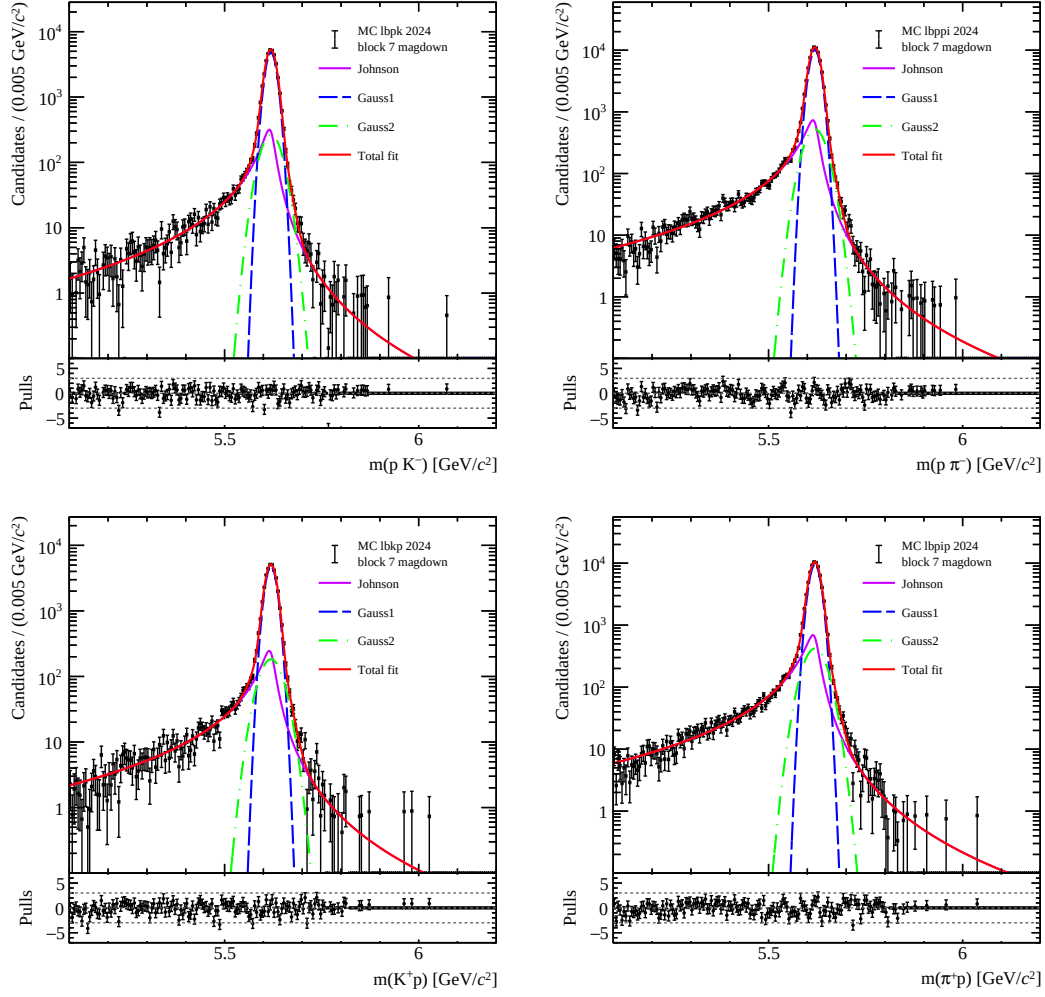


Figure 21: Fits to the invariant-mass distributions of the fully simulated $\Lambda_b^0 \rightarrow pK^-$ (top left), $\Lambda_b^0 \rightarrow p\pi^-$ (top right), $\bar{\Lambda}_b^0 \rightarrow \bar{p}K^+$ (bottom left), and $\bar{\Lambda}_b^0 \rightarrow \bar{p}\pi^+$ (bottom right) samples for the MagDown polarity.

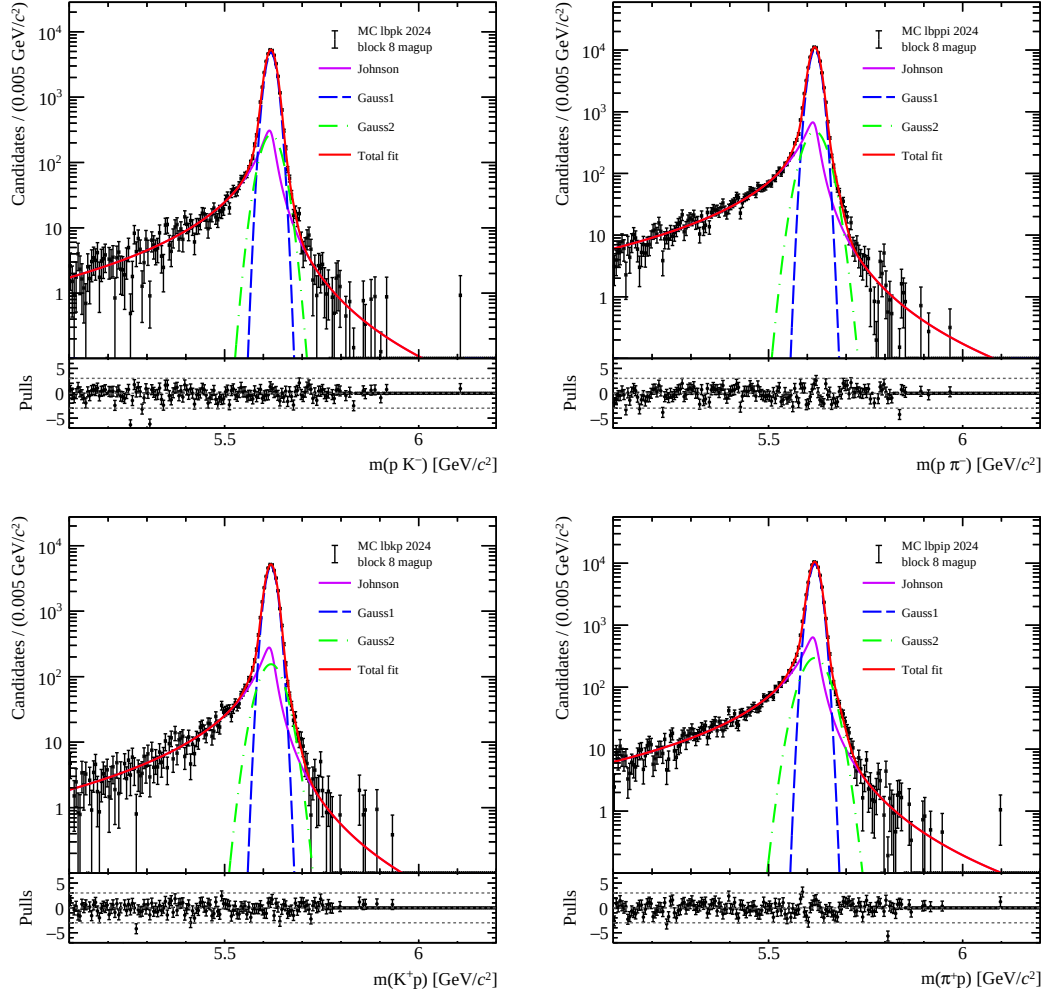


Figure 22: Fits to the invariant-mass distributions of the fully simulated $\Lambda_b^0 \rightarrow pK^-$ (top left), $\Lambda_b^0 \rightarrow p\pi^-$ (top right), $\Lambda_b^0 \rightarrow \bar{p}K^+$ (bottom left), and $\Lambda_b^0 \rightarrow \bar{p}\pi^+$ (bottom right) samples for the MagUp polarity.

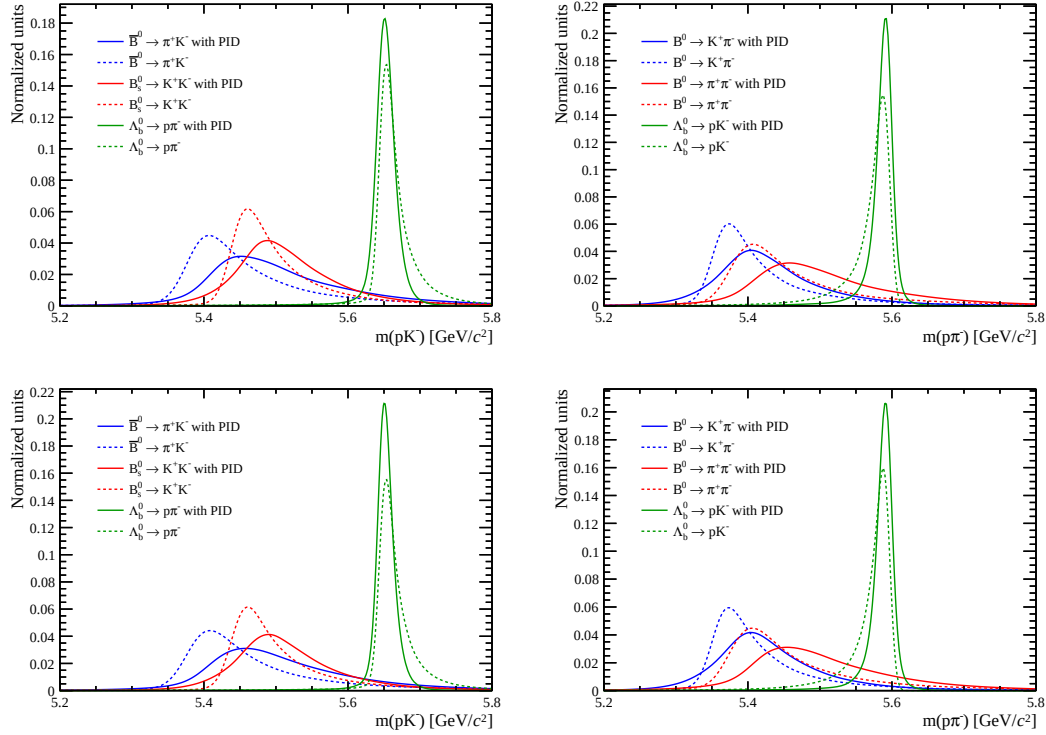


Figure 23: Cross-feed invariant-mass templates for the dominant background contributions reconstructed under the (left) pK^- and (right) $p\pi^-$ mass hypotheses. The upper (lower) row corresponds to the MagDown (MagUp) polarity. The dashed curves are obtained without applying PID-efficiency weights, while the solid curves include the event-by-event PID weighting.

3.3.5 BDT training

As mentioned in Section 3.3.1, a kinematic and geometrical selection based on a BDT is applied to all decay channels to suppress the combinatorial background. The BDT classifier is trained using the XGBoost machine learning library [48].

The signal samples are obtained from fully simulated $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decays. The background sample is extracted from real data by selecting events that satisfy the corresponding PID requirements for the pK^- and $p\pi^-$ final states and have an invariant mass, evaluated under the $\pi^+\pi^-$ hypothesis, larger than $5.6 \text{ GeV}/c^2$. This requirement provides a cleaner sample of combinatorial background. In the pK^- and $p\pi^-$ invariant-mass spectra, cross-feed backgrounds exhibit long tails extending into the right-hand sideband and would therefore contaminate the training sample. When the same events are evaluated under the $\pi^+\pi^-$ mass hypothesis, physical decays are shifted towards the lower-mass region, leaving the right-hand sideband populated predominantly by combinatorial background.

The variables used to train the classifier are:

- the p_T of the H_b candidate;
- the minimum and maximum p_T of the two daughter tracks;
- the IP and its χ^2 with respect to the associated PV of the H_b candidate;
- the natural logarithms of the minimum and maximum IP χ^2 of the two tracks with respect to the PV;
- the natural logarithm of the FD χ^2 of the H_b candidate from the PV;
- the DOCA between the two tracks;
- the natural logarithm of the χ^2/ndf of the H_b decay-vertex fit.

The distributions and correlations of these variables are shown in Figures 24 and 25 for signal and background events.

The available dataset is divided into a training sample, containing 70% of the events, and a validation sample, containing the remaining 30%. To mitigate overfitting, the training uses stochastic subsampling and an early-stopping criterion based on the Area Under the ROC Curve (AUC) evaluated on the validation sample. Figure 26 shows the BDT score distributions for the training and validation samples.

3 DETERMINATION OF ΔA_{CP}

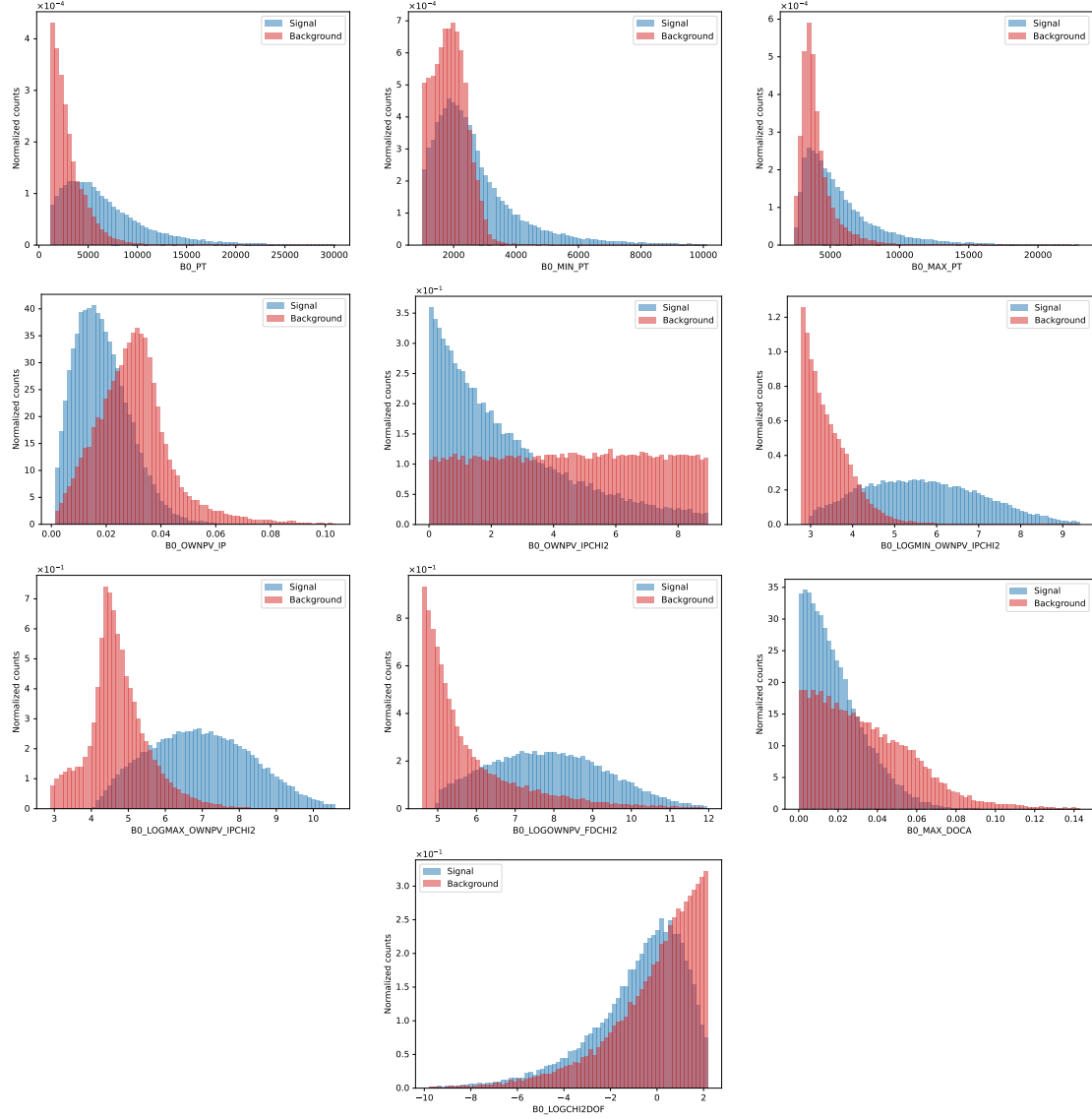


Figure 24: Normalized distributions of the variables used in the BDT training. The signal sample is shown in blue, while the combinatorial background is in red.

3 DETERMINATION OF ΔA_{CP}

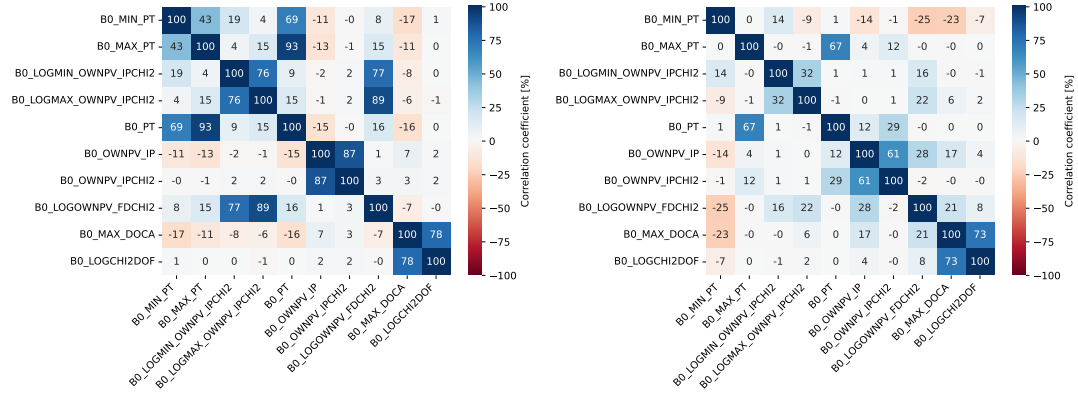


Figure 25: Correlation matrices of the variables used to train the BDT for (left) signal and (right) background samples.

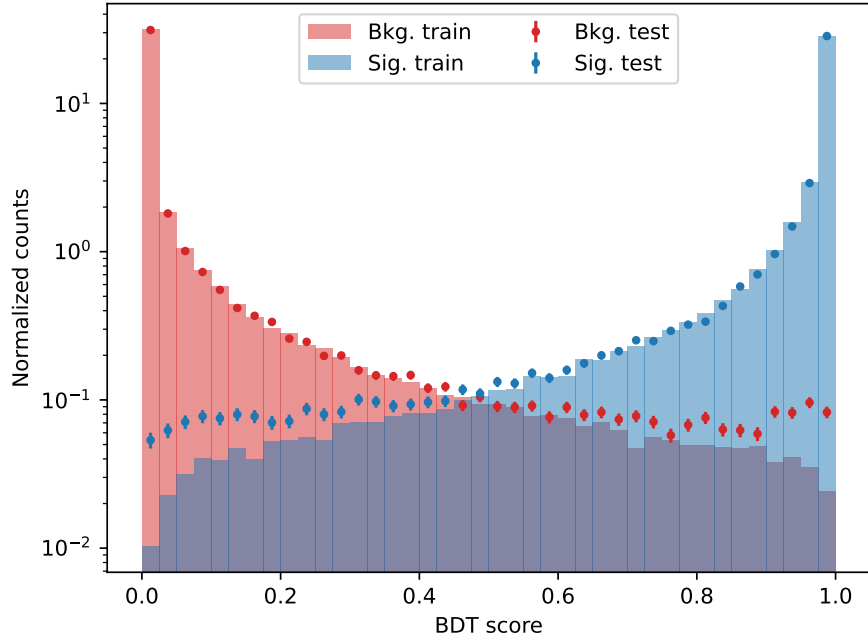


Figure 26: Distributions of the BDT score relative to the (lines) training and (dots) testing samples, divided for (blue) signal and (red) background events.

3.3.6 Simultaneous fit

The final step in the determination of the raw asymmetries is the simultaneous maximum-likelihood fit to the eight mutually exclusive final-state samples introduced previously. The simultaneous approach is particularly important because of the cross-feed background components, which can produce peaks very close to the invariant-mass signal regions of the correctly identified decays. This makes them both difficult to distinguish from the signal and a potentially significant source of bias. In the simultaneous fit, the yields of the cross-feed background due to the decay mode i in the final-state spectrum g (N_i^g) are not left completely free; instead, they are constrained to the yields of the same decay mode in the final-state spectrum f where it is properly identified (N_i^f). The relation is expressed as:

$$N_i^g = N_i^f \frac{\varepsilon_i^g}{\varepsilon_i^f}, \quad (32)$$

where $\varepsilon_i^{g,f}$ are the efficiencies for the decay i to be identified in the final state g or f by the corresponding PID requirements as determined in Section 3.3.1.

For each $H_b \rightarrow h^+ h'^-$ decay mode, the invariant-mass distribution is modeled using the PDF components described in Section 3.3.2. The results of the simultaneous fits are shown in Figures 27 and 28. The measured values of $A_{\text{raw}}(pK^-)$ and $A_{\text{raw}}(p\pi^-)$ for the two magnet polarities are reported in Table 2.

A_{raw} (%)	MagUp	MagDown
pK^-	3.2 ± 1.9	0.2 ± 1.5
$p\pi^-$	-2.8 ± 2.4	1.0 ± 1.8

Table 2: Measured raw asymmetries for the pK^- and $p\pi^-$ final states obtained from the simultaneous fit to the eight final-state samples, separately for the MagUp and MagDown magnet polarities.

