



UNIVERSIDADE FEDERAL DO RIO DE JANEIRO

**Measurement of the CP asymmetries difference
between $D^+ \rightarrow K^- K^+ \pi^+$ and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decays
in the LHCb experiment**

Danielle Martins Tostes



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Ph.D. Thesis presented to the Graduate Program
in Physics of the Institute of Physics of the Federal
University of Rio de Janeiro - UFRJ, as part of the
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in Sciences (Physics).

Advisor: Érica Ribeiro Polycarpo Macedo

Co-advisor: Alberto Corrêa dos Reis (CBPF)

Rio de Janeiro

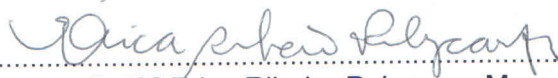
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Erica Ribeiro Polycarpo Macedo
Alberto Correa dos Reis

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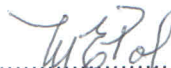
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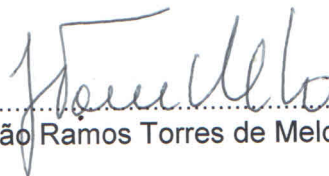
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Abstract

Measurement of the CP asymmetries difference between $D^+ \rightarrow K^- K^+ \pi^+$ and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decays in the LHCb experiment

Danielle Martins Tostes

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Abstract of the Ph.D. Thesis presented to the Graduate Program in Physics of the Institute of Physics of the Federal University of Rio de Janeiro - UFRJ, as part of the requirements to the obtention of the title of Doctor in Sciences (Physics).

The violation of the combined charge conjugation and parity symmetry, or simply CP violation, is one of the necessary conditions to explain the matter-antimatter asymmetry observed in the Universe. In the Standard Model, CP violation arises due to an irreducible complex phase in the Cabibbo-Kabayashi-Maskawa (CKM) matrix. However, this mechanism is not enough to explain the observed baryogenesis. New sources of CP violation are necessary. The Standard Model predicts very small CP violation in the charm sector, $\mathcal{O}(10^{-3})$ or less. This makes decays of D mesons an excellent tool in the search for these new sources. With the large sample collected at LHCb during Run I, corresponding to 1.0 fb^{-1} of pp collisions at $\sqrt{s} = 7 \text{ TeV}$ and 2.0 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, we can reach the upper limits of Standard Model predictions with several decay modes. In the Standard Model, direct CP violation in the charm sector can only occur in Cabibbo-suppressed (CS) decays. In this work,

we measure the difference between the CP asymmetries A_{CP} of the CS decays $D^+ \rightarrow K^- K^+ \pi^+$ and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (ΔA_{CP}), under the assumption that instrumental and production asymmetries cancel between the two modes.

The analysis uses as control channels, for the study of instrumental and production asymmetries, the Cabibbo-favoured decays $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$, where no CP violation is expected, and obtains the D^+ asymmetries in a blind way, by randomly inserting offsets to the actual fitted values. Once the study, which is currently under the Charm Working group review, is approved by the collaboration, the offsets will be removed and the ΔA_{CP} values will be known.

Keywords: Charm Physics, CP Violation, LHCb.

Resumo

Medida da diferença das assimetrias de CP dos decaimentos $D^+ \rightarrow K^- K^+ \pi^+$ e $D^+ \rightarrow \pi^- \pi^+ \pi^+$ no experimento LHCb

Danielle Martins Tostes

Orientador: Érica Ribeiro Polycarpo Macedo

Coorientador: Alberto Corrêa dos Reis (CBPF)

Resumo da Tese de Doutorado apresentada ao Programa de Pós-Graduação em Física do Instituto de Física da Universidade Federal do Rio de Janeiro - UFRJ, como parte dos requisitos necessários à obtenção do título de Doutor em Ciências (Física).