3.4 Determination of $A_{\text{det}}(K^- \pi^+)$

One of the main corrections to the raw asymmetry arises from the detection asymmetry $A_{\text{det}}(K^- \pi^+)$. This contribution is determined using large-statistics control samples of $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^+ \rightarrow K_S \pi^+$ decays, hereafter referred to as $K\pi\pi$ and $K_S\pi$, respectively, employing a procedure outlined in Ref. [58]. The raw

3 DETERMINATION OF ΔA_{CP}

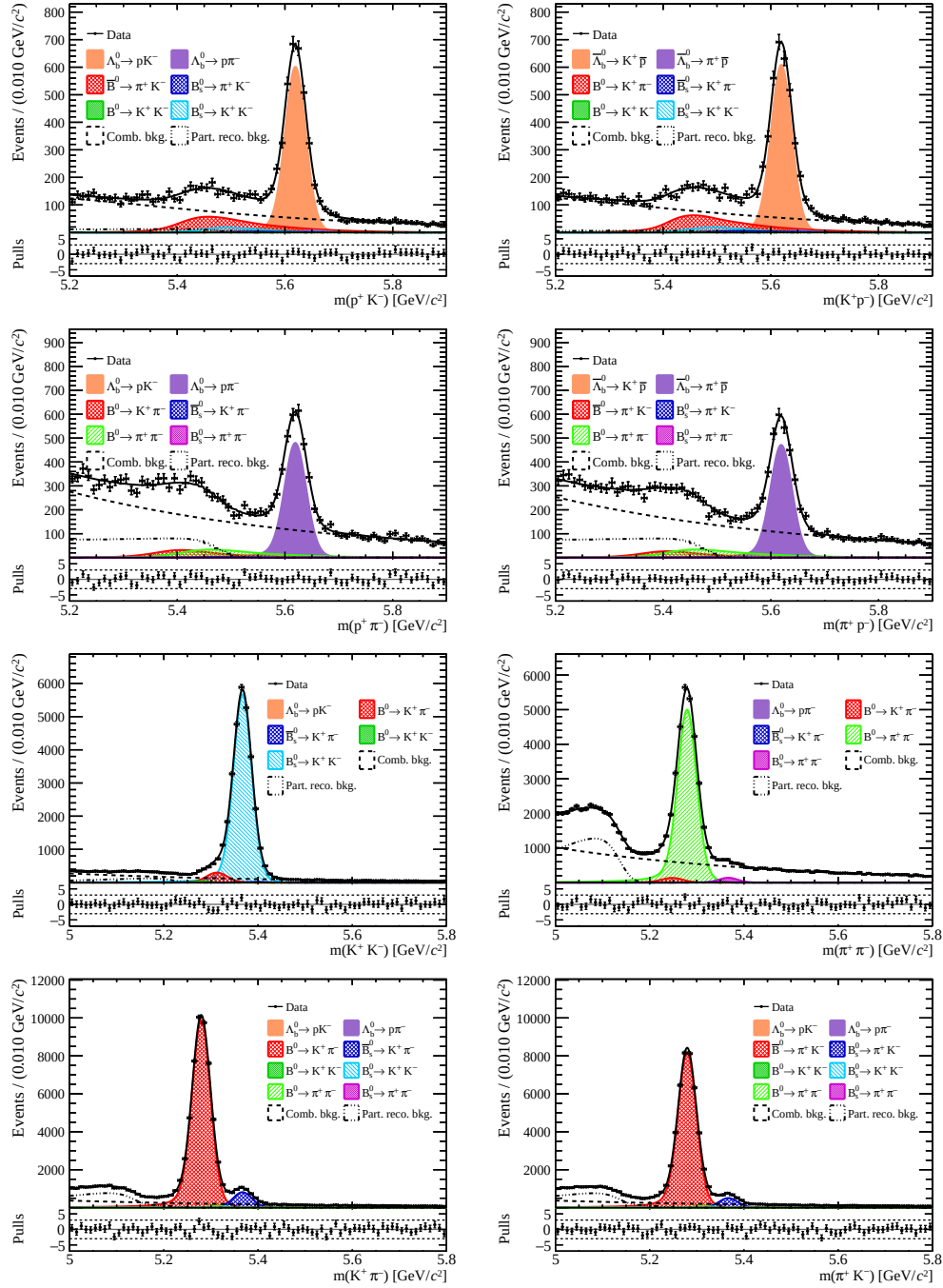


Figure 27: Simultaneous fit to the eight final-state samples for the MagDown polarity. From left to right and top to bottom, the distributions correspond to pK^- , $K^+\bar{p}$, $p\pi^-$, $\pi^+\bar{p}$, K^+K^- , $\pi^+\pi^-$, $K^+\pi^-$, and π^+K^- .

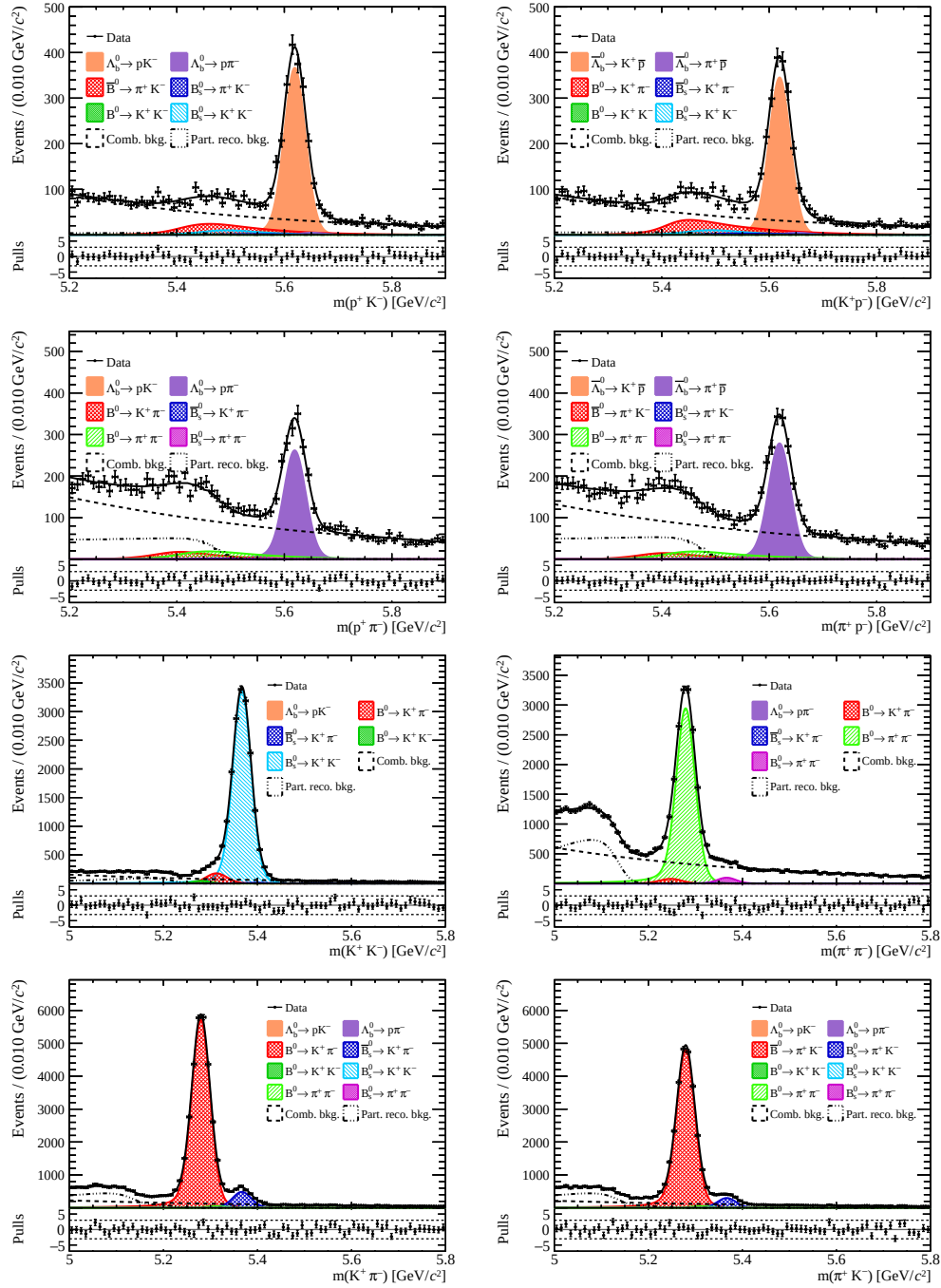


Figure 28: Simultaneous fit to the eight final-state samples for the MagUp polarity. From left to right and top to bottom, the distributions correspond to pK^- , $K^+\bar{p}$, $p\pi^-$, $\pi^+\bar{p}$, K^+K^- , $\pi^+\pi^-$, $K^+\pi^-$, and π^+K^- .

asymmetries of each decay channel can be written as

$$A_{\text{raw}}(K\pi\pi) = A_{\text{det}}(\pi_{\text{trig}}^+) + A_{\text{PID}}(\pi_{\text{trig}}^+) + A_{\text{P}}(D^+) + A_{\text{trig}}(\pi_{\text{trig}}^+) \quad (33)$$

$$+ A_{\text{det}}(K^-\pi^+) + A_{\text{PID}}(K^-\pi^+); \quad (34)$$

$$A_{\text{raw}}(K_S\pi) = A_{\text{det}}(\pi_{\text{trig}}^+) + A_{\text{PID}}(\pi_{\text{trig}}^+) + A_{\text{P}}(D^+) + A_{\text{trig}}(\pi_{\text{trig}}^+) \quad (35)$$

$$+ A_{\text{CP}}(K^0), \quad (36)$$

where π_{trig} denotes the pion that satisfies the trigger requirements used to select the event. In the $K\pi\pi$ channel, if both pions satisfy the trigger requirements, π_{trig} is chosen randomly between them. Since the K_S is a mass eigenstate, approximately given by a linear combination of the flavour eigenstates K^0 and $\bar{K}^0$, the CP asymmetry associated with the neutral-kaon system is conventionally expressed in terms of the underlying K^0 – $\bar{K}^0$ flavour eigenstates and denoted as $A_{CP}(K^0)$.

The basic idea is once again to consider the difference between the raw asymmetries of the two decay channels, yielding

$$\begin{aligned} A_{\text{raw}}(K\pi\pi) - A_{\text{raw}}(K_S\pi) &= A_{\text{det}}(K^-\pi^+) + A_{\text{PID}}(K^-\pi^+) - A_{CP}(K^0) \quad (37) \\ &+ \cancel{A_{\text{det}}(\pi_{\text{trig}}^+)} - \cancel{A_{\text{det}}(\pi_{\text{trig}}^+)} + \cancel{A_{\text{PID}}(\pi_{\text{trig}}^+)} - \cancel{A_{\text{PID}}(\pi_{\text{trig}}^+)} \\ &+ \cancel{A_{\text{P}}(D^+)} - \cancel{A_{\text{P}}(D^+)} + \cancel{A_{\text{trig}}(\pi_{\text{trig}}^+)} - \cancel{A_{\text{trig}}(\pi_{\text{trig}}^+)}. \end{aligned}$$

The cancellation of $A_{\text{det}}(\pi_{\text{trig}}^+)$, $A_{\text{PID}}(\pi_{\text{trig}}^+)$, $A_{\text{P}}(D^+)$, and $A_{\text{trig}}(\pi_{\text{trig}}^+)$ is valid only if the two decay channels have alike kinematic distributions. Since this condition is not satisfied, a reweighting procedure is applied to equalize the kinematic distributions of the two decays. The reweighted samples are then used to determine the raw asymmetries by means of a simultaneous fit to their invariant-mass distributions. The reweighting procedure is described in Section 3.4.1.

The difference between the raw asymmetries is subsequently corrected for the PID asymmetry $A_{\text{PID}}(K^-\pi^+)$, which is determined using a procedure similar to that described in Section 3.3.1. The evaluation of the PID correction is presented in Section 3.4.2. The CP asymmetry in the neutral kaon system is well known to be $A_{CP}(K^0) = (5.1 \pm 0.6) \times 10^{-4}$, as determined in Ref. [59]. The final detection asymmetry results are presented in Section 3.4.3.

3.4.1 Reweighting procedure

First, an empirical fiducial requirement in the (p_T, η) plane of the $D^\pm$ candidate is applied to remove sparsely populated regions of phase space from both decay channels. The corresponding selection criterion (with p_T expressed in GeV/ c) is

$$p_T \leq \min((36.0 - 5.48\eta), 20.0 \tanh(4.0(\eta - 1.8)), 100 - 19.5\eta).$$

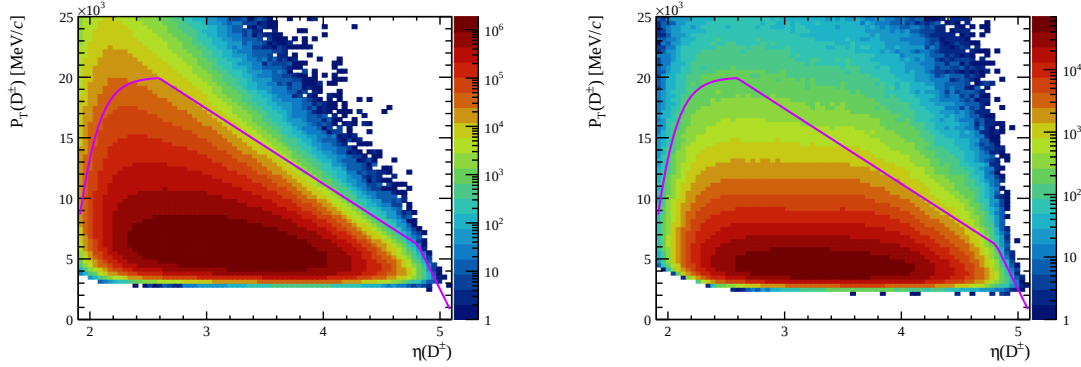


Figure 29: $D^\pm$ candidates p_T versus η distributions for the $K\pi\pi$ (left) and $K_S\pi$ (right) samples. The violet line indicates the boundary of the fiducial region.

The resulting fiducial boundary is superimposed on the (p_T, η) distributions in Figure 29.

The reweighting procedure is designed to equalize the kinematic distributions of the $D^\pm$ and $\pi_{\text{trig}}^\pm$ candidates, since the asymmetries that cancel in Eq. (37) are associated with these particles. As it is very difficult to match all of their kinematic variables simultaneously, only a representative subset is considered. Specifically, the reweighting procedure consists of the following steps:

- four-dimensional reweighting of the background-subtracted (p_T, η) distributions of the $D^\pm$ and $\pi_{\text{trig}}^\pm$ candidates;
- one-dimensional reweighting of the background-subtracted ϕ distribution of the $\pi_{\text{trig}}^\pm$ candidate.

Both steps are performed using the **hep-m1** package [60], implementing a gradient-boosted decision tree algorithm. The background-subtracted distributions are obtained using the sPlot technique [52]. The invariant-mass fits used to determine the sWeights³ for the sPlot procedure are shown in Figures 30 and 31. For the $K_S\pi$ sample, the invariant-mass distribution is adequately described by a PDF consisting of two Gaussian functions and a Johnson S_U function [57] for the signal, together with an exponential function for the combinatorial background. For the $K\pi\pi$ sample, an additional Gaussian component is required to describe the signal, owing to the larger sample size.

As shown in Figure 32, the interaction cross sections of π^+ and π^- are nearly identical over the entire momentum range, whereas those of K^+ and K^- differ

³An sWeight is the statistical weight assigned to each event by the sPlot technique [52]. Conceptually, it quantifies how closely a given event resembles the signal component rather than the background.

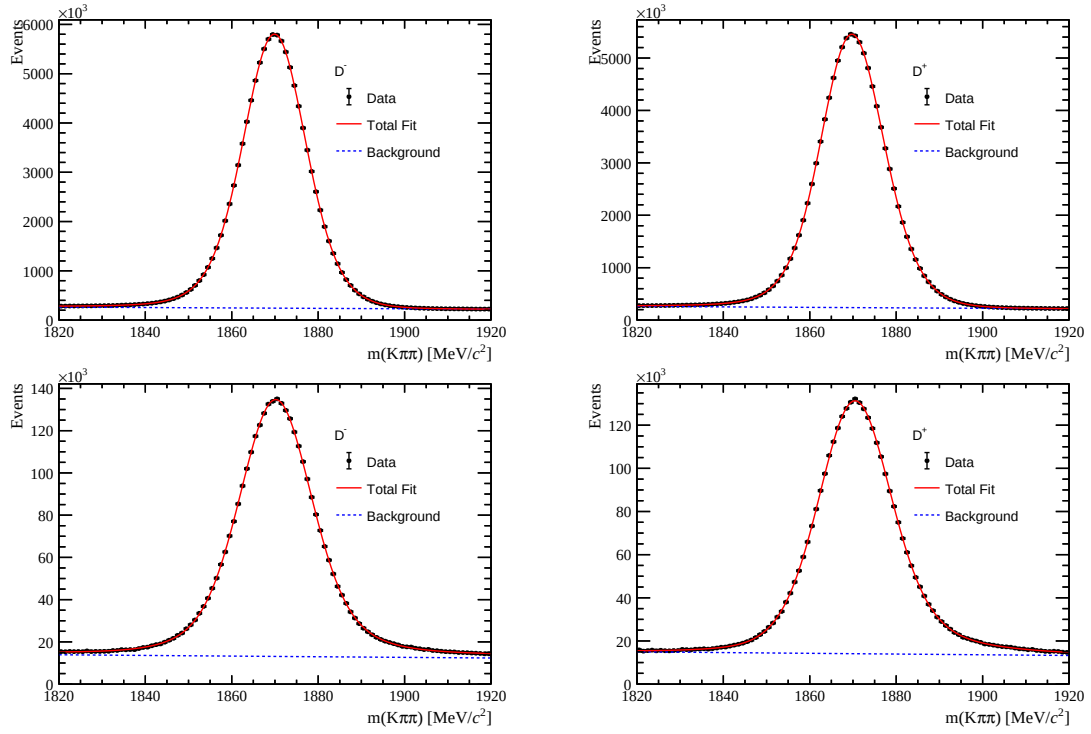


Figure 30: Invariant-mass fits to the $K\pi\pi$ (top row) and $K_S\pi$ (bottom row) MagUp samples used to determine the sWeights for the sPlot procedure. The left and right columns show the fits for the D^- and D^+ candidates, respectively.

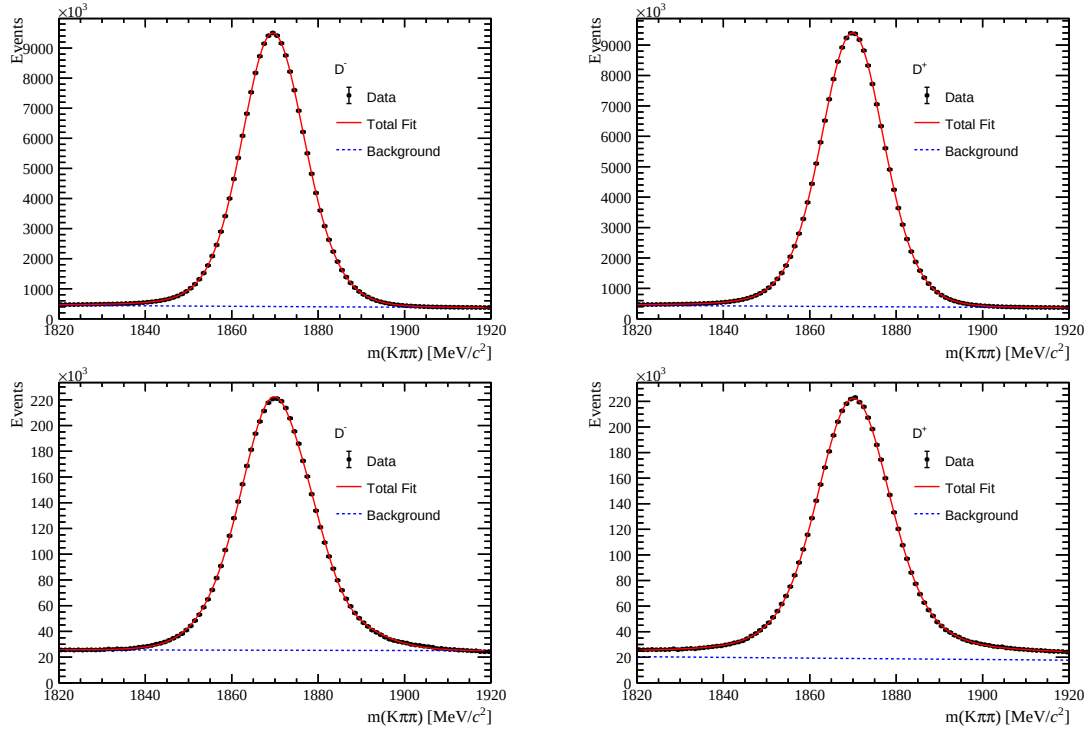


Figure 31: Invariant-mass fits to the $K\pi\pi$ (top row) and $K_S\pi$ (bottom row) Mag-Down samples used to determine the sWeights for the sPlot procedure. The left and right columns show the fits for the D^- and D^+ candidates, respectively.

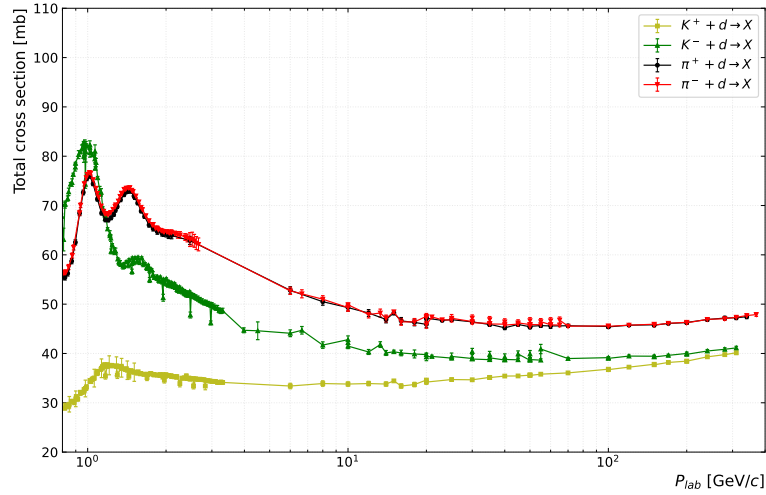


Figure 32: Total interaction cross section of charged pions and kaons impacting on a deuterium target. Data from Ref. [35].

significantly and exhibit a strong momentum dependence. Since the detection asymmetry originates from the difference between the interaction cross sections of particles and antiparticles, $A_{\text{det}}(K^-\pi^+)$ mainly depends on the kaon momentum. Therefore, the asymmetry measured in the control sample can be directly used to correct the signal sample only if the kaon momentum distributions in the two samples are sufficiently similar, which is not the case here. The control-sample asymmetry must therefore be determined in bins of kaon momentum and subsequently weighted according to the kaon momentum distribution observed in the signal sample. To this end, the $K\pi\pi$ sample is divided into eleven bins of kaon momentum, and the detection asymmetry is determined independently in each bin. The resulting measurements are subsequently combined into a single value, as described in Section 3.4.3, to obtain the correction used in the determination of ΔA_{CP} . The binning scheme, reported in Table 3, is chosen such that each bin contains approximately the same number of events.

	Kaon momentum (GeV/ c)
Bin 1	2–7.8
Bin 2	7.8–10.3
Bin 3	10.3–12.6
Bin 4	12.6–15
Bin 5	15–17.7
Bin 6	17.7–20.8
Bin 7	20.8–24.4
Bin 8	24.4–29
Bin 9	29–35.3
Bin 10	35.3–45.5
Bin 11	45.5–100

Table 3: Kaon momentum binning choice for $K\pi\pi$ sample.

For each kaon-momentum bin, the entire $K_S\pi$ sample is reweighted to match the corresponding $K\pi\pi$ subsample. Bin-dependent fiducial requirements are applied to ensure that the reweighting is performed only in regions of phase space populated by both decay channels. These requirements are reported in Appendix B.1.

Since the same $K_S\pi$ sample is reused for every $K\pi\pi$ bin, the resulting bin-by-bin measurements of the detection asymmetry are statistically correlated. The correlation coefficient between bins i and j is given by

$$\rho_{ij} = \frac{\sum_k \sum_l (w_k w_l)}{\sqrt{\sum_k w_k^2 \sum_l w_l^2}}; \quad (38)$$

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where $w_{k,l}$ are the kinematic weights and the indices k and l run over the $K_S\pi$ candidates weighted for kaon-momentum bins i and j , respectively. The resulting correlation matrices are shown in Figure 33. The block-like structure observed in the matrices reflects the fact that the bin-dependent fiducial requirements do not vary continuously with the kaon momentum.

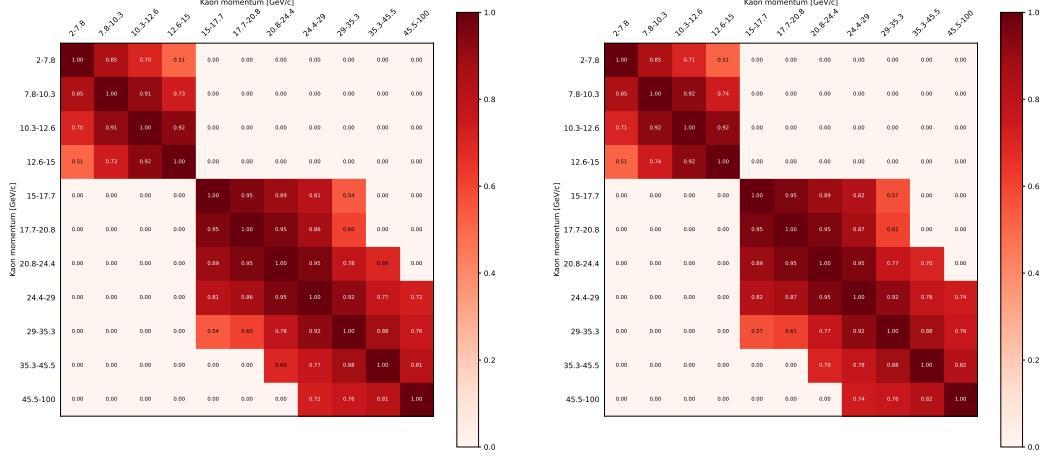


Figure 33: Correlation matrices of the $K_S\pi$ event weights used for the different kaon-momentum-bin reweightings, for the MagDown (left) and MagUp (right) samples.

Examples of the reweighting performances are shown in Figures 34 and 35. The remaining reweighting-performances plots are reported in Appendix B.2.

Finally, a simultaneous fit is performed independently in each kaon-momentum bin to the invariant-mass distributions of the $K\pi\pi$ and reweighted $K_S\pi$ samples in order to determine the corresponding raw asymmetries. The kinematic weights obtained from the reweighting procedure are applied to the $K_S\pi$ sample. The signal component is modeled by the sum of a Gaussian function and a one-sided Crystal Ball function, the latter describing the low-mass tail produced by final-state radiation, while the combinatorial background is modeled by an exponential function. The fit results for the first kaon-momentum bin are shown in Figures 36 and 37. The corresponding fits for the remaining bins are reported in Appendix B.3. The measured values of $A_{\text{raw}}(K\pi\pi)$ and $A_{\text{raw}}(K_S\pi)$ in all kaon-momentum bins are reported in Tables 4 and 5.

3.4.2 PID asymmetry correction

From Eq. (37), the determination of $A_{\text{det}}(K^-\pi^+)$ requires correcting the difference of raw asymmetries for the contributions from $A_{\text{PID}}(K^-\pi^+)$ and the known CP

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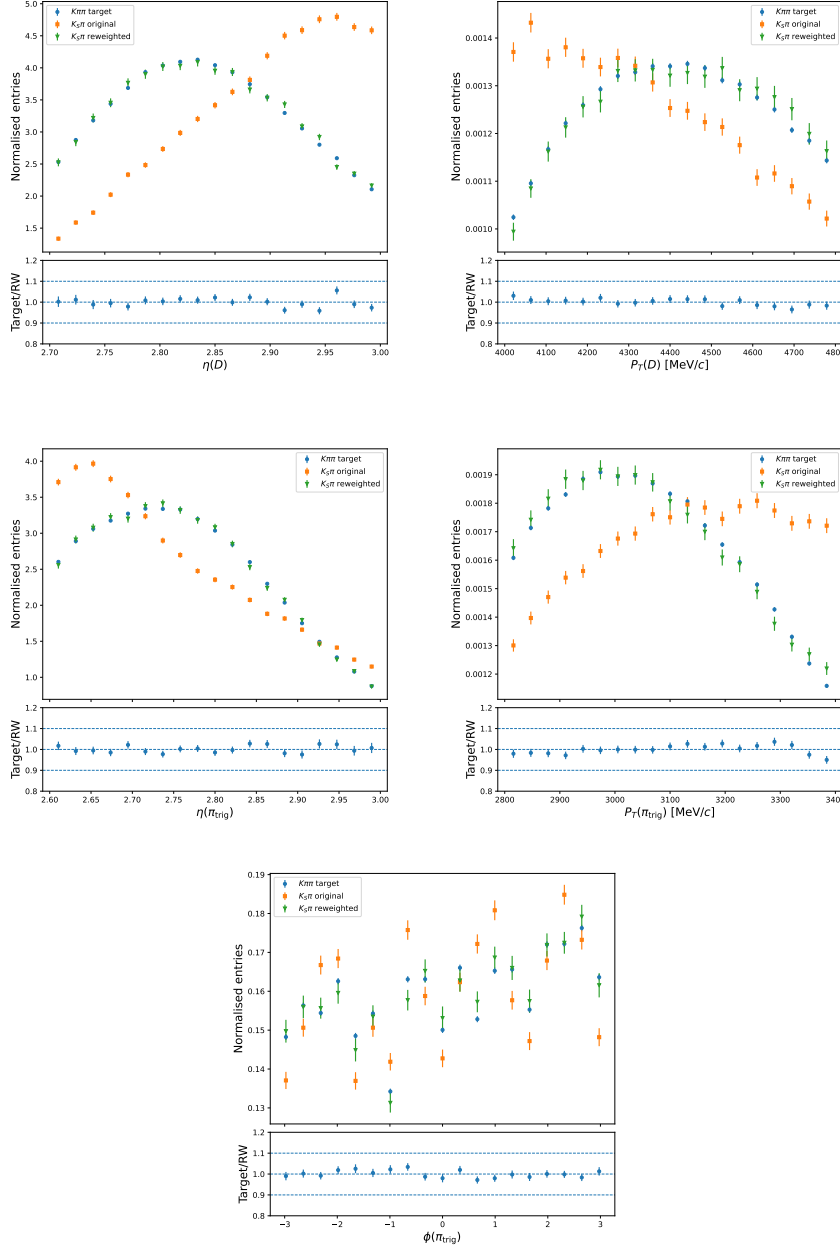


Figure 34: Reweighting performances for the first kaon-momentum bin MagDown. The lower panel of each plot shows the ratio between the target and the reweighted distributions. The upper two plots correspond to the reweighted $D^\pm$ variables, while the lower three correspond to the $\pi_{\text{trig}}^\pm$ variables.

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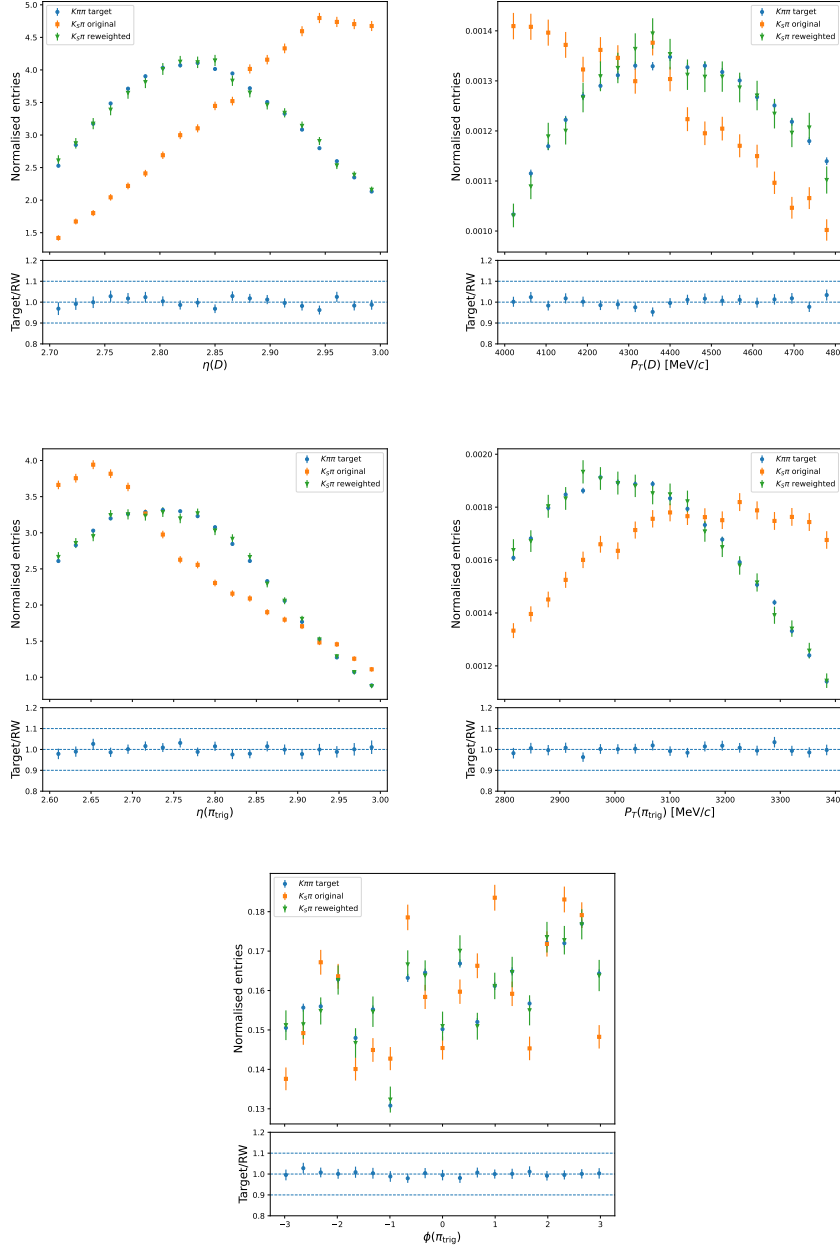


Figure 35: Reweighting performances for the first kaon-momentum bin MagUp. The lower panel of each plot shows the ratio between the target and the reweighted distributions. The upper two plots correspond to the reweighted $D^\pm$ variables, while the lower three correspond to the $\pi^\pm_{\text{trig}}$ variables.

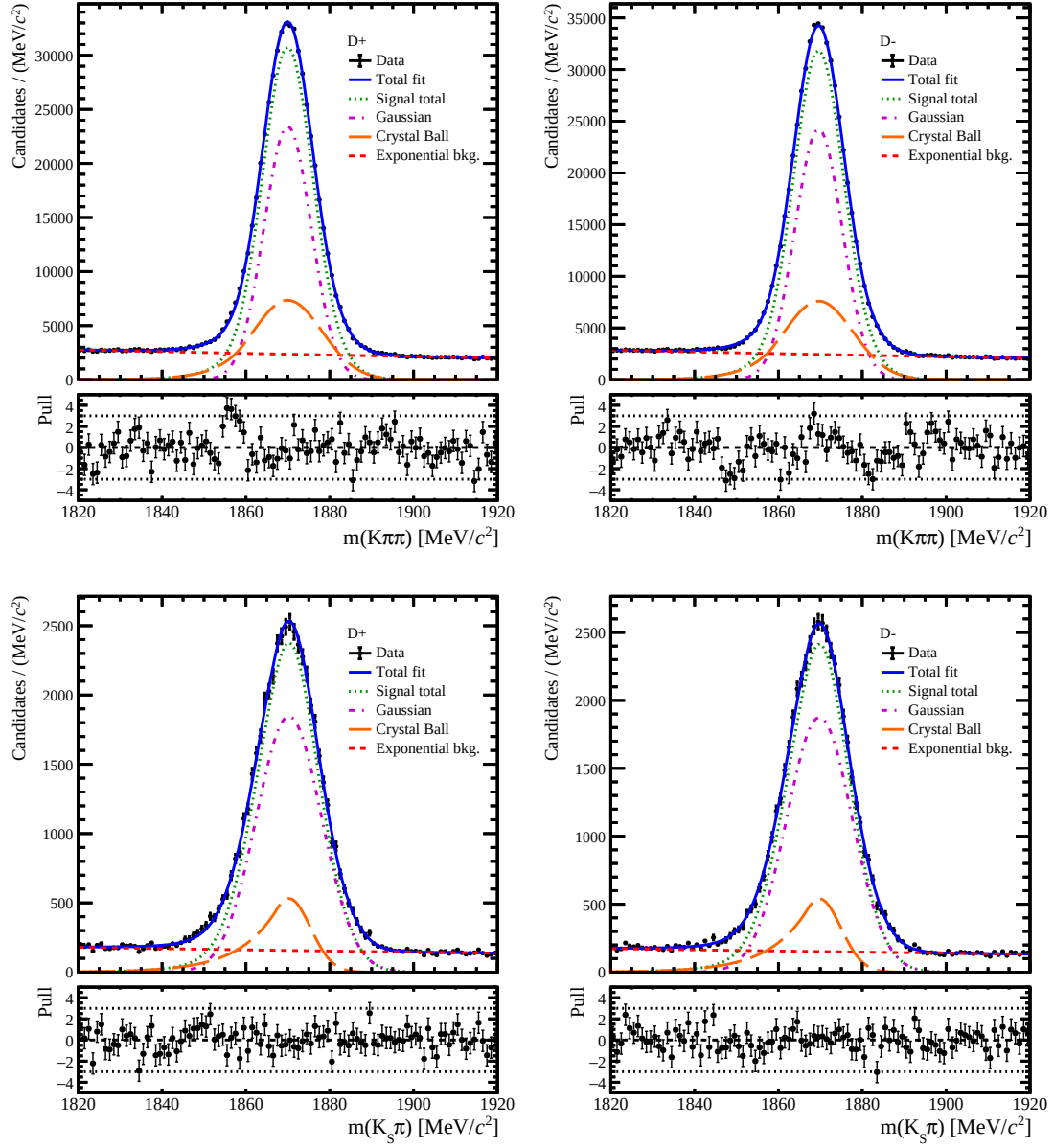


Figure 36: Simultaneous fit to the $K\pi\pi$ (upper row) and reweighted $K_S\pi$ (lower row) samples in the first kaon-momentum bin for the MagDown polarity. The left and right columns show the fits for the D^+ and D^- candidates, respectively.

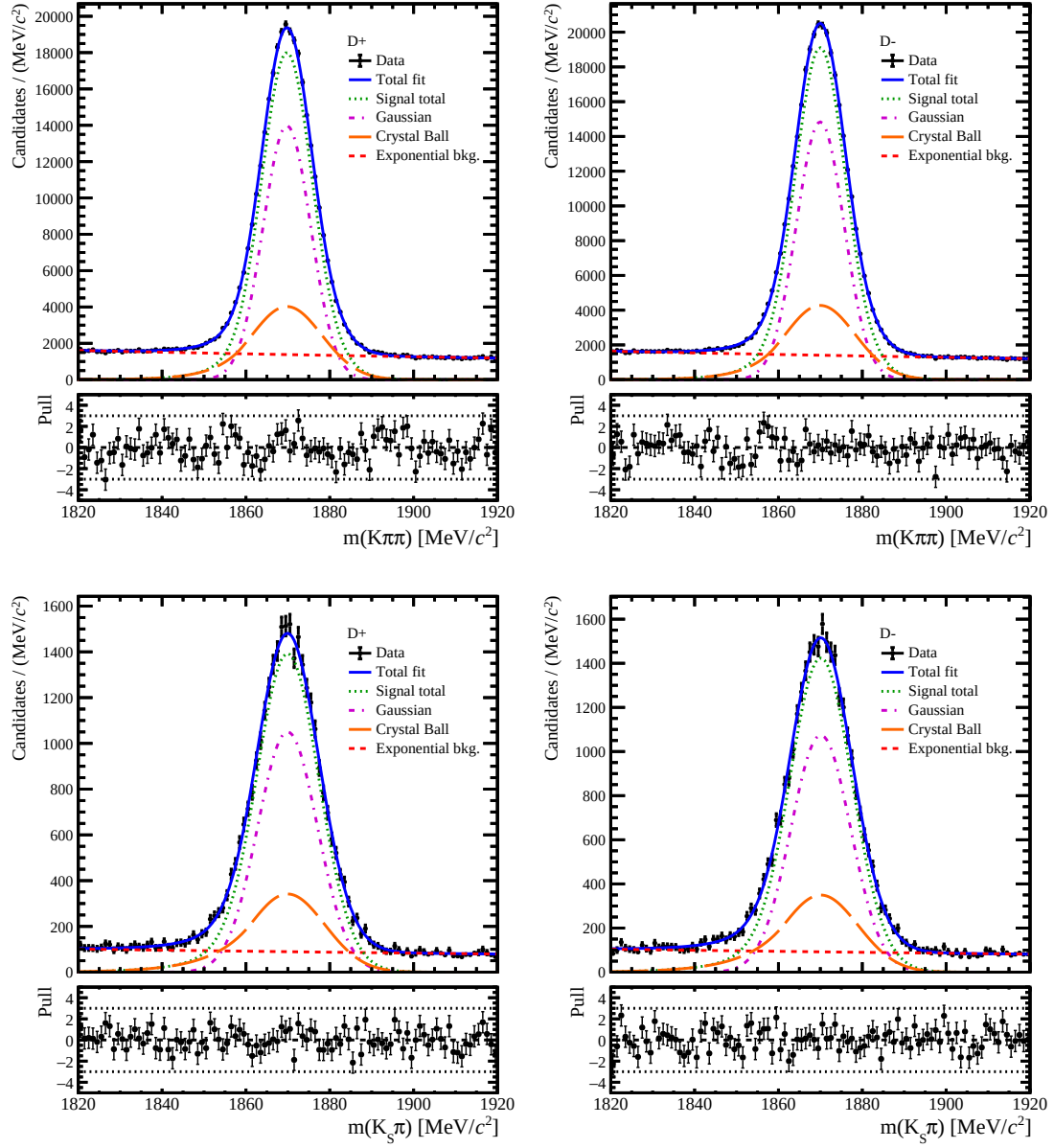


Figure 37: Simultaneous fit to the $K\pi\pi$ (upper row) and reweighted $K_S\pi$ (lower row) samples in the first kaon-momentum bin for the MagUp polarity. The left and right columns show the fits for the D^+ and D^- candidates, respectively.

Kaon momentum (GeV/c)	$A_{\text{raw}}(K\pi\pi)$ (%)	$A_{\text{raw}}^R(K_S\pi)$ (%)	$A_{\text{raw}}^{NR}(K_S\pi)$ (%)
2–7.8	-1.7 ± 0.1	-0.8 ± 0.4	-0.7 ± 0.3
7.8–10.3	-1.4 ± 0.1	-0.5 ± 0.5	-0.7 ± 0.3
10.3–12.6	-0.8 ± 0.1	-0.5 ± 0.5	-0.8 ± 0.3
12.6–15	-0.8 ± 0.2	-0.5 ± 0.5	-0.6 ± 0.3
15–17.7	-0.7 ± 0.1	-0.3 ± 0.4	-0.3 ± 0.3
17.7–20.8	-0.6 ± 0.1	-0.5 ± 0.4	-0.5 ± 0.3
20.8–24.4	-1.0 ± 0.1	-0.5 ± 0.4	-0.5 ± 0.3
24.4–29	-1.1 ± 0.1	-0.7 ± 0.5	-0.6 ± 0.3
29–35.3	-1.4 ± 0.1	-0.5 ± 0.6	-0.6 ± 0.3
35.3–45.5	-1.7 ± 0.2	-0.8 ± 0.7	-0.5 ± 0.5
45.5–100	-1.7 ± 0.1	-0.2 ± 0.9	-0.1 ± 0.5

Table 4: Raw asymmetries $A_{\text{raw}}(K\pi\pi)$, $A_{\text{raw}}(K_S\pi)$ determined in each kaon-momentum bin for the MagDown sample. $A_{\text{raw}}^R(K_S\pi)$ and $A_{\text{raw}}^{NR}(K_S\pi)$ denote the asymmetries obtained after and before the kinematic reweighting, respectively.

Kaon momentum (GeV/c)	$A_{\text{raw}}(K\pi\pi)$ (%)	$A_{\text{raw}}^R(K_S\pi)$ (%)	$A_{\text{raw}}^{NR}(K_S\pi)$ (%)
2–7.8	-3.0 ± 0.1	-1.1 ± 0.5	-0.8 ± 0.4
7.8–10.3	-3.3 ± 0.2	-1.2 ± 0.6	-0.8 ± 0.4
10.3–12.6	-3.0 ± 0.2	-0.2 ± 0.6	-0.6 ± 0.4
12.6–15	-3.3 ± 0.2	-0.7 ± 0.7	-0.9 ± 0.4
15–17.7	-2.9 ± 0.2	-1.3 ± 0.5	-1.7 ± 0.3
17.7–20.8	-2.8 ± 0.2	-1.2 ± 0.6	-1.4 ± 0.4
20.8–24.4	-2.4 ± 0.2	-1.1 ± 0.6	-1.4 ± 0.4
24.4–29	-2.0 ± 0.2	-1.8 ± 0.6	-1.4 ± 0.4
29–35.3	-2.3 ± 0.2	-1.7 ± 0.7	-1.4 ± 0.4
35.3–45.5	-2.9 ± 0.2	-0.8 ± 1.0	-0.1 ± 0.6
45.5–100	-1.8 ± 0.2	0.5 ± 1.1	-1.0 ± 0.7

Table 5: Raw asymmetries $A_{\text{raw}}(K\pi\pi)$, $A_{\text{raw}}(K_S\pi)$ determined in each kaon-momentum bin for the MagUp sample. $A_{\text{raw}}^R(K_S\pi)$ and $A_{\text{raw}}^{NR}(K_S\pi)$ denote the asymmetries obtained after and before the kinematic reweighting, respectively.

asymmetry of the neutral kaon system, $A_{CP}(K^0)$. The PID correction is determined by constructing three-dimensional PID-efficiency maps following the procedure described in Section 3.3.1. In this case, the PID requirements used to distinguish kaons from pions are

- Kaon: $\Delta \log(\mathcal{L}_{K-\pi}) > 5$;
- Pion: $\Delta \log(\mathcal{L}_{K-\pi}) < 5$.