A violação da simetria combinada de conjugação de carga e paridade, ou simplesmente violação de CP, é uma das condições necessárias para explicar a assimetria matéria-antimatéria observada no Universo. No Modelo Padrão, a violação de CP surge de uma fase complexa irreduzível na matriz de Cabibbo-Kabayashi-Maskawa (CKM). No entanto, este mecanismo não é o suficiente para explicar a bariogênese observada. Novas fontes de violação de CP são necessárias. O Modelo Padrão prevê uma violação de CP muito pequena no setor de charme, $\mathcal{O}(10^{-3})$ ou menor. Isto faz dos decaimentos dos mésons D uma excelente ferramenta na busca por essas novas fontes. Com a grande amostra coletada no LHCb durante o *Run I*, correspondendo a $1,0 \text{ fb}^{-1}$ de colisões pp a $\sqrt{s} = 7 \text{ TeV}$ e $2,0 \text{ fb}^{-1}$ a $\sqrt{s} = 8 \text{ TeV}$, podemos alcançar os limites superiores das previsões do Modelo Padrão com diversos modos de decaimento. No Modelo Padrão, a violação de CP direta no setor de charme só pode

ocorrer em decaimentos suprimidos por Cabibbo (CS). Neste trabalho, medimos a diferença entre as assimetrias de CP A_{CP} dos decaimentos CS $D^+ \rightarrow K^- K^+ \pi^+$ e $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (ΔA_{CP}), sob a suposição de que as assimetrias instrumentais e de produção cancelam entre os dois modos.

A análise utiliza como canais de controle, para o estudo de assimetrias instrumentais e de produção, os decaimentos favorecidos por Cabibbo $D_s^+ \rightarrow K^- K^+ \pi^+$ e $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$, onde não é esperada violação de CP, e obtém as assimetrias de D^+ de modo “cego”, aleatoriamente inserindo *offsets* aos valores ajustados. Uma vez que o estudo, que está atualmente sob revisão no grupo de trabalho de charme, seja aprovado pela colaboração, os *offsets* serão removidos e os valores de ΔA_{CP} serão conhecidos.

Palavras-chave: Física de Charm, Violação de CP, LHCb.

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Chapter 1

Introduction

CP violation (CPV) is one of the necessary conditions to explain the matter-antimatter asymmetry in the Universe. In the primordial Universe, particles and antiparticles would have been equally likely to be created and would have been annihilated. However, it is observed that matter prevailed over antimatter as the observable Universe is made of matter.

The CP symmetry is a combination of the symmetries of charge conjugation C, where all internal quantum numbers of the particle are reversed, and parity P, which changes the sign of spatial coordinates. The C and P symmetries are maximally violated in the weak interactions. For a long time, the CP combined symmetry was thought to be conserved but, in 1964, CP violation was observed in the decays of neutral kaons [1]. In the last decades, several measurements of CP violation were performed in decays of B mesons, where the effects are larger than in kaons [2, 3].

The Standard Model (SM) is compatible with all the CP asymmetries measured so far, but it can not account for the matter-antimatter asymmetry observed in the Universe. The small asymmetries predicted by the Standard Model for charm decays make them interesting tools for seeking Physics beyond the SM [4].

Searches for CP violation in charm have been performed in the past years using the decay of the neutral meson D^0 into two hadrons. In 2012, evidence of CP violation was measured in those decays [5, 6]. Studies showed this effect could be

described by the Standard Model [7] and later measurements have not confirmed this evidence [8–10].

CPV studies using decays of D^+ meson into three hadrons are the natural extension of the neutral meson D^0 decays into two hadrons. The Cabibbo suppressed (CS) decays $D^+ \rightarrow K^- K^+ \pi^+$ and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ are channels often used to search for CP violation in charm and were chosen for the work of this thesis. They are largely produced at the LHCb. Searches for CP violation across the 3-body phase space were previously performed for both channels using 2010 and 2011 data taken by LHCb [11, 12].

Asymmetries measured in hadronic 3-body charmless decays of the charged B meson [13–15] suggest that contributions from final state rescattering ($KK \leftrightarrow \pi\pi$) may be relevant. Such contributions would have a larger impact in the smaller phase space of D^+ decays. Since they introduce asymmetries with the same sign across the phase space, they would lead to a global phase space integrated asymmetry.

In pp collisions, there is a production asymmetry of D^+ and D^- of order 1–2%. Several factors can cause a small difference in the detection asymmetry of D^+ and D^- . Such effects combined would be larger than an eventual CP asymmetry, making this observation problematic. Experimentally, we measure an effective raw asymmetry which combines production and detection effects and the CP violation,

$$A_{\text{raw}} = \frac{N_{\text{obs}}(D^+ \rightarrow f) - N_{\text{obs}}(D^- \rightarrow \bar{f})}{N_{\text{obs}}(D^+ \rightarrow f) + N_{\text{obs}}(D^- \rightarrow \bar{f})}. \quad (1.1)$$

If the production and detection asymmetries do not depend on the final state, a possible solution would be to measure the difference of charge asymmetries A_{raw} between the two decay modes which, under this assumption, becomes a measurement of the pure CP asymmetries difference:

$$\Delta A_{CP} = A_{CP}(D^+ \rightarrow K^- K^+ \pi^+) - A_{CP}(D^+ \rightarrow \pi^- \pi^+ \pi^+). \quad (1.2)$$

¹The charged conjugated decays $D^- \rightarrow K^+ K^- \pi^-$ and $D^- \rightarrow \pi^+ \pi^- \pi^-$ are implicitly included, except in the definitions of asymmetries.

In this work, we measure the difference between the CP asymmetries A_{CP} of the CS decays $D^+ \rightarrow K^- K^+ \pi^+$ and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (ΔA_{CP}), under the assumption that instrumental and production asymmetries cancel between the two modes. The analysis uses as control channels, for the study of instrumental and production asymmetries, the Cabibbo-favoured decays $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$, where no CP violation is expected, and obtains the D^+ asymmetries in a blind way, by randomly inserting offsets to the actual fitted values. Once the study, which is currently under the Charm Working group review, is approved by the collaboration, the offsets will be removed and the ΔA_{CP} values will be known.

This measurement is complementary to the studies of local asymmetries in the Dalitz plot [11,12,16] and to amplitude analyses performed by other experiments [17, 18] or ongoing within our experiment.

The thesis is structured as follows. In Chapter 2, there is a brief description of the theoretical aspects related to this measurement. In Chapter 3, the LHCb detector, experimental apparatus which provided the data used for the experimental result, is described. The data selection and analysis strategy are explained in Chapter 4 and Chapter 5, respectively. The results are presented in Chapter 6. Chapter 7 contains studies of potential systematic effects to the measurement. Conclusions are discussed in Chapter 8. Complementary material can be found in the Appendices.

Chapter 2

Theoretical Aspects and Related Measurements

The charm quark was discovered in 1974 at Brookhaven National Laboratory and SLAC with the observation of the resonance J/ψ ($c\bar{c}$) [19,20]. Its existence had been discussed since 1964 [21] and was required for the GIM mechanism [22]. The open charm mesons D^0 ($c\bar{u}$) and D^+ ($c\bar{d}$) were first observed in 1976 [23,24]. Since then, charm physics has been an important research field, with many dedicated experiments.

The decays of charm particles are important tools for the understanding of QCD at the low energy regime, where the perturbative approach is not applicable. CPV studies in these decays are especially helpful in the search for New Physics (NP). Different from what happens to kaons and B mesons, the SM predicts very small CP asymmetries in charm transitions [4]. An observation of CP asymmetries at rates of the order of 1% would be a clear signal for Physics beyond the Standard Model. However, recent results from the LHCb experiment, based on very large data sets, already reached the limits of the SM expectations [25].

In the Standard Model, CP violation is included in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [26,27], which relates the quark mass eigenstates to the weak interaction eigenstates. Due to unitarity, this matrix has three real parameters and a complex phase. This complex phase introduces the CP violation. If there were

only two quark generations, the quark mixing mechanism could not give rise to CP violation. All three generations are required for CP violation to occur in a particular process [28]. The CKM matrix is given by

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

It can be parameterized by three mixing angles and the CP violating phase. A standard form of representation is

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \quad (2.1)$$

where $s_{ij} = \sin \theta_{ij}$, $c_{ij} = \cos \theta_{ij}$ and δ is the phase responsible for the CP violation in flavor changing processes in the Standard Model [29]. Due to differences among the mixing angles, the matrix elements of V_{CKM} have very different magnitudes [30]. A parametrization where this becomes evident is the one suggested by Wolfenstein [31]

$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta + \frac{i}{2}\eta\lambda^2) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2(1 + i\eta\lambda^2) \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \quad (2.2)$$

Here $\lambda = \sin \theta_C \approx 0.23$ acts as expansion parameter and η represents the CP-violating phase [29]. The parameter θ_C is known as Cabibbo angle, which determines the weak coupling of quark c with quarks s or d . Since the value of θ_C is small ($\theta_C \sim 0.23$ rad), the decays with $c \rightarrow d$ transitions are suppressed by a factor $\tan^2 \theta_C$ with respect to decays with $c \rightarrow s$ transitions. This is the called Cabibbo suppression [32]. The most relevant source for CP violation in charm decays is the phase in V_{cs} which is $\simeq -\eta A^2 \lambda^4 \simeq -6 \cdot 10^{-4}$ [4, 33].