Since the quantity of interest is now an asymmetry, separate PID-efficiency maps are constructed for particles and antiparticles (or equivalently positively and negatively charged particles). As in Section 3.3.1, the detector-occupancy dimension is integrated out, resulting in two-dimensional (p, η) efficiency maps. This step is necessary because the three-dimensional maps exhibit sparsely populated bins in low-occupancy regions, leading to non-physical PID efficiencies (i.e. $\varepsilon_{\text{PID}} < 0$ or $\varepsilon_{\text{PID}} > 1$). These values arise from the use of sWeights, which are used to subtract the background and can take negative values or values larger than unity. By integrating over the occupancy dimension, information from neighbouring occupancy bins with the same (p, η) coordinates compensates for these statistical fluctuations, yielding physically meaningful efficiency values.

From the two-dimensional efficiency maps, the corresponding PID-asymmetry maps are obtained according to

$$A_{\text{PID}}^i(h^+) = \frac{\varepsilon_{\text{PID}}^i(h^+) - \varepsilon_{\text{PID}}^i(h^-)}{\varepsilon_{\text{PID}}^i(h^+) + \varepsilon_{\text{PID}}^i(h^-)}, \quad (39)$$

where i denotes the (p, η) bin and $h = K, \pi$. Each event in the $K\pi\pi$ sample is then assigned two PID asymmetries, one corresponding to the kaon and one to the pion, according to the appropriate bin of the asymmetry maps. Assuming that the PID efficiencies of the two final-state particles are independent, the PID asymmetry of the two-body final state can be approximated as the sum of the individual particle asymmetries. Finally, the PID asymmetry is evaluated independently in each kaon-momentum bin by computing the sWeighted average

$$A_{\text{PID}}(K^-\pi^+) = \frac{\sum_{i=1}^N w^i A_{\text{PID}}^i(K^-\pi^+)}{\sum_{i=1}^N w^i} = \frac{\sum_{i=1}^N w^i [A_{\text{PID}}^i(K^-) + A_{\text{PID}}^i(\pi^+)]}{\sum_{i=1}^N w^i}; \quad (40)$$

where w^i is the sWeight associated with event i , and the sum extends over all events in the corresponding kaon-momentum bin. The resulting PID asymmetries are shown in Figure 38, while their numerical values are reported in Table 6.

Kaon momentum (GeV/c)	$A_{PID}(K^-\pi^+)$ (%) MagDown	$A_{PID}(K^-\pi^+)$ (%) MagUp
2–7.8	0.0740 ± 0.0006	-0.2533 ± 0.0006
7.8–10.3	-0.0207 ± 0.0005	-0.1678 ± 0.0006
10.3–12.6	0.0037 ± 0.0003	-0.1011 ± 0.0003
12.6–15	-0.0315 ± 0.0002	-0.0651 ± 0.0002
15–17.7	-0.0357 ± 0.0002	-0.0649 ± 0.0002
17.7–20.8	-0.0489 ± 0.0002	-0.0464 ± 0.0002
20.8–24.4	-0.0407 ± 0.0002	-0.0317 ± 0.0002
24.4–29	-0.0423 ± 0.0002	-0.0486 ± 0.0002
29–35.3	-0.0573 ± 0.0002	-0.0416 ± 0.0002
35.3–45.5	-0.0478 ± 0.0002	-0.0826 ± 0.0003
45.5–100	-0.1029 ± 0.0003	-0.1242 ± 0.0003

Table 6: PID asymmetry corrections $A_{PID}(K^-\pi^+)$ determined in each kaon-momentum bin for the MagDown and MagUp samples.

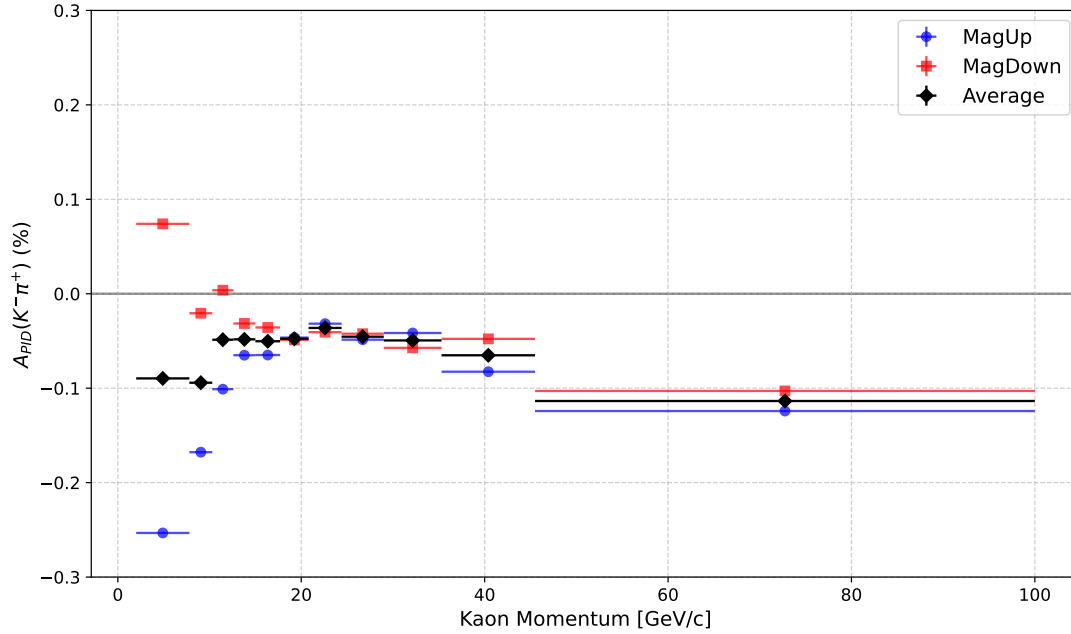


Figure 38: PID asymmetry correction $A_{PID}(K^-\pi^+)$ as a function of the kaon momentum. The horizontal error bars indicate the widths of the kaon-momentum bins and do not represent uncertainties on the measured values.

3.4.3 Detection asymmetry results

The final step in the determination of $A_{\text{det}}(K^-\pi^+)$ is the combination of the previously derived results. From Eq. (37), the detection asymmetry is given by

$$A_{\text{det}}(K^-\pi^+) = A_{\text{raw}}(K\pi\pi) - A_{\text{raw}}(K_S\pi) - A_{\text{PID}}(K^-\pi^+) + A_{\text{CP}}(K^0). \quad (41)$$

The resulting detection asymmetries in each kaon-momentum bin are reported in Table 7 and shown graphically in Figure 39.

Kaon momentum (GeV/c)	$A_{\text{det}}(K^-\pi^+)$ (%) MagDown	$A_{\text{det}}(K^-\pi^+)$ (%) MagUp
2–7.8	-0.9 ± 0.4	-1.5 ± 0.5
7.8–10.3	-0.8 ± 0.5	-1.9 ± 0.6
10.3–12.6	-0.3 ± 0.5	-2.7 ± 0.6
12.6–15	-0.2 ± 0.6	-2.5 ± 0.7
15–17.7	-0.4 ± 0.4	-1.5 ± 0.5
17.7–20.8	0.0 ± 0.5	-1.5 ± 0.6
20.8–24.4	-0.4 ± 0.5	-1.2 ± 0.6
24.4–29	-0.3 ± 0.5	-0.1 ± 0.6
29–35.3	-0.8 ± 0.6	-0.4 ± 0.7
35.3–45.5	-0.8 ± 0.8	-2.0 ± 1.0
45.5–100	-1.4 ± 0.9	-2.1 ± 1.2

Table 7: Detection asymmetry $A_{\text{det}}(K^-\pi^+)$ determined in each kaon-momentum bin for the MagDown and MagUp samples.

To obtain the value of $A_{\text{det}}(K^-\pi^+)$ used in the determination of ΔA_{CP} , each event in the $\Lambda_b^0 \rightarrow pK^-$ and $\bar{\Lambda}_b^0 \rightarrow \bar{p}K^+$ samples is assigned the detection asymmetry corresponding to its kaon-momentum bin. The overall correction is then obtained by computing the sWeighted average

$$A_{\text{det}}(K^-\pi^+) = \frac{\sum_{i=1}^N w^i A_{\text{det}}^i(K^-\pi^+)}{\sum_{i=1}^N w^i}, \quad (42)$$

where the sum extends over all $\Lambda_b^0 \rightarrow pK^-$ and $\bar{\Lambda}_b^0 \rightarrow \bar{p}K^+$ candidates, and w^i is the sWeight associated with event i . The resulting values are:

$$\begin{aligned} A_{\text{det}}^{\text{MagUp}}(K^-\pi^+) &= (-1.6 \pm 0.4)\%; \\ A_{\text{det}}^{\text{MagDown}}(K^-\pi^+) &= (-0.8 \pm 0.3)\%. \end{aligned}$$

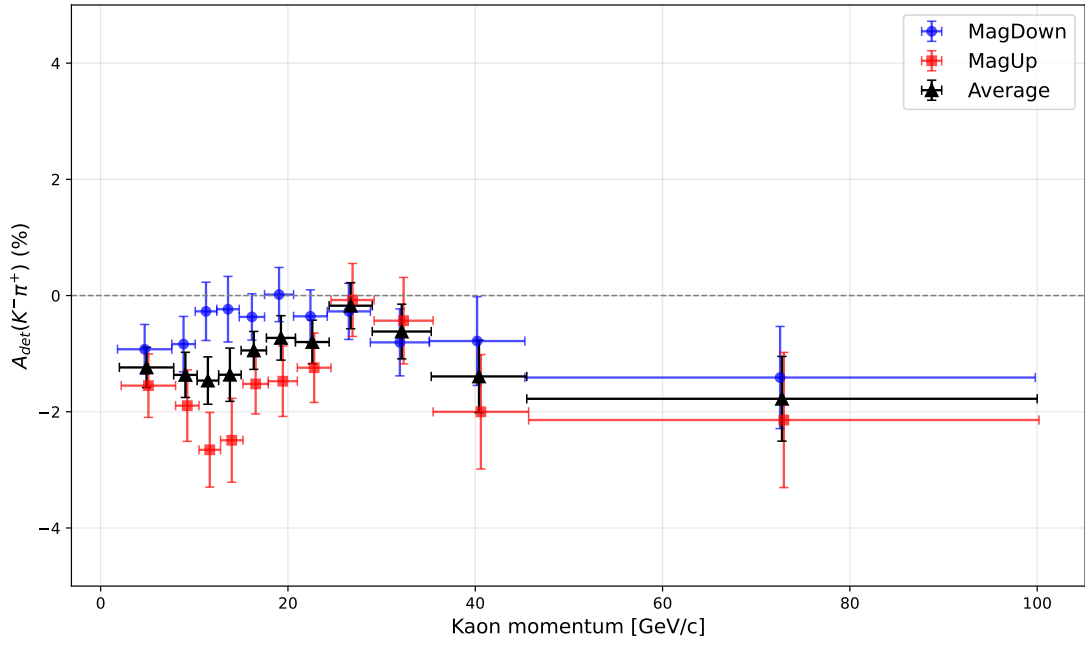


Figure 39: Detection asymmetry $A_{\text{det}}(K^-\pi^+)$ as a function of the kaon momentum. The horizontal error bars indicate the widths of the kaon-momentum bins and do not represent uncertainties on the measured values.

3.5 Particle identification asymmetries

$A_{\text{PID}}(pK^-)$ and $A_{\text{PID}}(p\pi^-)$ are determined using a procedure analogous to those described in Sections 3.3.1 and 3.4.2. Three-dimensional (p, η, Θ) PID-efficiency maps are first constructed separately for particles and antiparticles as the ratio between the number of calibration events passing the PID requirements and the total number of calibration events. The PID requirements, together with the fiducial and BDT selections, are identical to those introduced in Section 3.3.1. From these efficiency maps, three-dimensional PID-asymmetry maps are derived for pions, kaons, and protons. Two-dimensional projections of the resulting asymmetry maps are shown in Figure 40 for illustration.

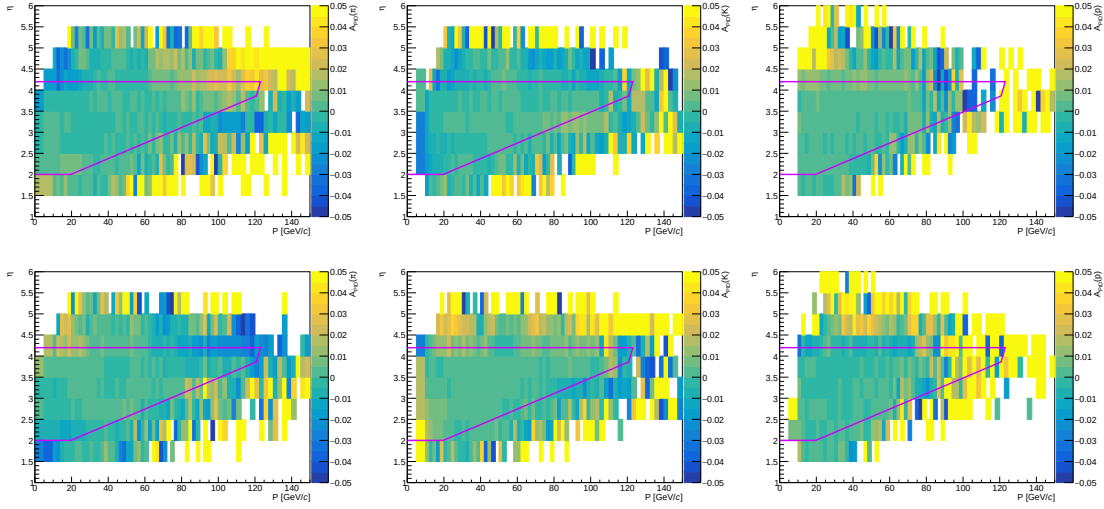


Figure 40: Two-dimensional (p, η) projections of the three-dimensional PID-asymmetry maps for the MagDown (top row) and MagUp (bottom row) samples. From left to right the maps show $A_{\text{PID}}(\pi)$, $A_{\text{PID}}(K)$ and $A_{\text{PID}}(p)$. The violet line indicates the boundary of the fiducial region.

Each event in the $\Lambda_b^0 \rightarrow pK^-$, $\Lambda_b^0 \rightarrow p\pi^-$, $\bar{\Lambda}_b^0 \rightarrow \bar{p}K^+$, and $\bar{\Lambda}_b^0 \rightarrow \bar{p}\pi^+$ samples is assigned two PID asymmetries, one corresponding to the proton and one to the accompanying meson, according to the appropriate bin of the PID-asymmetry maps. The overall PID asymmetries for the two signal channels are then obtained by computing the sWeighted averages

$$A_{\text{PID}}(pK^-) = \frac{\sum_{i=1}^N w^i A_{\text{PID}}^i(pK^-)}{\sum_{i=1}^N w^i} = \frac{\sum_{i=1}^N w^i [A_{\text{PID}}^i(p) + A_{\text{PID}}^i(K^-)]}{\sum_{i=1}^N w^i}; \quad (43)$$

$$A_{\text{PID}}(p\pi^-) = \frac{\sum_{i=1}^N w^i A_{\text{PID}}^i(p\pi^-)}{\sum_{i=1}^N w^i} = \frac{\sum_{i=1}^N w^i [A_{\text{PID}}^i(p) + A_{\text{PID}}^i(\pi^-)]}{\sum_{i=1}^N w^i}; \quad (44)$$

where w^i is the sWeight associated with event i , and the sum extends over all candidates in the corresponding $\Lambda_b^0/\bar{\Lambda}_b^0$ decay sample. The resulting values of $A_{\text{PID}}(pK^-)$ and $A_{\text{PID}}(p\pi^-)$ are reported in Table 8.

A_{PID} (%)	MagUp	MagDown
pK^-	-0.2 ± 0.1	0.2 ± 0.2
$p\pi^-$	0.3 ± 0.2	0.1 ± 0.1

Table 8: Measured PID asymmetries for the pK^- and $p\pi^-$ final states, separately for the MagUp and MagDown magnet polarities.

3.6 Trigger asymmetries

The final corrections to be determined are the trigger asymmetries $A_{\text{trig}}(pK^-)$ and $A_{\text{trig}}(p\pi^-)$, which arise from the HLT1 trigger requirements described in Section 3.2. These asymmetries are measured using the following semileptonic control channels:

- $\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK^-\pi^+)\mu^-\bar{\nu}_\mu X$ for protons;
- $B^0 \rightarrow D^0(\rightarrow K^+\pi^-)\mu^-\bar{\nu}_\mu X$ for kaons and pions.

The semileptonic events are selected by requiring the muon to satisfy the HLT1 trigger requirements. In this way, the selection is independent of the hadronic final-state particles, providing an unbiased sample for measuring their trigger efficiencies.

First, the combinatorial background is removed using a sideband subtraction. This approach is suitable given the high purity of the samples and the approximately flat invariant-mass distributions away from the signal peak. A signal region is defined around the signal peak, together with two sideband regions on either side of it, each with half the width of the signal region. The background contribution is then estimated from the sum of the events in the two sidebands and subtracted from the signal region. The signal regions are defined as windows of width 15 and 25 MeV/ c^2 centered around 2286 and 1865 MeV/ c^2 for Λ_c^+ and D^0 , respectively, while the two sidebands regions have half the size each and are centered around 2247.5 and 2327.5 MeV/ c^2 for Λ_c^+ and 1827.5 and 1902.5 MeV/ c^2 for D^0 . The invariant-mass distributions of the semileptonic control channels are shown in Figure 41.

The HLT1 trigger-efficiency maps are then constructed from the background-subtracted data, separately for particles and antiparticles as the ratio between

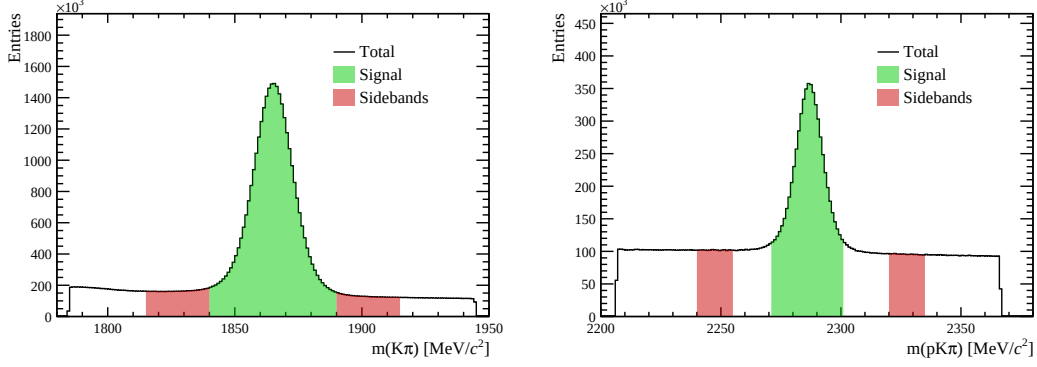


Figure 41: Invariant-mass distribution of the semileptonic samples $B^0 \rightarrow D^0(\rightarrow K^+\pi^-)\mu^-\bar{\nu}_\mu X$ (left) and $\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK^-\pi^+)\mu^-\bar{\nu}_\mu X$ (right).

the number of events in which both the hadron and the muon satisfy the trigger requirements and the number of events in which only the muon satisfies them. The efficiency maps are two-dimensional, depending on the transverse momentum p_T and the logarithm of χ_{IP}^2 , which are the discriminating variables used by the `Hlt1TrackMVA` trigger line, employed in this analysis, to make a selection. In particular here it is evaluated the asymmetry related to the `Hlt1TrackMVA_TOS` trigger requirement, that could have an affirmative decision due to any of the two oppositely charge particles of the signal candidates. While the HLT2 trigger stage is not expected to give any asymmetry, since it applies a selection after full decay chain reconstruction and its requirements do not discriminate between positively and negatively charged particles.

The binning scheme used to build the trigger-efficiency maps is the following:

- p_T bin edges (in GeV/c): 0, 1.65, 1.8, 1.92, 2.04, 2.16, 2.28, 2.52, 2.76, 2.88, 3.24, 3.6, 4.08, 4.68, 6, 12;
- $\log(\chi_{IP}^2)$ bin edges: 2, 3.5, 4, 4.5, 4.9, 5.3, 5.6, 5.9, 6.1, 6.4, 6.7, 7, 7.3, 7.6, 8, 8.6, 12.

This choice has been taken from a similar analysis outlined in Refs. [50, 51]. The resulting efficiency maps are shown in Figures 42 and 43.

Each event in the $\Lambda_b^0 \rightarrow pK^-$, $\Lambda_b^0 \rightarrow p\pi^-$, $\bar{\Lambda}_b^0 \rightarrow \bar{p}K^+$, and $\bar{\Lambda}_b^0 \rightarrow \bar{p}\pi^+$ samples is assigned four trigger efficiencies: one for the proton (ε_p), one for the antiproton ($\varepsilon_{\bar{p}}$), one for the meson (ε_{h^-}), and one for the antimeson (ε_{h^+}). These values, extracted from the corresponding efficiency maps, are then combined to calculate

3 DETERMINATION OF ΔA_{CP}

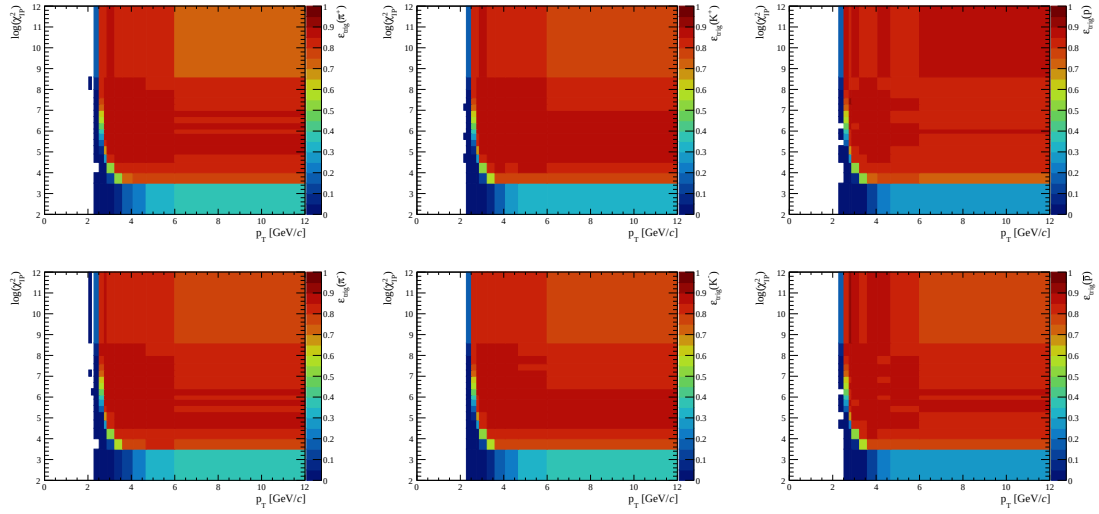


Figure 42: Two-dimensional $(p_T, \log(\chi_{IP}^2))$ HLT1 trigger-efficiency maps for the MagDown sample. The top row shows positive charged particles maps, while the bottom row negative ones. From left to right there are the maps for pions, kaons and protons.