The CKM matrix elements can be most precisely determined using a global fit to all available measurements and imposing the SM constraints. The fit results to all nine CKM elements are [29]

$$V_{CKM} = \begin{pmatrix} 0.97427 \pm 0.00014 & 0.22536 \pm 0.00061 & 0.00355 \pm 0.00015 \\ 0.22522 \pm 0.00061 & 0.97343 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.00886^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{pmatrix} \quad (2.3)$$

There are three types of CP violation in meson decays: CPV in the decay, in the mixing and in the interference between decay and mixing.

The CP violation in decay (or direct) can be measured through the difference between the partial widths of conjugated decays. It is defined by $|\bar{A}_{\bar{f}}/A_f| \neq 1$, i.e., the amplitude A_f of a meson M decay into a final state f is different from the amplitude $\bar{A}_{\bar{f}}$ of the conjugated decay $\bar{M} \rightarrow \bar{f}$. Considering a general case with the decay amplitudes as a sum of two terms with different weak and strong phases, we have

$$\begin{aligned} A_f &= |a_1|e^{i(\delta_1+\phi_1)} + |a_2|e^{i(\delta_2+\phi_2)}, \\ \bar{A}_{\bar{f}} &= |a_1|e^{i(\delta_1-\phi_1)} + |a_2|e^{i(\delta_2-\phi_2)}, \end{aligned} \quad (2.4)$$

where ϕ_1 and ϕ_2 are the weak, CP-violating phases and δ_1 and δ_2 are the strong, CP-conserving phases [34].

The asymmetry between the partial decay rates is quantified by the observable A_{CP}

$$A_{CP} = \frac{\Gamma(M \rightarrow f) - \Gamma(\bar{M} \rightarrow \bar{f})}{\Gamma(M \rightarrow f) + \Gamma(\bar{M} \rightarrow \bar{f})}. \quad (2.5)$$

Using the amplitudes defined in Eq. (2.4), the asymmetry in Eq. (2.5) becomes

$$A_{CP} = \frac{2|a_1 a_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)}{|a_1|^2 + |a_2|^2 + 2|a_1 a_2| \cos(\delta_2 - \delta_1) \cos(\phi_2 - \phi_1)} \quad (2.6)$$

From this equation, it is possible to see that a requirement for direct CPV is the existence of at least two different amplitudes leading to the same final state, with different strong and weak phases [34].

The direct CPV is the only source of CP asymmetries in charged meson decays, where mixing effects are absent [29].

Another type of CP violation arises in mixing. This is classified as indirect CPV and manifests itself as a difference between the oscillation rate of mesons and antimesons.

Mixing is well known and common to all neutral mesons with flavour (K^0 , B^0 e D^0). It occurs when flavour eigenstates are different from mass eigenstates. Due to

the weak interactions, an initial state meson M^0 can evolve to its antiparticle $\overline{M}^0$ before decaying and vice versa. Their temporal evolution can be represented by

$$i\hbar \frac{d}{dt} \begin{pmatrix} M^0(t) \\ \overline{M}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2} \mathbf{\Gamma} \right) \begin{pmatrix} M^0(t) \\ \overline{M}^0(t) \end{pmatrix} \quad (2.7)$$

where $\mathbf{M}$ and $\mathbf{\Gamma}$ are Hermitian matrices. The meson mass eigenstates $M_{1,2}$, with masses m_1 and m_2 and widths Γ_1 and Γ_2 , can be written as a linear combination of the flavour eigenstates:

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle, \quad |p|^2 + |q|^2 = 1 \quad (2.8)$$

The mixing parameters are expressed in terms of x and y parameters, defined in terms of the masses and decay widths differences, being $x = (m_1 - m_2)/\Gamma$, $y = (\Gamma_1 - \Gamma_2)/2\Gamma$ and $\Gamma = (\Gamma_1 + \Gamma_2)/2$ [35].

CP violation in mixing is defined by $|q/p| \neq 1$ and can only occur in decays of neutral mesons. In this case, the probability of meson M^0 evolve to antimeson $\overline{M}^0$ is different from the probability of the reverse process occur, i.e., $\mathcal{P}(M^0 \rightarrow \overline{M}^0; t) \neq \mathcal{P}(\overline{M}^0 \rightarrow M^0; t)$. In charged-current semileptonic neutral meson decays $M, \overline{M} \rightarrow \ell^\pm X$ this is the only source of CP violation [29].

CP violation in the interference between decay and mixing occurs when a final state is accessible for both meson and antimeson. A decay of $M^0 \rightarrow f$ can proceed directly without mixing, or through mixing ($M^0 \rightarrow \overline{M}^0 \rightarrow f$). The relative phase between these two possibilities may be different for initial states that are meson or antimeson. Figure 2.1 illustrates these three types of CP violation.

In charm, SM CP violation, either direct or indirect, can only occur in Cabibbo-suppressed (CS) decays, where two amplitudes guided by $c \rightarrow d\bar{d}u$ and $c \rightarrow s\bar{s}u$ can interfere and generate CP asymmetries, predicted to be of order 10^{-3} or smaller. Such mechanism does not exist in Cabibbo-favoured (CF) and doubly Cabibbo-suppressed (DCS) decays, where there is only one weak amplitude.

CP violation in CS decays could arise from the interference between tree-level (Figs. 2.2a and 2.3a) and penguin (Figs. 2.2b and 2.3b) processes [36]. It is important

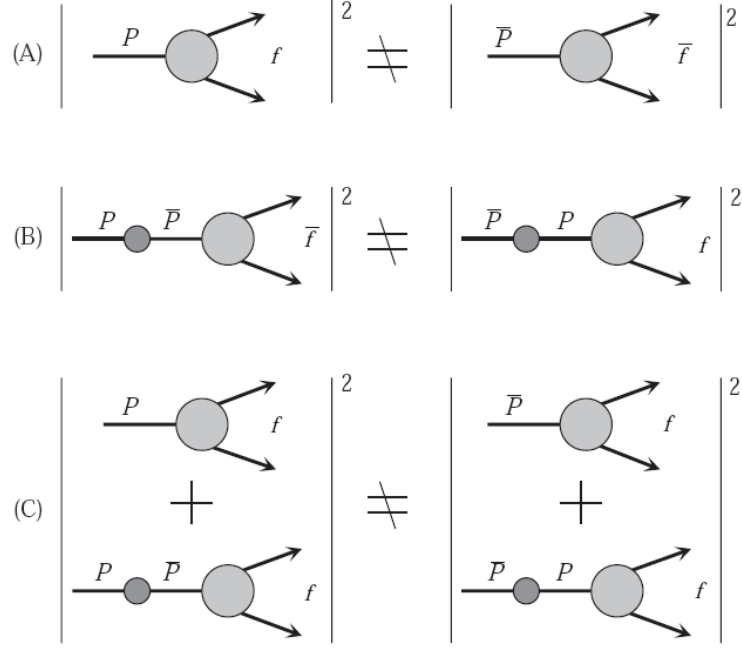


Figure 2.1: Three types of CP violation: (A) direct CP violation; (B) indirect CP violation (in the presence of $M^0 - \bar{M}^0$ oscillations); and (C) interference when both mechanisms are possible [33].

to notice that contributions from penguin diagrams are much smaller than the ones from tree-level diagrams and this is one of the reasons why asymmetries generated by this interference are so small.

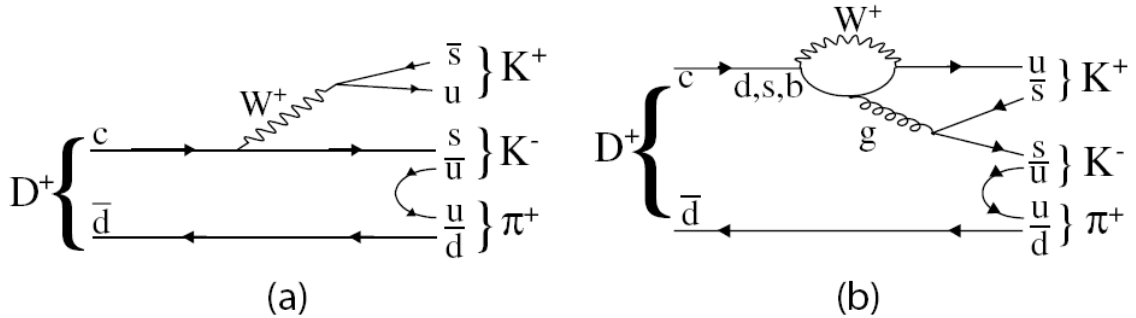


Figure 2.2: Parton-level diagrams for $D^+ \rightarrow K^- K^+ \pi^+$ decays: (a) a tree diagram, and (b) a penguin process [36].