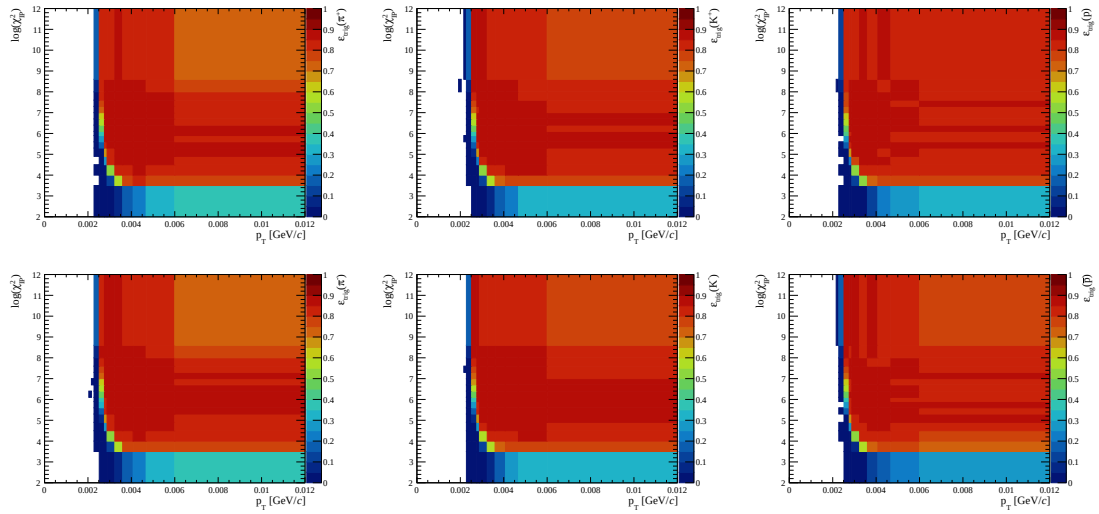


Figure 43: Two-dimensional $(p_T, \log(\chi_{IP}^2))$ HLT1 trigger-efficiency maps for the MagUp sample. The top row shows positive charged particles maps, while the bottom row negative ones. From left to right there are the maps for pions, kaons and protons.

the Λ_b^0 and $\bar{\Lambda}_b^0$ trigger efficiencies:

$$\varepsilon_{\Lambda_b^0} = \varepsilon_p(1 - \varepsilon_{h-}) + (1 - \varepsilon_p)\varepsilon_{h-} + \varepsilon_p\varepsilon_{h-} \quad (45)$$

$$\varepsilon_{\bar{\Lambda}_b^0} = \varepsilon_{\bar{p}}(1 - \varepsilon_{h+}) + (1 - \varepsilon_{\bar{p}})\varepsilon_{h+} + \varepsilon_{\bar{p}}\varepsilon_{h+}; \quad (46)$$

where $h = \pi/K$. The above expressions account for the probability that at least one of the two final-state particles satisfies the HLT1 trigger requirements.

Finally, the trigger asymmetry is computed for each event, and the overall trigger asymmetry is obtained by performing an sWeighted average over all candidates in the corresponding $\Lambda_b^0/\bar{\Lambda}_b^0 \rightarrow pK^-/\bar{p}K^+$ or $\Lambda_b^0/\bar{\Lambda}_b^0 \rightarrow p\pi^-/\bar{p}\pi^+$ sample:

$$A_{\text{trig}}(ph^-) = \frac{\sum_{i=1}^N w^i A_{\text{trig}}^i(ph^-)}{\sum_{i=1}^N w^i} \quad \text{where} \quad A_{\text{trig}}^i(ph^-) = \frac{\varepsilon_{\Lambda_b^0}^i - \varepsilon_{\bar{\Lambda}_b^0}^i}{\varepsilon_{\Lambda_b^0}^i + \varepsilon_{\bar{\Lambda}_b^0}^i}. \quad (47)$$

The resulting values of $A_{\text{trig}}(pK^-)$ and $A_{\text{trig}}(p\pi^-)$ are reported in Table 9.

A_{trig} (%)	MagUp	MagDown
pK^-	0.2 ± 0.1	0.0 ± 0.1
$p\pi^-$	0.1 ± 0.1	0.1 ± 0.1

Table 9: Measured HLT1 trigger asymmetries for the pK^- and $p\pi^-$ final states, separately for the MagUp and MagDown magnet polarities.

3.7 ΔA_{CP} cancellations check

The ΔA_{CP} technique introduced in Section 3.1 relies on the cancellation of $A_{\text{det}}(p)$ and $A_{\text{prod}}(\Lambda_b^0)$ in the difference between the two CP asymmetries. These cancellations, in turn, require the relevant kinematic distributions of the two decay modes to be sufficiently similar.

To assess this assumption, the normalized and background-subtracted distributions of the proton and Λ_b^0 kinematic variables p , p_T , η , and ϕ are compared between the $\Lambda_b^0/\bar{\Lambda}_b^0 \rightarrow pK^-/\bar{p}K^+$ and $\Lambda_b^0/\bar{\Lambda}_b^0 \rightarrow p\pi^-/\bar{p}\pi^+$ decay modes. Background subtraction is performed using the sPlot technique [52], employing the results of the simultaneous fit described in Section 3.3.6. The resulting comparisons are shown in Figures 44 and 45.

3.8 Results

The values of the raw asymmetries and of all correction terms entering the determination of ΔA_{CP} are summarized in Table 10. Unless otherwise stated, all

3 DETERMINATION OF ΔA_{CP}

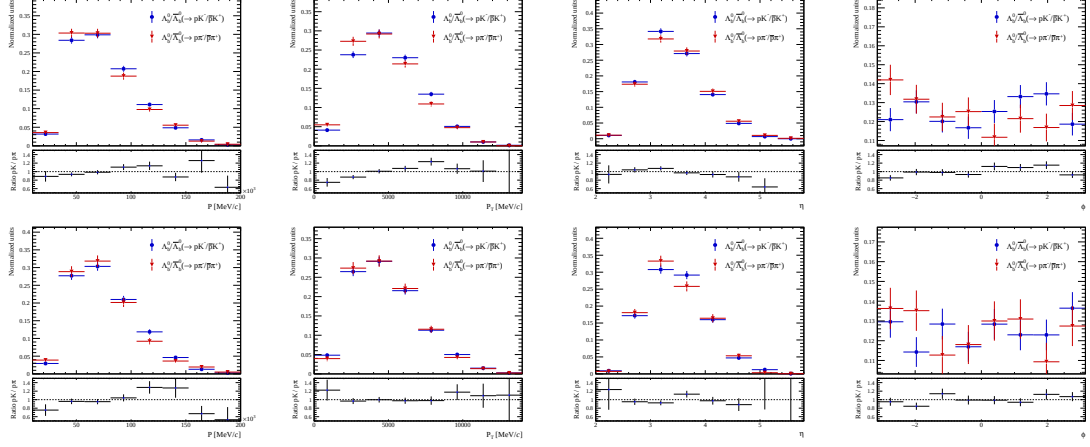


Figure 44: Comparison of the p , p_T , η and ϕ normalized distributions (from left to right) of $\Lambda_b^0/\bar{\Lambda}_b^0$ candidates reconstructed in the decay modes under investigation. The top and bottom rows correspond to the MagDown and MagUp samples, respectively.

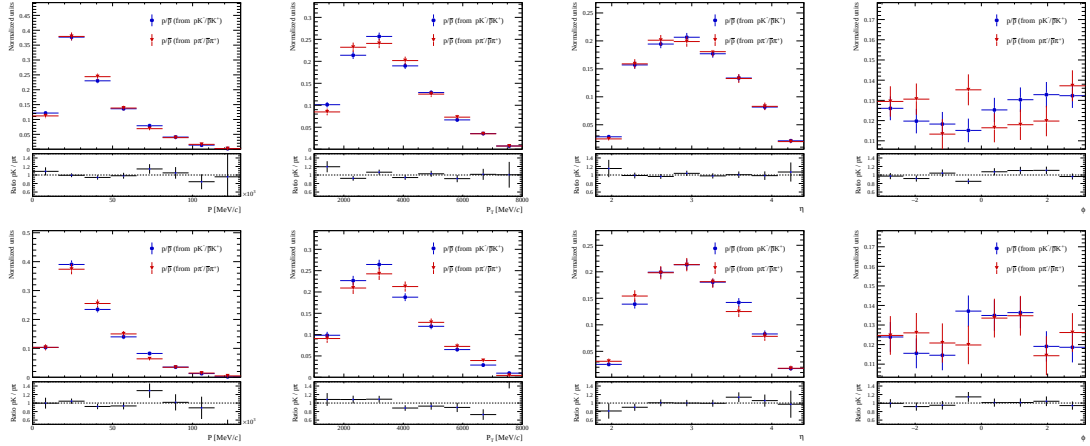


Figure 45: Comparison of the p , p_T , η and ϕ normalized distributions (from left to right) of $p/\bar{p}$ candidates reconstructed in the decay modes under investigation. The top and bottom rows correspond to the MagDown and MagUp samples, respectively.

Asymmetry	MagUp	MagDown
$A_{\text{raw}}(pK^-)$	3.2 ± 1.9	0.2 ± 1.5
$A_{\text{raw}}(p\pi^-)$	-2.8 ± 2.4	1.0 ± 1.8
$A_{\text{det}}(K^- \pi^+)$	-1.6 ± 0.4	0.8 ± 0.3
$A_{\text{PID}}(pK^-)$	-0.2 ± 0.1	0.2 ± 0.2
$A_{\text{PID}}(p\pi^-)$	0.3 ± 0.2	0.1 ± 0.1
$A_{\text{trig}}(pK^-)$	0.2 ± 0.1	0.0 ± 0.1
$A_{\text{trig}}(p\pi^-)$	0.1 ± 0.1	0.1 ± 0.1

Table 10: Measured raw asymmetries and correction terms entering the determination of ΔA_{CP} for the MagUp and MagDown samples. All values are given in percent.

quoted uncertainties in this chapter are statistical only. Using Eq. (23), the corresponding values of ΔA_{CP} are obtained separately for the two magnet polarities. The results, together with their weighted average, are:

$$\begin{aligned}\Delta A_{CP}^{\text{MagUp}} &= (7.9 \pm 3.1 \pm 0.9)\%, \\ \Delta A_{CP}^{\text{MagDown}} &= (-0.7 \pm 2.4 \pm 0.4)\%, \\ \Delta A_{CP}^{\text{Avg}} &= (2.4 \pm 1.9 \pm 0.4)\%,\end{aligned}$$

where the first uncertainty arises from the raw asymmetry measurements, and the second from the detection, PID, and trigger corrections.

The measurements obtained with the two magnet polarities are consistent within 2.1σ and the weighted average is compatible with zero within 1.2σ . No evidence of CP violation is found. This result is also compatible within 1.7σ with the most recent previous measurements from Refs. [50, 51].

Conclusions

The search for new sources of CP violation remains one of the central goals of contemporary particle physics, as it may provide insights into physics beyond the Standard Model and help explain the observed matter–antimatter asymmetry of the Universe. Beauty-hadron decays constitute an excellent laboratory for such studies, offering a unique opportunity to perform precise tests of the Standard Model predictions.

The goal of this thesis is to investigate CP violation in the $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decay modes using 1.5 fb^{-1} of data collected by the LHCb experiment during Run 3. To this end, the difference between the CP asymmetries of the two decay modes, ΔA_{CP} , is measured. By measuring this difference rather than the individual CP asymmetries, several nuisance asymmetries cancel out, as the Λ_b^0 production and the proton detection asymmetries. Nevertheless, as shown in Eq. 23, determining ΔA_{CP} still requires to account for the remaining correction terms. The analysis is performed separately for the two magnet polarities, MagUp and MagDown, and the resulting ΔA_{CP} measurements are subsequently averaged to suppress any residual magnet-induced asymmetries.

The first step of the analysis is determining the raw asymmetries, $A_{\text{raw}}(pK^-)$ and $A_{\text{raw}}(p\pi^-)$. Following the necessary data-selection procedures, these are extracted via a simultaneous fit to the invariant-mass distributions of eight mutually exclusive final-state samples.

Next, the detection asymmetry $A_{\text{det}}(K^-\pi^+)$ is evaluated using $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^+ \rightarrow K_S\pi^+$ control samples. This measurement relies on the difference between the raw asymmetries of these two modes, allowing the detection asymmetry to be isolated according to Eq. 41. A kinematic reweighting is first applied to ensure compatible kinematic distributions between the samples in order to cancel spurious asymmetries. The raw asymmetries are then extracted via a simultaneous fit, and their difference is corrected for residual PID and CP asymmetries.

The PID asymmetries, $A_{\text{PID}}(ph^-)$ where $h \in \{\pi, K\}$, are subsequently evaluated through a data-driven method using high-purity calibration samples of $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ decays for pions and kaons, and of $\Lambda^0 \rightarrow p\pi^-$ decays for protons.

Finally, the trigger asymmetries $A_{\text{trig}}(ph^-)$ are determined using dedicated semileptonic control samples: $\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK^-\pi^+)\mu^-\bar{\nu}_\mu X$ for protons, and $B^0 \rightarrow D^0(\rightarrow K^+\pi^-)\mu^-\bar{\nu}_\mu X$ for kaons and pions. By combining these corrections, the physical CP contribution is obtained from the measured raw asymmetries. The

resulting values of ΔA_{CP} are:

$$\begin{aligned}\Delta A_{CP}^{\text{MagUp}} &= (-7.9 \pm 3.1 \pm 0.9)\%, \\ \Delta A_{CP}^{\text{MagDown}} &= (-0.7 \pm 2.4 \pm 0.4)\%, \\ \Delta A_{CP}^{\text{Avg}} &= (-2.4 \pm 1.9 \pm 0.4)\%,\end{aligned}$$

where both uncertainties are statistical, the first associated with the raw asymmetry measurements and the second with the detection, PID, and trigger correction terms.

The MagUp and MagDown results are compatible within 2.1 standard deviations (σ), while the averaged result is consistent with zero within 1.2σ . Therefore, no evidence for CP violation is observed in the analyzed dataset. It should be noted, however, that a measurement of ΔA_{CP} alone cannot exclude the scenario in which the individual CP asymmetries are both non-zero but possess similar magnitudes.

This work presents the first measurement of the CP-asymmetry difference between the $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decay modes using LHCb Run 3 data. The result is consistent within 1.7σ with the most recent previous measurement from Ref. [50, 51], which extracted the individual CP asymmetries by analysing the full LHCb Run 1 and Run 2 dataset.

The analysis presented in this thesis can be further developed through a comprehensive study of the systematic uncertainties associated with the techniques described in Chapter 3. Furthermore, the measurement could be extended to the individual CP asymmetries by determining the Λ_b^0 production asymmetry and the proton detection asymmetry. Such a measurement would also benefit from the full Run 3 dataset, providing a substantial increase in statistical power and thus improving the sensitivity to CP violation in these baryonic decay modes.

Appendix

A Signal fit plots for the Λ_b^0 raw asymmetries

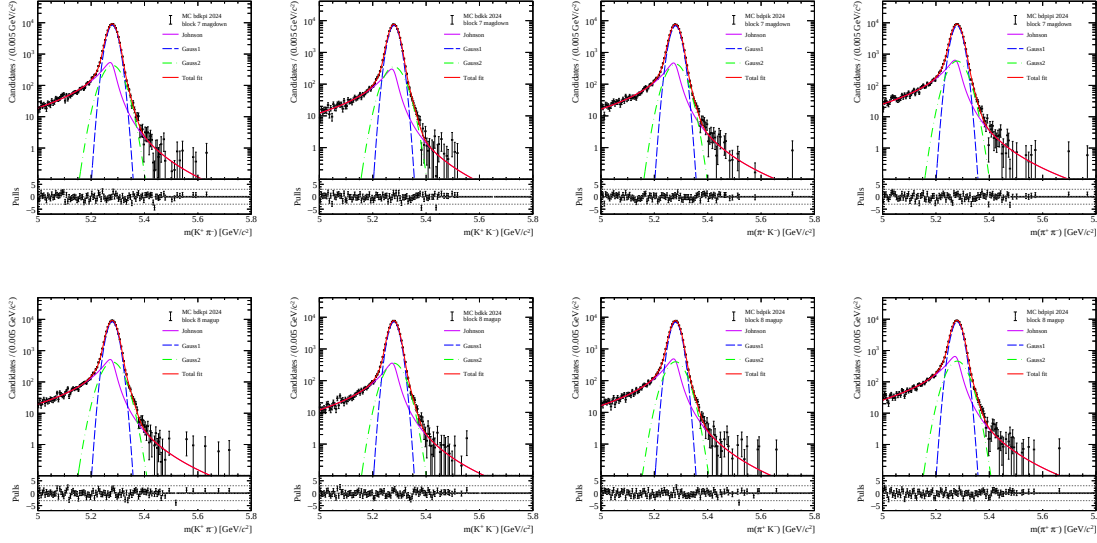


Figure 46: Fits to the invariant-mass distributions of the fully simulated $B^0 \rightarrow K^+\pi^-$ (first column), $B^0/\bar{B}^0 \rightarrow K^+K^-$ (second column), $\bar{B}^0 \rightarrow \pi^+K^-$ (third column), and $B^0/\bar{B}^0 \rightarrow \pi^+\pi^-$ (fourth column) samples. The top row shows the MagDown polarity, while the bottom row shows the MagUp polarity.

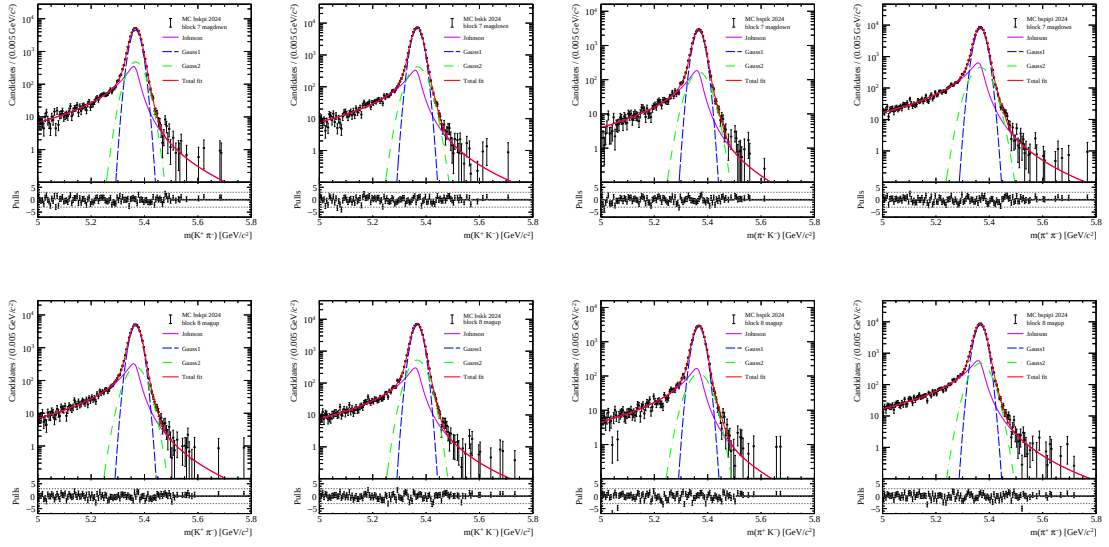


Figure 47: Fits to the invariant-mass distributions of the fully simulated $\bar{B}_s^0 \rightarrow K^+\pi^-$ (first column), $B_s^0/\bar{B}_s^0 \rightarrow K^+K^-$ (second column), $B_s^0 \rightarrow \pi^+K^-$ (third column), and $B_s^0/\bar{B}_s^0 \rightarrow \pi^+\pi^-$ (fourth column) samples. The top row shows the MagDown polarity, while the bottom row shows the MagUp polarity.

B Additional material for $A_{\text{det}}(K^-\pi^+)$

B.1 Bin-specific requirements for the reweighting procedure

For completeness, Table 11 reports the bin-specific requirements applied to the $K\pi\pi$ and $K_S\pi$ samples in the reweighting procedure. These requirements were defined separately for each bin to ensure a successful reweighting.