A large number of CPV searches have been performed in the charm sector in the last years. Most of the recent measurements are listed by the Heavy Flavor Averag-

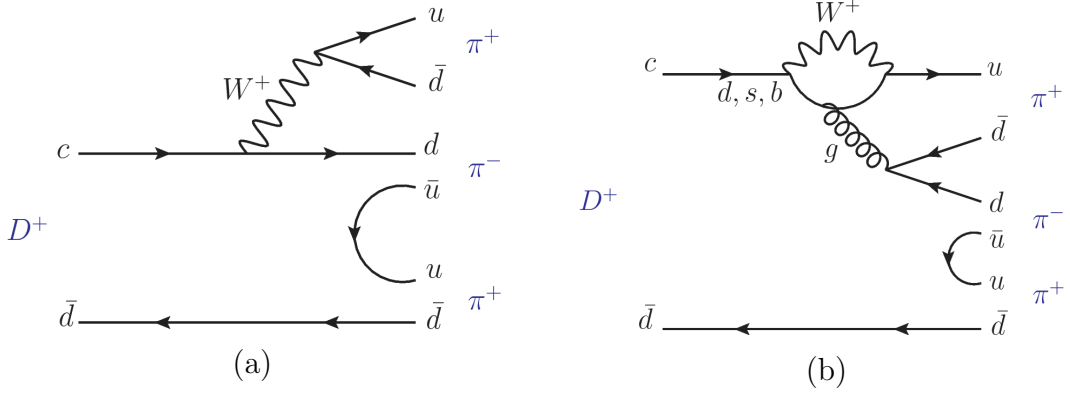


Figure 2.3: Parton-level diagrams for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decays: (a) a tree diagram, and (b) a penguin process.

ing Group (HFAG) in [37]. In the neutral sector, there are contributions from direct and indirect CP asymmetries. The combination of A_Γ and ΔA_{CP} measurements in the hadronic two body decays of the neutral D^0 meson is shown in Figure 2.4.

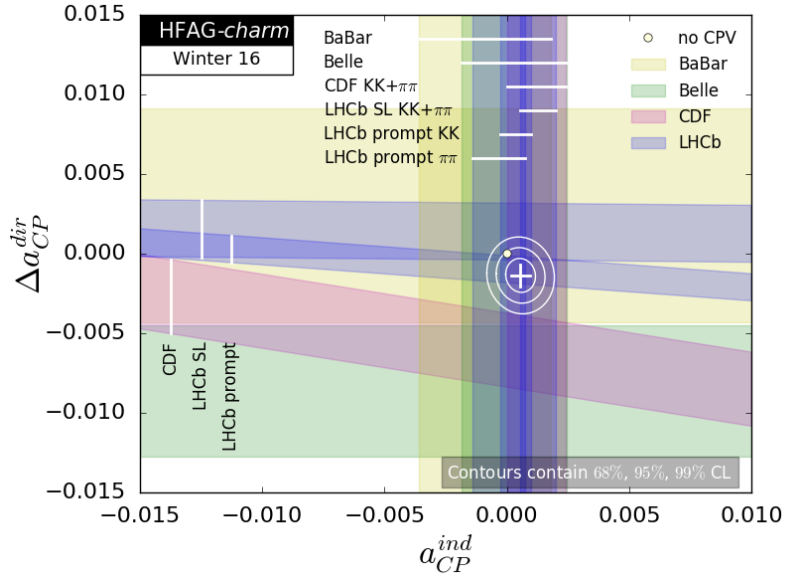


Figure 2.4: This combination plot shows the measurements listed by Heavy Flavor Averaging Group (HFAG) [38] for ΔA_{CP} and A_Γ , where the bands represent $\pm 1\sigma$ intervals. The point of no CP violation (0,0) is shown as a filled circle, and two-dimensional 68% CL, 95% CL, and 99.7% CL regions are plotted as ellipses with the best fit value as a cross indicating the one-dimensional uncertainties in their center. [39]

A search for direct CPV in D^+ decays is the subject of this thesis. In particular, the decays into the hadronic final states $K^-K^+\pi^+$ and $\pi^-\pi^+\pi^+$ are analyzed. Both of them are Cabibbo-suppressed decays and have branching ratios of $(9.54 \pm 0.26) \times 10^{-3}$ and $(3.18 \pm 0.18) \times 10^{-3}$, respectively [29].