Bin number	Requirement
1	$[4000 < p_T(D^\pm) < 4800] \cup [2800 < p_T(\pi_{\text{trig}}^\pm) < 3400] \cup [2.7 < \eta(D^\pm) < 3] \cup [2.6 < \eta(\pi_{\text{trig}}^\pm) < 3]$
2	$[4000 < p_T(D^\pm) < 4800] \cup [2800 < p_T(\pi_{\text{trig}}^\pm) < 3400] \cup [2.7 < \eta(D^\pm) < 3] \cup [2.6 < \eta(\pi_{\text{trig}}^\pm) < 3]$
3	$[4000 < p_T(D^\pm) < 4800] \cup [2800 < p_T(\pi_{\text{trig}}^\pm) < 3400] \cup [2.8 < \eta(D^\pm) < 3.1] \cup [2.6 < \eta(\pi_{\text{trig}}^\pm) < 3]$
4	$[4000 < p_T(D^\pm) < 4800] \cup [2700 < p_T(\pi_{\text{trig}}^\pm) < 3300] \cup [2.8 < \eta(D^\pm) < 3.1] \cup [2.6 < \eta(\pi_{\text{trig}}^\pm) < 3]$
5	$[4000 < p_T(D^\pm) < 4800] \cup [2700 < p_T(\pi_{\text{trig}}^\pm) < 3300] \cup [3.1 < \eta(D^\pm) < 3.6] \cup [3 < \eta(\pi_{\text{trig}}^\pm) < 3.5]$
6	$[4000 < p_T(D^\pm) < 4800] \cup [2700 < p_T(\pi_{\text{trig}}^\pm) < 3300] \cup [3.2 < \eta(D^\pm) < 3.6] \cup [3.1 < \eta(\pi_{\text{trig}}^\pm) < 3.6]$
7	$[4200 < p_T(D^\pm) < 5000] \cup [2700 < p_T(\pi_{\text{trig}}^\pm) < 3300] \cup [3.3 < \eta(D^\pm) < 3.7] \cup [3.1 < \eta(\pi_{\text{trig}}^\pm) < 3.6]$
8	$[4300 < p_T(D^\pm) < 5100] \cup [2700 < p_T(\pi_{\text{trig}}^\pm) < 3300] \cup [3.4 < \eta(D^\pm) < 3.8] \cup [3.2 < \eta(\pi_{\text{trig}}^\pm) < 3.7]$
9	$[4300 < p_T(D^\pm) < 5100] \cup [2700 < p_T(\pi_{\text{trig}}^\pm) < 3300] \cup [3.4 < \eta(D^\pm) < 3.8] \cup [3.2 < \eta(\pi_{\text{trig}}^\pm) < 3.7]$
10	$[4500 < p_T(D^\pm) < 5200] \cup [2700 < p_T(\pi_{\text{trig}}^\pm) < 3300] \cup [3.6 < \eta(D^\pm) < 3.9] \cup [3.4 < \eta(\pi_{\text{trig}}^\pm) < 3.9]$
11	$[5000 < p_T(D^\pm) < 6000] \cup [2800 < p_T(\pi_{\text{trig}}^\pm) < 3500] \cup [3.7 < \eta(D^\pm) < 4] \cup [3.5 < \eta(\pi_{\text{trig}}^\pm) < 3.9]$

Table 11: Bin-specific requirements applied to the $K\pi\pi$ and $K_S\pi$ samples in the reweighting procedure.

B.2 Reweighting performance plots

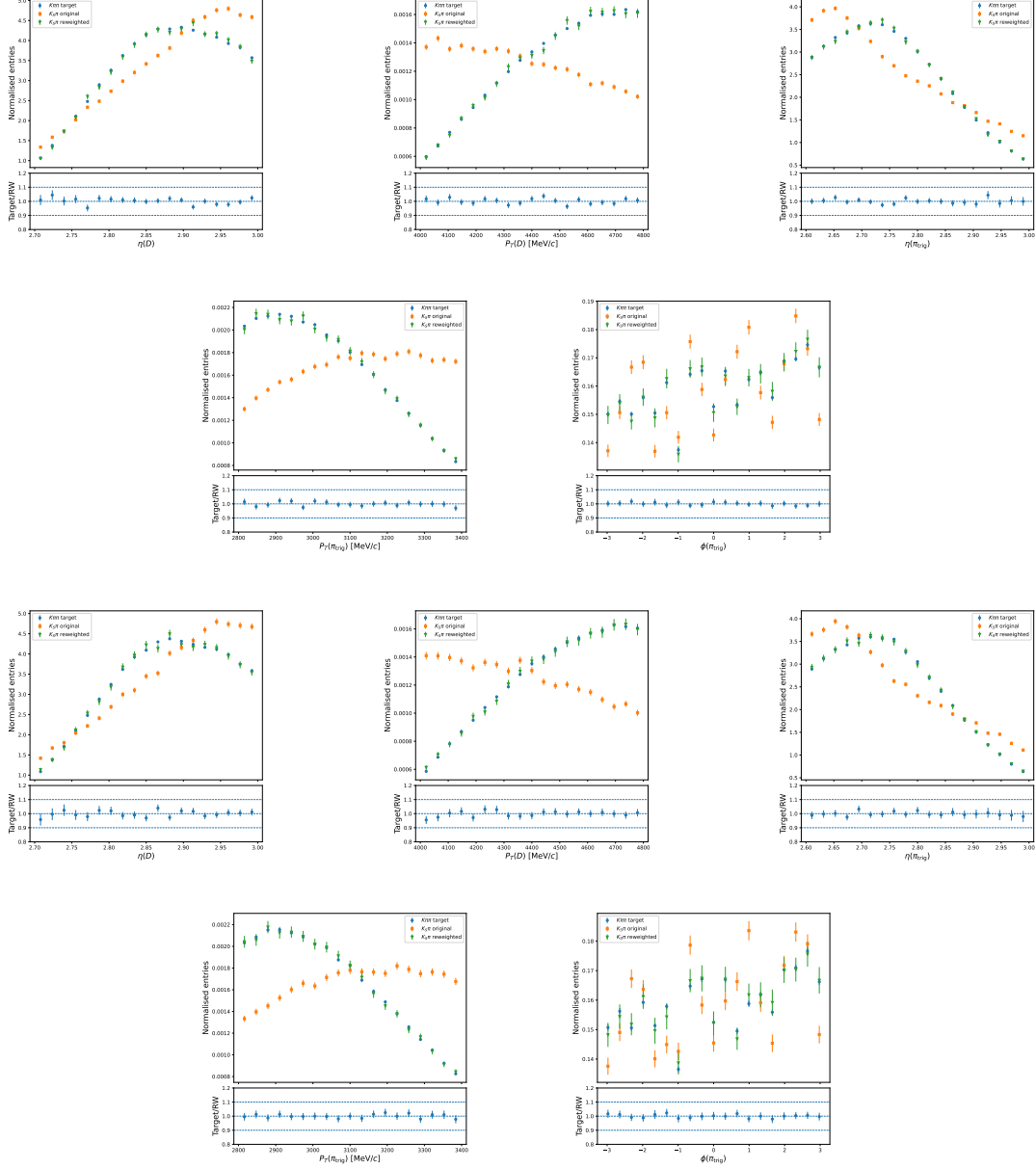


Figure 48: Reweighting performance for the second kaon-momentum bin. The top two rows correspond to MagDown, while the bottom two rows correspond to MagUp. In each block, distributions for $D^\pm \eta$, $D^\pm p_T$, and $\pi_{\text{trig}}^\pm \eta$ are on the first row, while $\pi_{\text{trig}}^\pm p_T$ and $\pi_{\text{trig}}^\pm \phi$ are on the second row.

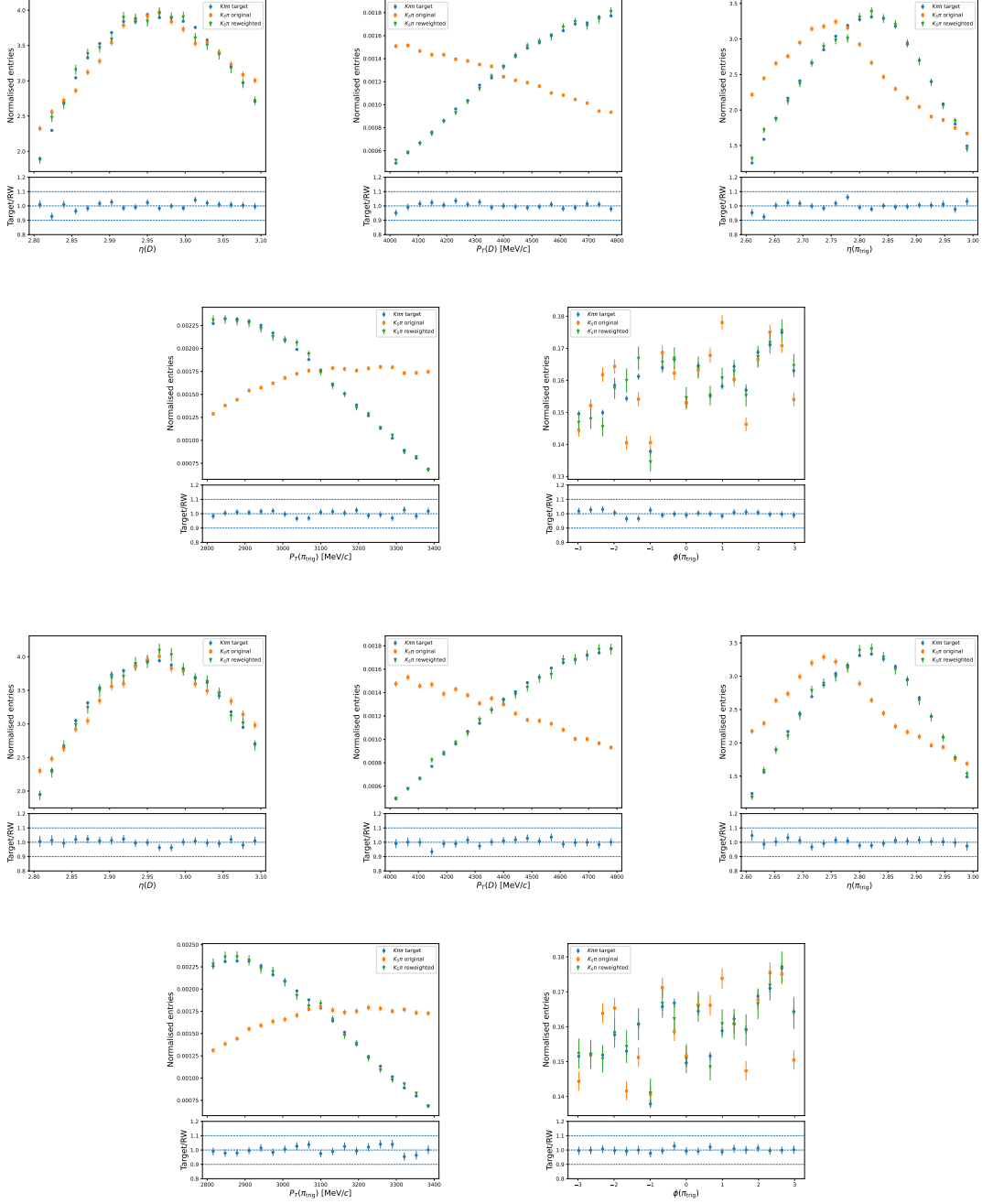


Figure 49: Reweighting performance for the third kaon-momentum bin. The top two rows correspond to MagDown, while the bottom two rows correspond to MagUp. In each block, distributions for $D^\pm \eta$, $D^\pm p_T$, and $\pi_{\text{trig}}^\pm \eta$ are on the first row, while $\pi_{\text{trig}}^\pm p_T$ and $\pi_{\text{trig}}^\pm \phi$ are on the second row.

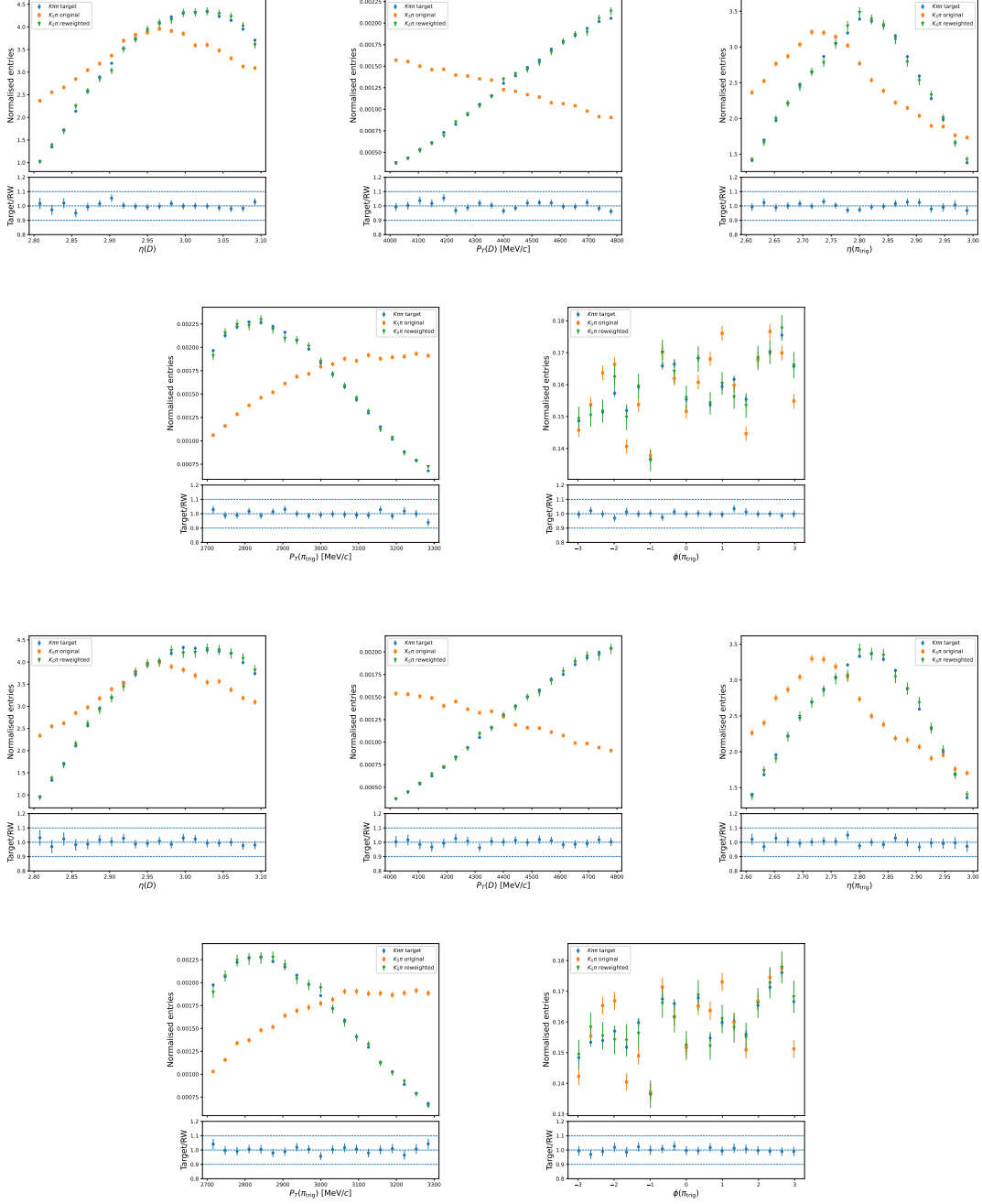


Figure 50: Reweighting performance for the fourth kaon-momentum bin. The top two rows correspond to MagDown, while the bottom two rows correspond to MagUp. In each block, distributions for $D^\pm \eta$, $D^\pm p_T$, and $\pi_{\text{trig}}^\pm \eta$ are on the first row, while $\pi_{\text{trig}}^\pm p_T$ and $\pi_{\text{trig}}^\pm \phi$ are on the second row.

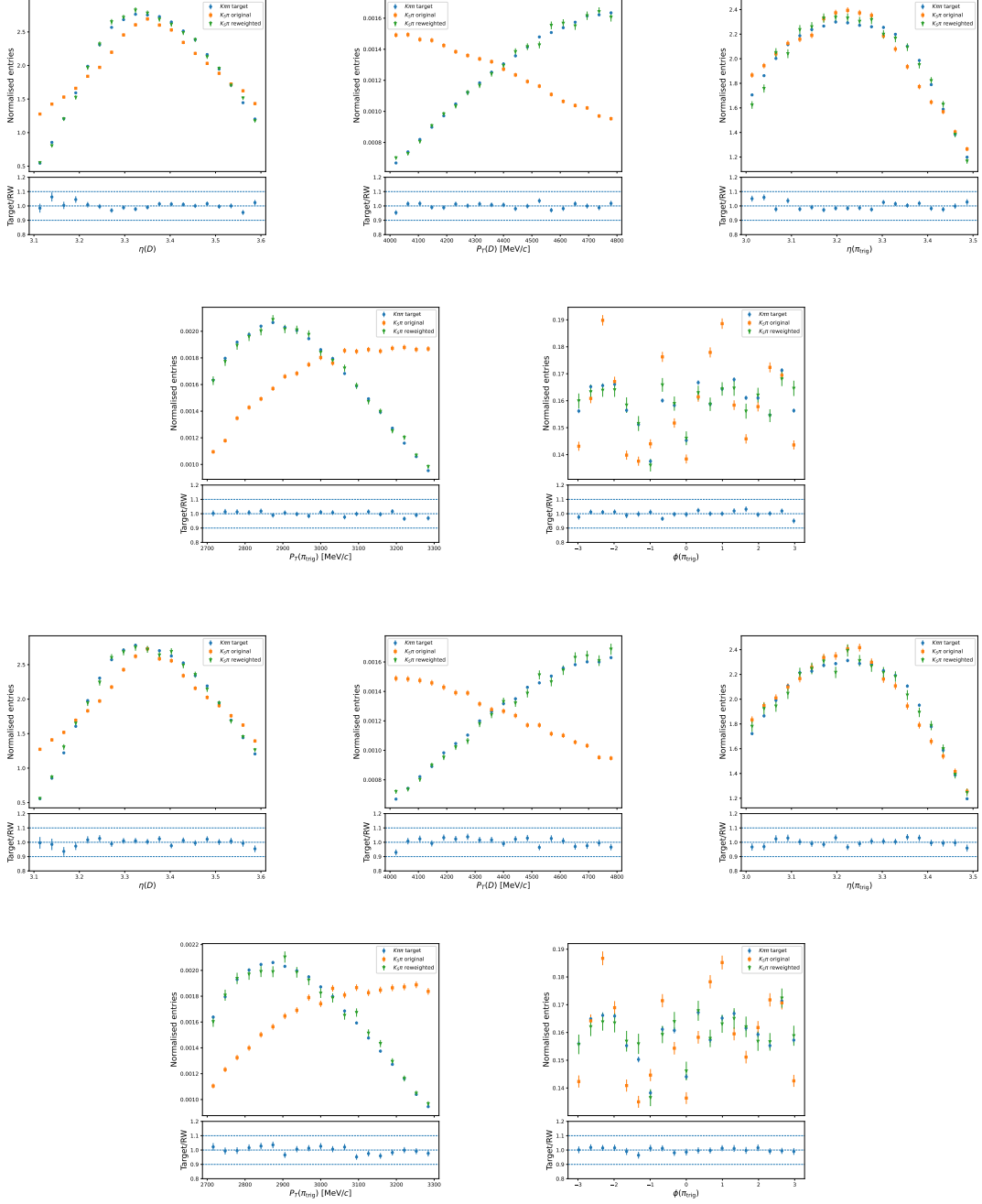


Figure 51: Reweighting performance for the fifth kaon-momentum bin. The top two rows correspond to MagDown, while the bottom two rows correspond to MagUp. In each block, distributions for $D^\pm \eta$, $D^\pm p_T$, and $\pi_{\text{trig}}^\pm \eta$ are on the first row, while $\pi_{\text{trig}}^\pm p_T$ and $\pi_{\text{trig}}^\pm \phi$ are on the second row.

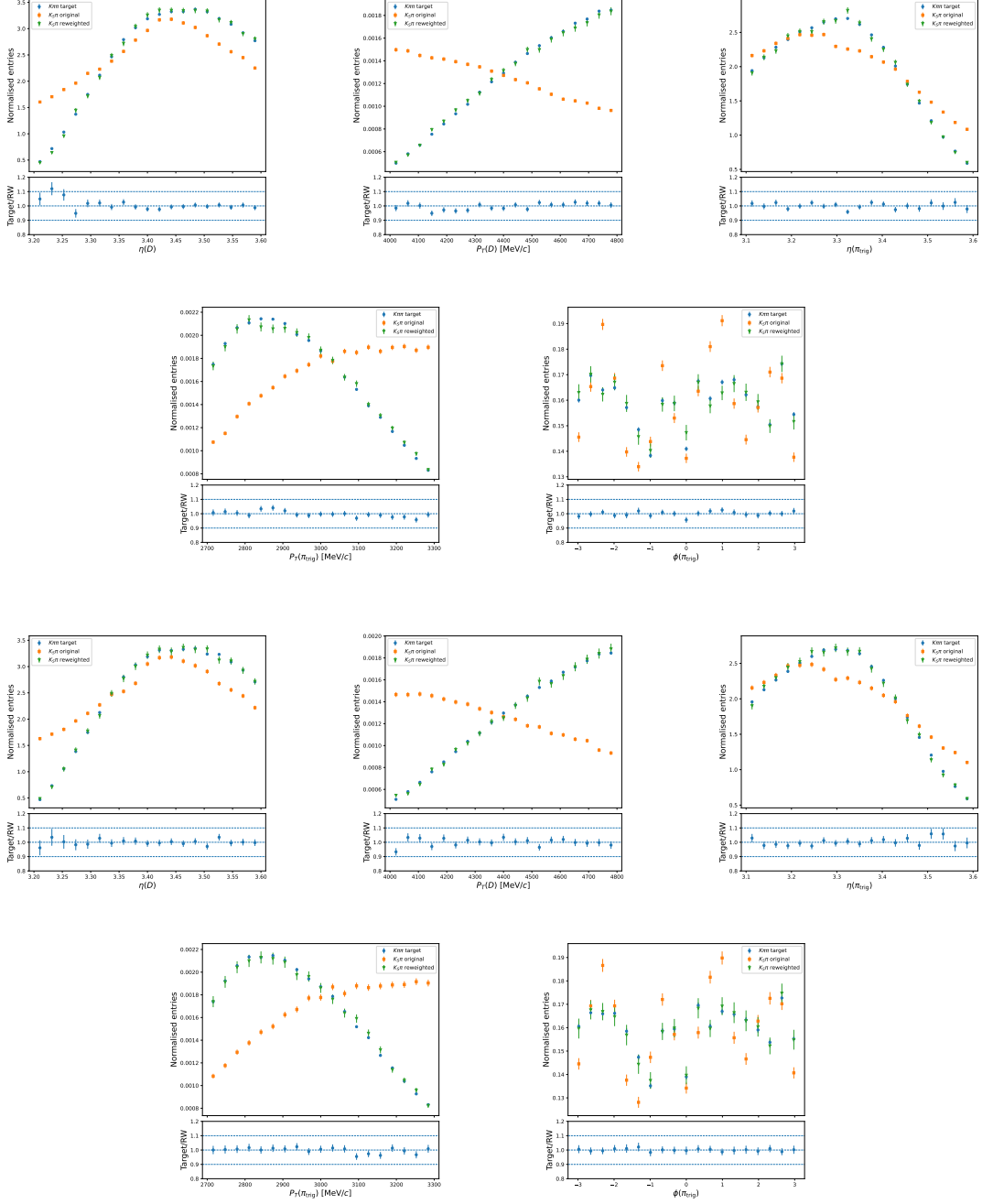


Figure 52: Reweighting performance for the sixth kaon-momentum bin. The top two rows correspond to MagDown, while the bottom two rows correspond to MagUp. In each block, distributions for $D^\pm \eta$, $D^\pm p_T$, and $\pi_{\text{trig}}^\pm \eta$ are on the first row, while $\pi_{\text{trig}}^\pm p_T$ and $\pi_{\text{trig}}^\pm \phi$ are on the second row.

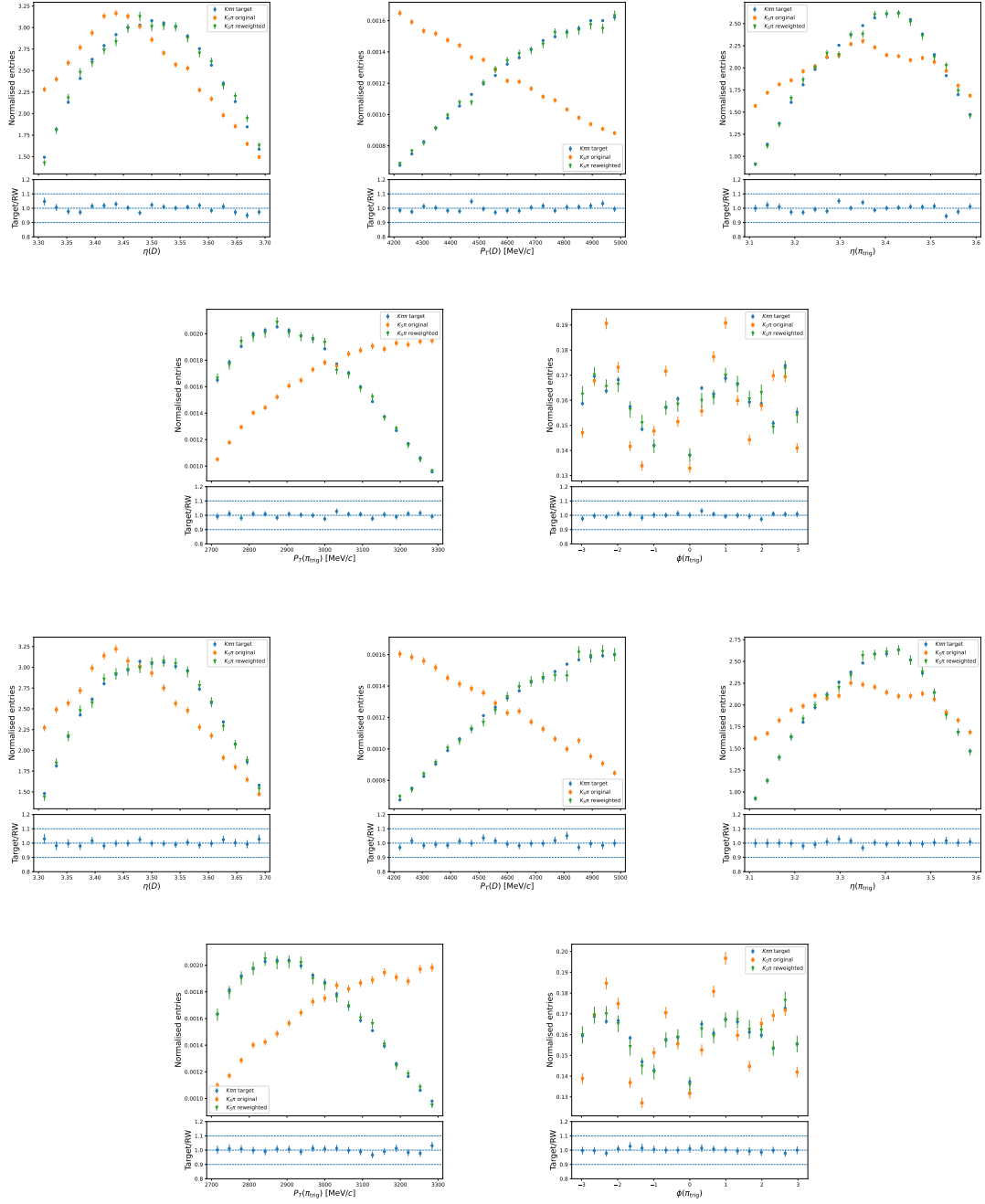


Figure 53: Reweighting performance for the seventh kaon-momentum bin. The top two rows correspond to MagDown, while the bottom two rows correspond to MagUp. In each block, distributions for $D^\pm \eta$, $D^\pm p_T$, and $\pi_{\text{trig}}^\pm \eta$ are on the first row, while $\pi_{\text{trig}}^\pm p_T$ and $\pi_{\text{trig}}^\pm \phi$ are on the second row.

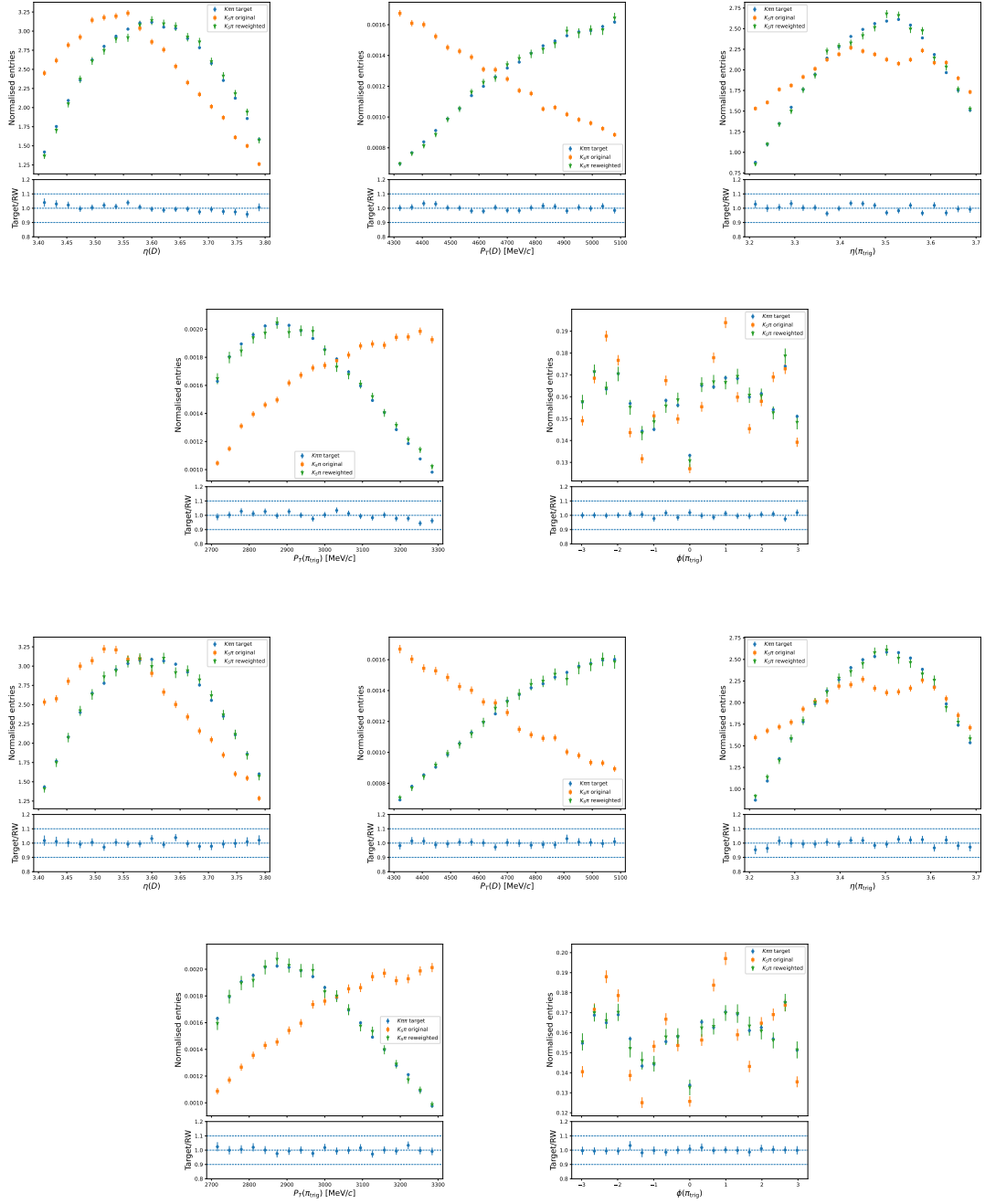


Figure 54: Reweighting performance for the eighth kaon-momentum bin. The top two rows correspond to MagDown, while the bottom two rows correspond to MagUp. In each block, distributions for $D^\pm \eta$, $D^\pm p_T$, and $\pi_{\text{trig}}^\pm \eta$ are on the first row, while $\pi_{\text{trig}}^\pm p_T$ and $\pi_{\text{trig}}^\pm \phi$ are on the second row.

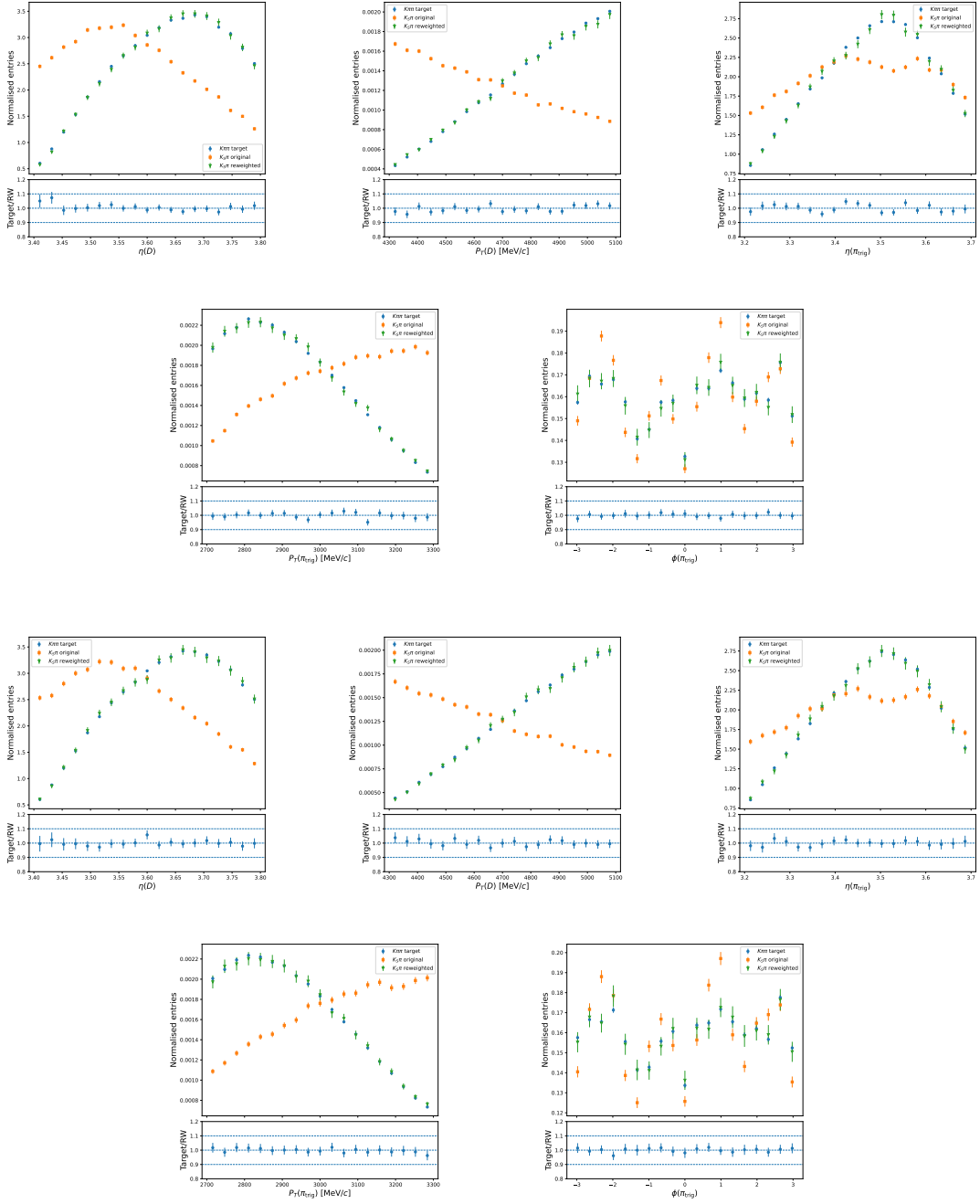


Figure 55: Reweighting performance for the ninth kaon-momentum bin. The top two rows correspond to MagDown, while the bottom two rows correspond to MagUp. In each block, distributions for $D^\pm \eta$, $D^\pm p_T$, and $\pi_{\text{trig}}^\pm \eta$ are on the first row, while $\pi_{\text{trig}}^\pm p_T$ and $\pi_{\text{trig}}^\pm \phi$ are on the second row.

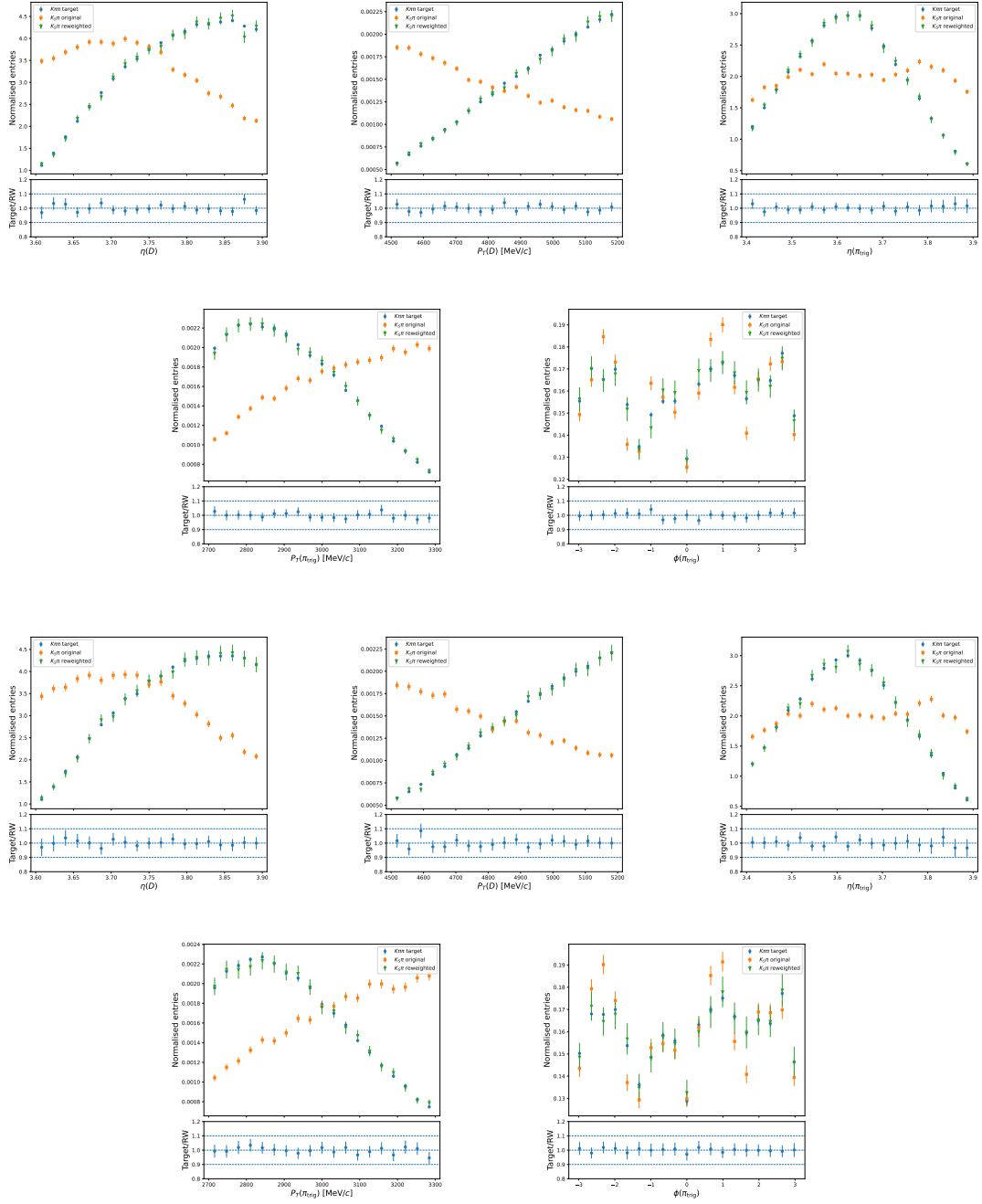


Figure 56: Reweighting performance for the tenth kaon-momentum bin. The top two rows correspond to MagDown, while the bottom two rows correspond to MagUp. In each block, distributions for $D^\pm \eta$, $D^\pm p_T$, and $\pi_{\text{trig}}^\pm \eta$ are on the first row, while $\pi_{\text{trig}}^\pm p_T$ and $\pi_{\text{trig}}^\pm \phi$ are on the second row.

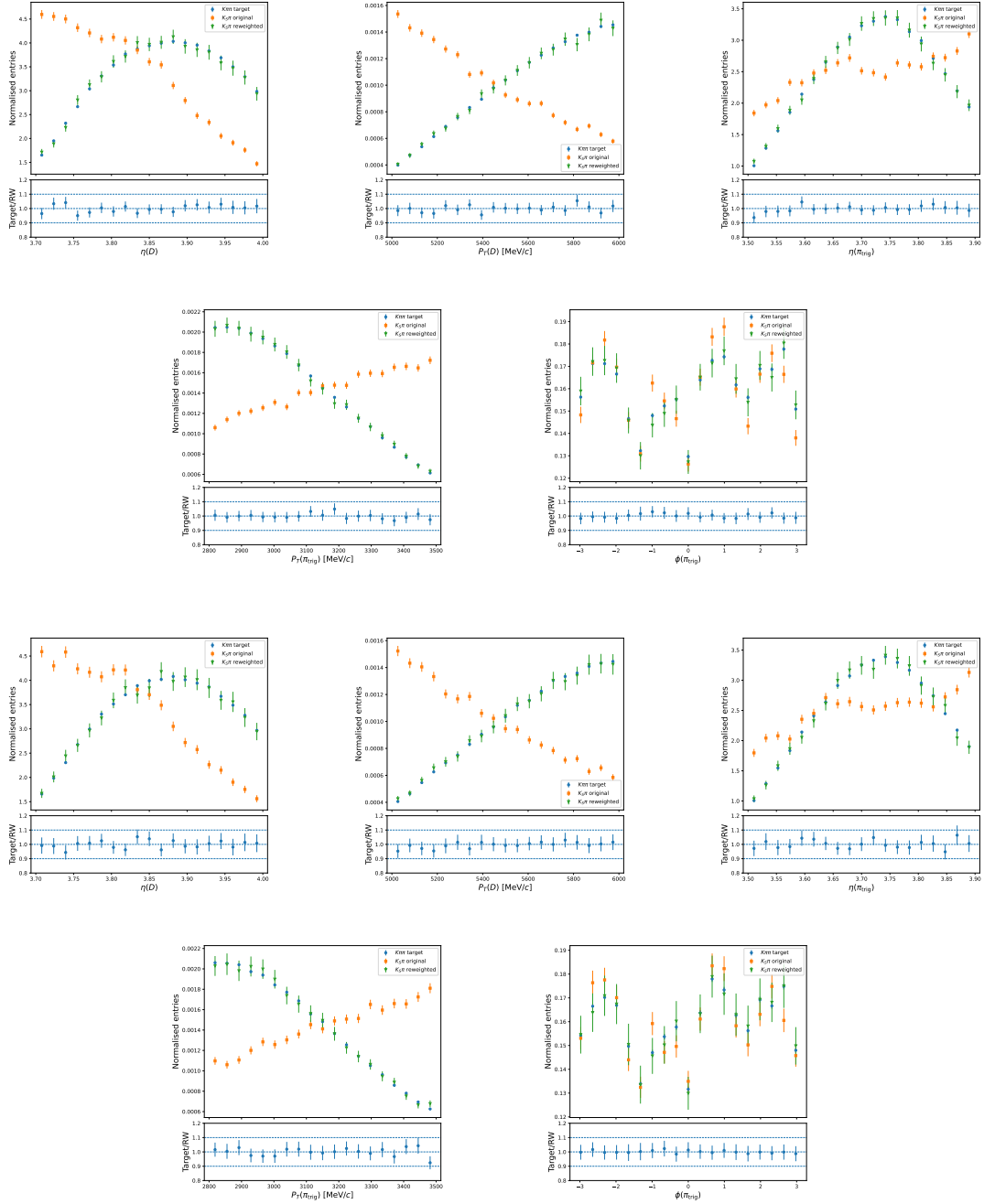


Figure 57: Reweighting performance for the eleventh kaon-momentum bin. The top two rows correspond to MagDown, while the bottom two rows correspond to MagUp. In each block, distributions for $D^\pm \eta$, $D^\pm p_T$, and $\pi_{\text{trig}}^\pm \eta$ are on the first row, while $\pi_{\text{trig}}^\pm p_T$ and $\pi_{\text{trig}}^\pm \phi$ are on the second row.

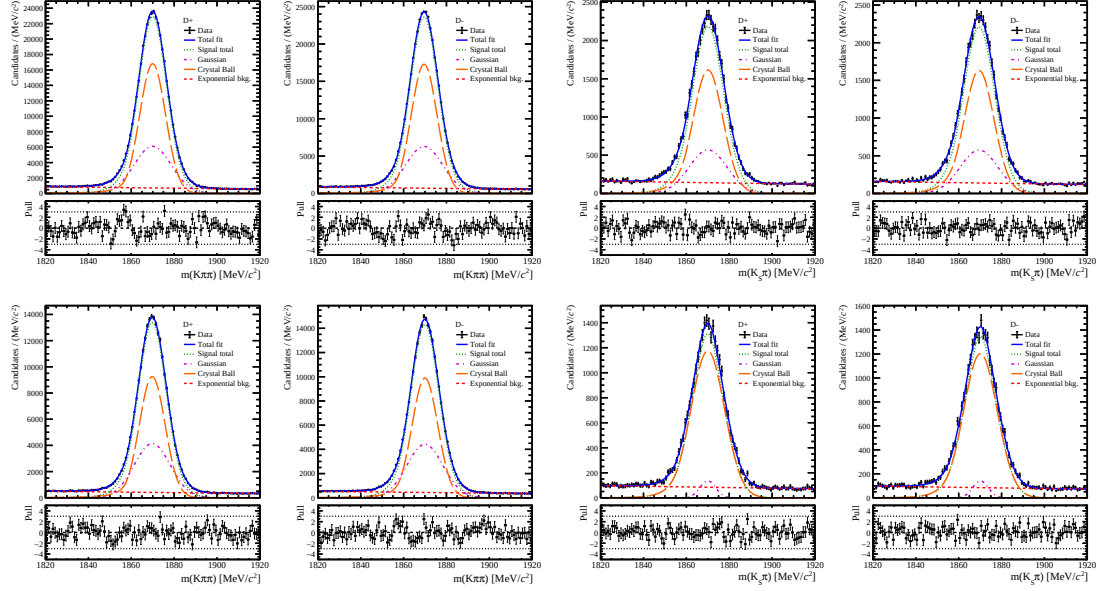
B.3 $K\pi\pi$ and $K_S\pi$ simultaneous fit plots

Figure 58: Simultaneous fit to the $K\pi\pi$ (left two columns) and reweighted $K_S\pi$ (right two columns) samples in the second kaon-momentum bin. The MagDown and MagUp samples are shown in the upper and lower rows, respectively.