The first measurement of CPV in charged D meson decays was performed by the E687 collaboration, in 1994 [40]. Using the data collected in the 1990–1991 run of their photoproduction experiment, where a photon beam with mean energy ~ 220 GeV interacted with a beryllium target, they measured the A_{CP} of four charm decay modes, including the $D^+ \rightarrow K^-K^+\pi^+$. For this decay, the asymmetry measured was $A_{CP} = (-3.1 \pm 6.8)\%$.

In 1997, the E791 collaboration reported results of a search for CPV in CS decays including a new measurement for $D^+ \rightarrow K^-K^+\pi^+$ and the first measurement for the $D^+ \rightarrow \pi^-\pi^+\pi^+$ [41]. The charm sample was produced through 500 MeV/ c $\pi - N$ interactions in a platinum-diamond target in the 1991–1992 fixed-target run. The asymmetries were measured to be $A_{CP}(K^-K^+\pi^+) = (-1.4 \pm 2.9)\%$ and $A_{CP}(\pi^-\pi^+\pi^+) = (-1.7 \pm 4.2)\%$.

FOCUS (E831) was a heavy-flavor photoproduction experiment of Fermilab, an upgraded version of its predecessor E687. It collected data during the 1996–1997 fixed-target run. In 2000, with the tens of thousand $D^\pm \rightarrow K^-K^+\pi^\pm$ candidates, the collaboration reported a measurement of A_{CP} as $(+0.6 \pm 1.1 \pm 0.5)\%$, where the first error is statistical and the second error is systematic [42].

The B-factories also produced a large sample of charm data. With a data sample of 79.9 fb^{-1} collected by the BaBar detector on and below the $\Upsilon(4S)$ resonance at the PEP-II asymmetric energy e^+e^- storage ring at SLAC, a measurement of the A_{CP} for the $D^+ \rightarrow K^-K^+\pi^+$ was reported in 2005 [36]. The measured asymmetry was $A_{CP} = (+1.4 \pm 1.0 \pm 0.8)\%$. This measurement was updated in 2013 with a larger sample, 476 fb^{-1} and hundreds of thousand $D^\pm \rightarrow K^-K^+\pi^\pm$ candidates, and the new result was $A_{CP} = (+0.37 \pm 0.30 \pm 0.15)\%$ [16].

In 2014, the CLEO collaboration also measured asymmetries in their report of hadronic branching fractions and cross section [43]. Using the full CLEO-c data sample of 818 pb^{-1} of e^+e^- data taken at the $\psi(3770)$ resonance, which is just above the threshold for $D\bar{D}$ production, they measured $A_{CP} = (-0.1 \pm 0.9 \pm 0.4)\%$.

The current COMBOS average provided by HFAG for CP asymmetry in $D^+ \rightarrow K^- K^+ \pi^+$ is $(+0.32 \pm 0.31)\%$.

For three-body decays, in addition to the global asymmetry A_{CP} used in the measurements listed above, it is possible to search for CPV in the phase space. Asymmetries localized in regions of the two-dimensional phase space may have opposite signs. When integrated over the phase space, these effects would cancel, resulting on a very small net effect.

The CLEO collaboration published in 2008 a search for CPV in the Dalitz-plot analysis of $D^+ \rightarrow K^- K^+ \pi^+$ [17]. With 818 pb^{-1} of e^+e^- collision data collected at a centre-of-mass energy of 3774 MeV, they analyzed the resonant substructure of the decay and searched for CPV in the resonant channels. No evidence for CPV was found and the measurement of an integrated CP asymmetry across the Dalitz plot led to $\mathcal{A}_{CP} = (-0.4 \pm 2.0^{+0.2+0.6}_{-0.5-0.3})\%$, where the errors are statistical, experimental systematic and decay-model systematic, respectively.

The LHCb collaboration performed a search for direct CP violation in the decay $D^+ \rightarrow K^- K^+ \pi^+$, published in 2011 [11], using the pp collision data taken in 2010, corresponding to an integrated luminosity of 35 pb^{-1} . The normalized Dalitz plot distributions for D^+ and D^- were compared using different binning schemes sensitive to different manifestations of CP violation. No evidence for CPV was found in this study.

In the report where BaBar updated their A_{CP} measurement, there were also searches for CPV in the phase space using different strategies [16]: looking at the CP asymmetry in four regions of the Dalitz plot, a comparison of the binned D^+ and D^- Dalitz plots, a comparison of the Legendre polynomial moment distributions for

the K^+K^- and $K^-\pi^+$ systems, and a comparison of the parameterized fits to the Dalitz plots. No evidence for CPV was found.