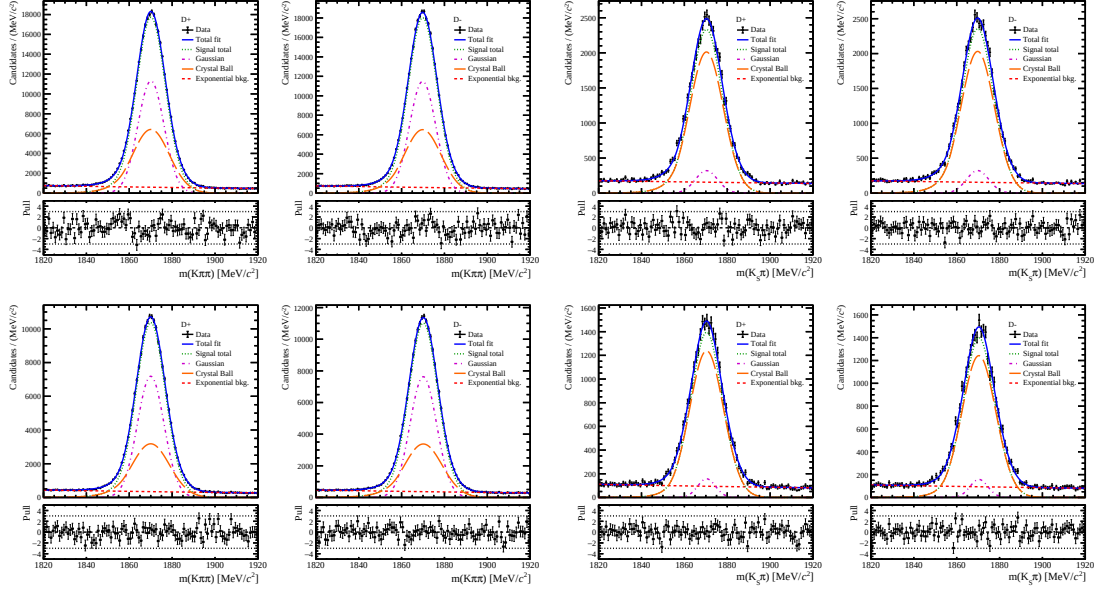


Figure 59: Simultaneous fit to the $K\pi\pi$ (left two columns) and reweighted $K_S\pi$ (right two columns) samples in the third kaon-momentum bin. The MagDown and MagUp samples are shown in the upper and lower rows, respectively.

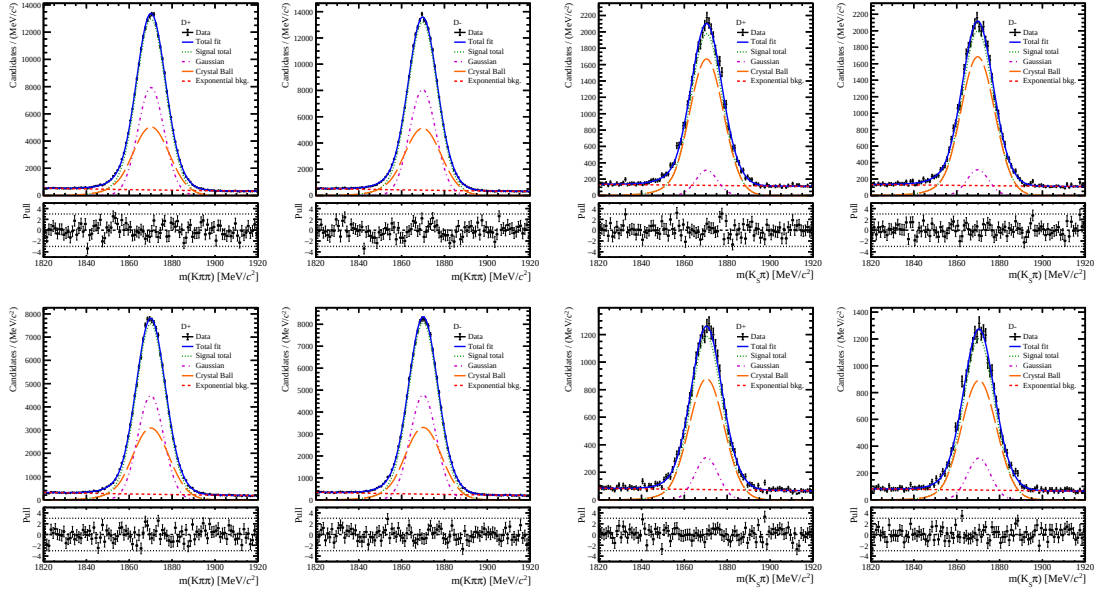


Figure 60: Simultaneous fit to the $K\pi\pi$ (left two columns) and reweighted $K_S\pi$ (right two columns) samples in the fourth kaon-momentum bin. The MagDown and MagUp samples are shown in the upper and lower rows, respectively.

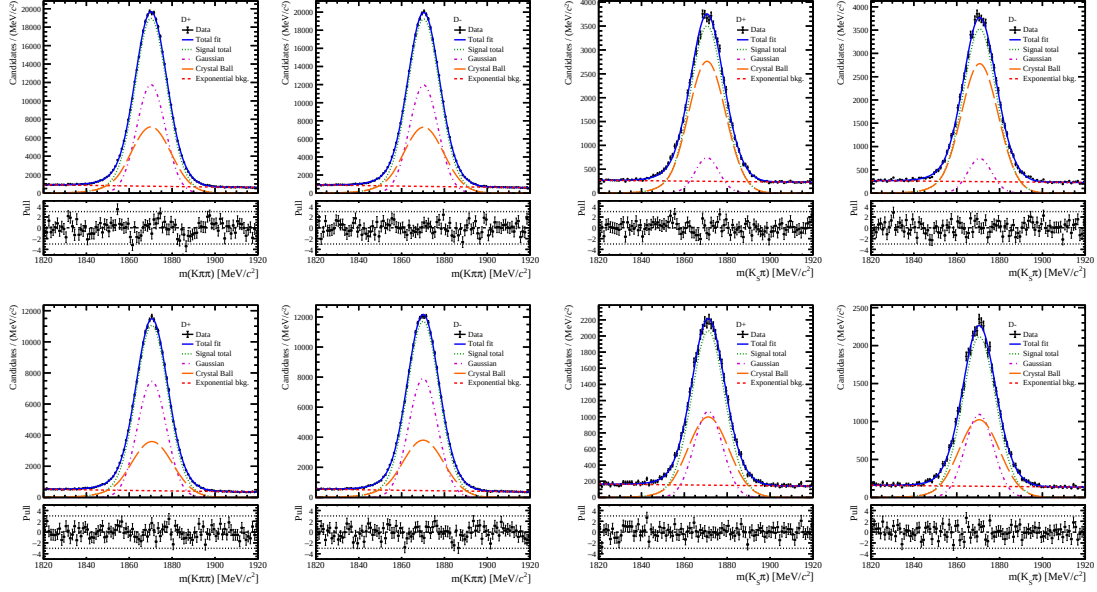


Figure 61: Simultaneous fit to the $K\pi\pi$ (left two columns) and reweighted $K_S\pi$ (right two columns) samples in the fifth kaon-momentum bin. The MagDown and MagUp samples are shown in the upper and lower rows, respectively.

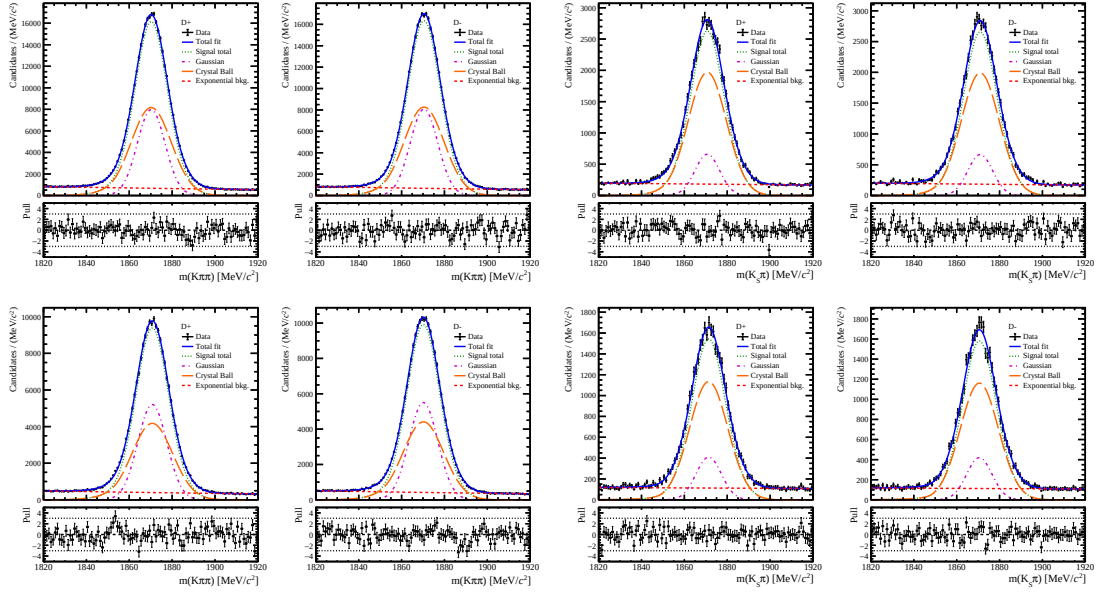


Figure 62: Simultaneous fit to the $K\pi\pi$ (left two columns) and reweighted $K_S\pi$ (right two columns) samples in the sixth kaon-momentum bin. The MagDown and MagUp samples are shown in the upper and lower rows, respectively.

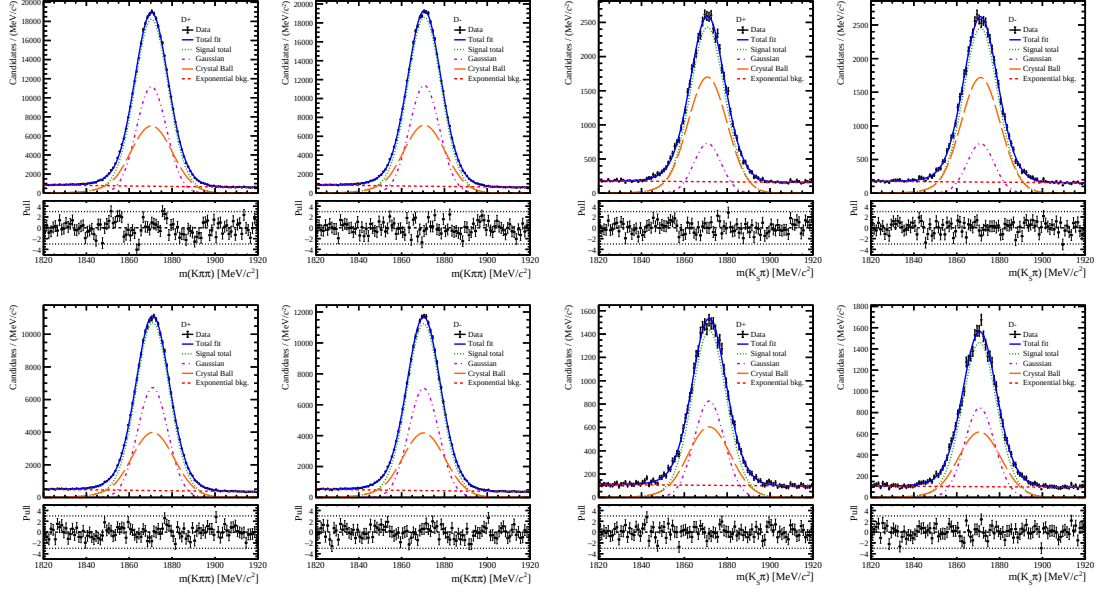


Figure 63: Simultaneous fit to the $K\pi\pi$ (left two columns) and reweighted $K_S\pi$ (right two columns) samples in the seventh kaon-momentum bin. The MagDown and MagUp samples are shown in the upper and lower rows, respectively.

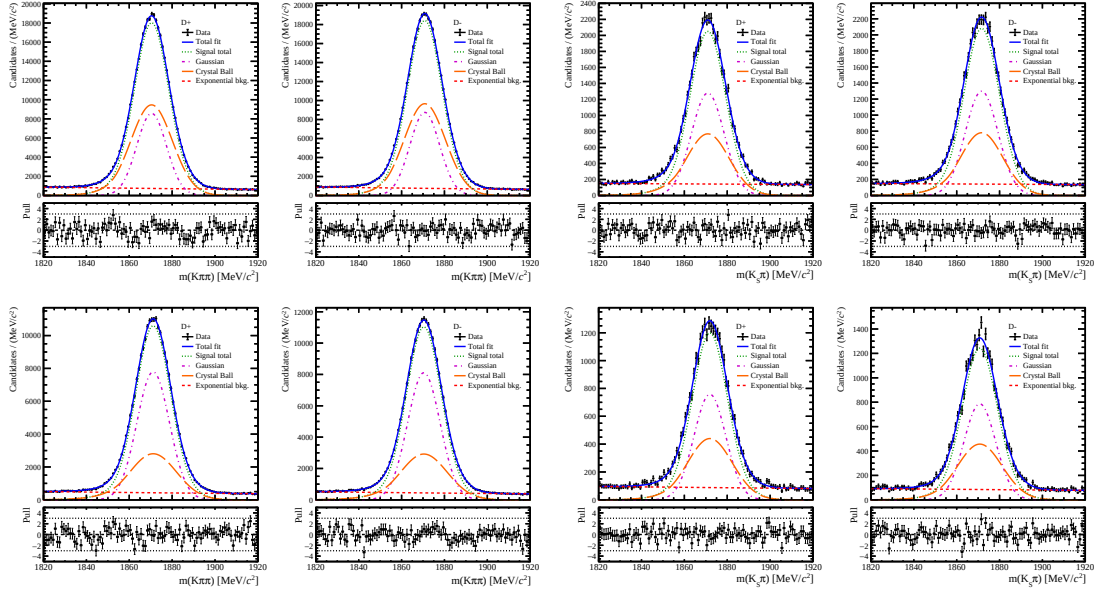


Figure 64: Simultaneous fit to the $K\pi\pi$ (left two columns) and reweighted $K_S\pi$ (right two columns) samples in the eighth kaon-momentum bin. The MagDown and MagUp samples are shown in the upper and lower rows, respectively.

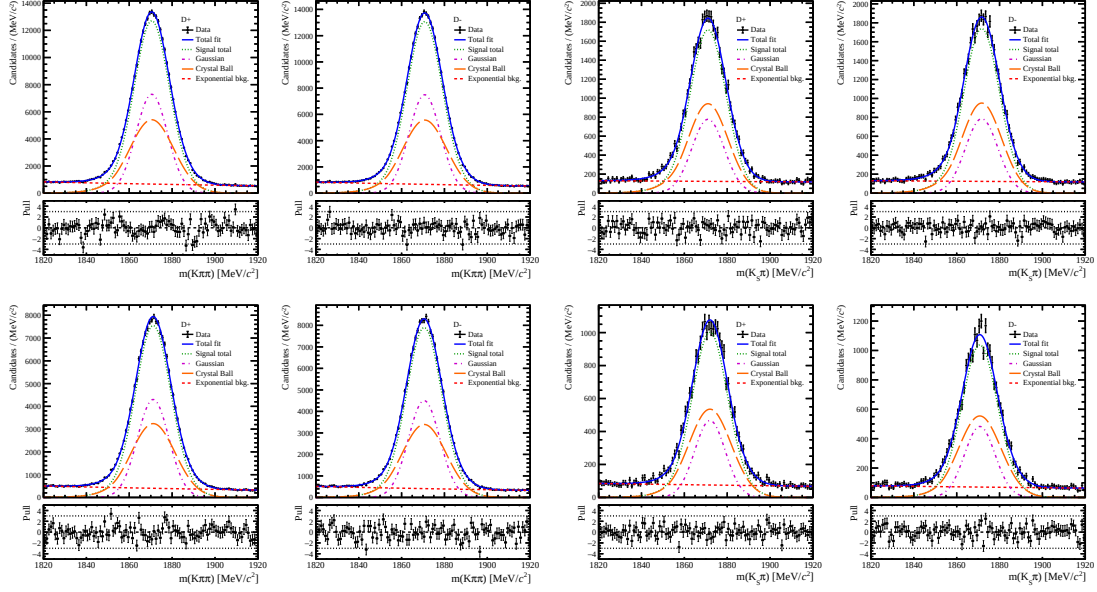


Figure 65: Simultaneous fit to the $K\pi\pi$ (left two columns) and reweighted $K_S\pi$ (right two columns) samples in the ninth kaon-momentum bin. The MagDown and MagUp samples are shown in the upper and lower rows, respectively.

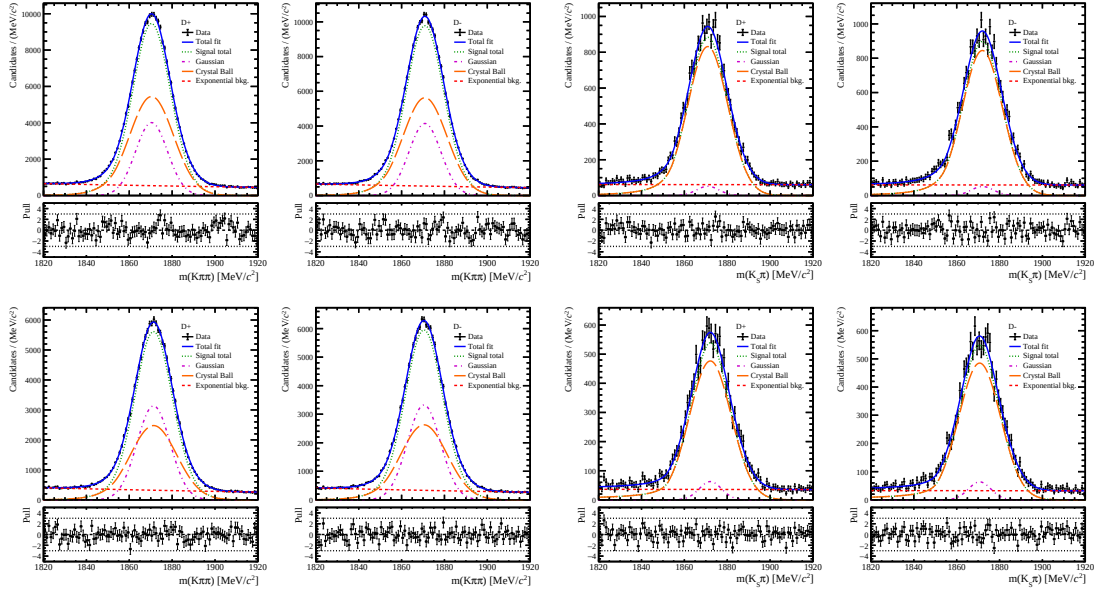


Figure 66: Simultaneous fit to the $K\pi\pi$ (left two columns) and reweighted $K_S\pi$ (right two columns) samples in the tenth kaon-momentum bin. The MagDown and MagUp samples are shown in the upper and lower rows, respectively.

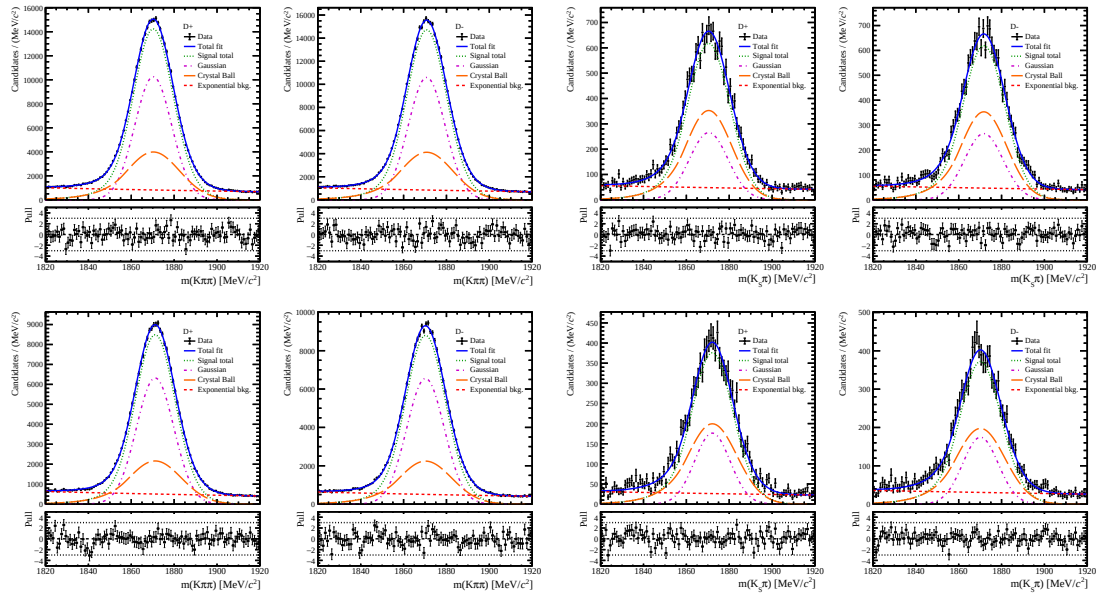


Figure 67: Simultaneous fit to the $K\pi\pi$ (left two columns) and reweighted $K_S\pi$ (right two columns) samples in the eleventh kaon-momentum bin. The MagDown and MagUp samples are shown in the upper and lower rows, respectively.

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