In 2013, the LHCb collaboration reported a search for CP violation in the phase space of the decay $D^+ \rightarrow \pi^-\pi^+\pi^+$ [12] using the pp collision data taken in 2011 at a centre-of-mass energy of 7 TeV, corresponding to an integrated luminosity of 1.0 fb^{-1} . The Dalitz plot distributions for 3.1×10^6 D^+ and D^- candidates were compared with binned and unbinned model independent techniques. No evidence for CP violation was found in this search.

CPV studies in decays of $B^+ \rightarrow h_1^+ h_2^- h_3^+$ ($h_i^\pm = K^\pm, \pi^\pm$) at LHCb [13–15] obtained surprising results: asymmetries of up to 80% were observed in regions of the phase space. In addition, large asymmetries were observed in regions away from resonances. In the latter case, the observed asymmetries have same sign across the Dalitz plot, being positive or negative depending on the final state. In the $B^+ \rightarrow K^+K^-K^+$ and $B^+ \rightarrow K^+\pi^-\pi^+$ decays, the asymmetries have opposite sign and nearly the same intensity. The same happens to the $B^+ \rightarrow K^+K^-\pi^+$ and $B^+ \rightarrow \pi^+\pi^-\pi^+$ decays.

A possible interpretation for this result is based on a mechanism for CPV not yet considered: the hadronic final state rescattering. In this case, the rescattering $K^+K^- \leftrightarrow \pi^+\pi^-$ that connects the different final states provides the strong phase difference required for CPV to occur. The CPT symmetry imposes that the total decay width of particle and antiparticle must be equal. For a family of final states with same quantum numbers, this constraint implies the sum of partial widths to be the same for particle and antiparticle,

$$\sum_i \Gamma(P \rightarrow f_i) = \sum_i \Gamma(\bar{P} \rightarrow \bar{f}_i) \quad (2.9)$$

In other words, a negative asymmetry in one channel of the family must be followed by a positive asymmetry in other channels of the same family. In this way, the CPV happens in elementary processes at parton level but is spread by final

state interactions among several channels. The intensity of the effect observed in B^+ mesons indicates the importance of this mechanism.

In the charm scenario, the phase space is reduced in comparison to the one of B^+ mesons. The rescattering $K^+K^- \leftrightarrow \pi^+\pi^-$ affects the full phase space of the $D^+ \rightarrow K^-K^+\pi^+$ and a large part of the $D^+ \rightarrow \pi^-\pi^+\pi^+$ decay. The result is a global, phase space integrated asymmetry.

According to these arguments, the rescattering is expected to produce global asymmetries of opposite signs in the $D^+ \rightarrow K^-K^+\pi^+$ and $D^+ \rightarrow \pi^-\pi^+\pi^+$ decays. Therefore, the difference between the asymmetries would be an observable of larger sensitivity than the individual asymmetries for each channel. In addition, the difference allows the cancellation of production and detection asymmetries common to both decay modes.

Chapter 3

The LHCb detector

The LHCb (Large Hadron Collider beauty experiment) is one of the four main experiments at the LHC (Large Hadron Collider). Its primary goal is to look for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons [44]. In this chapter, the main features of the LHC accelerator and the LHCb detector are described.

3.1 The LHC accelerator

The LHC [45] is a hadron collider built on the border between France and Switzerland. It was built in the 27-kilometer tunnel of its predecessor LEP (Large Electron-Positron Collider), about 100 m underground. It was designed to collide proton beams with a center-of-mass energy ($\sqrt{s}$) of up to 14 TeV.

Before the injection into the LHC, the protons are pre-accelerated in a succession of machines with increasingly higher energies in the CERN accelerator complex (Figure 3.1). The protons are taken from hydrogen atoms and injected into a linear accelerator (Linac2), where they reach an energy of 50 MeV. They are then injected into the PSB (Proton Synchrotron Booster), where they reach 1.4 GeV. Following the chain, they go through the PS (Proton Synchrotron) reaching 25 GeV. In the sequence, the protons are sent to the SPS (Super Proton Synchrotron), where they

are accelerated to 450 GeV. Finally, they are injected into the LHC to reach the maximum energy of 7 TeV. The LHC also operates with heavy ion beams.

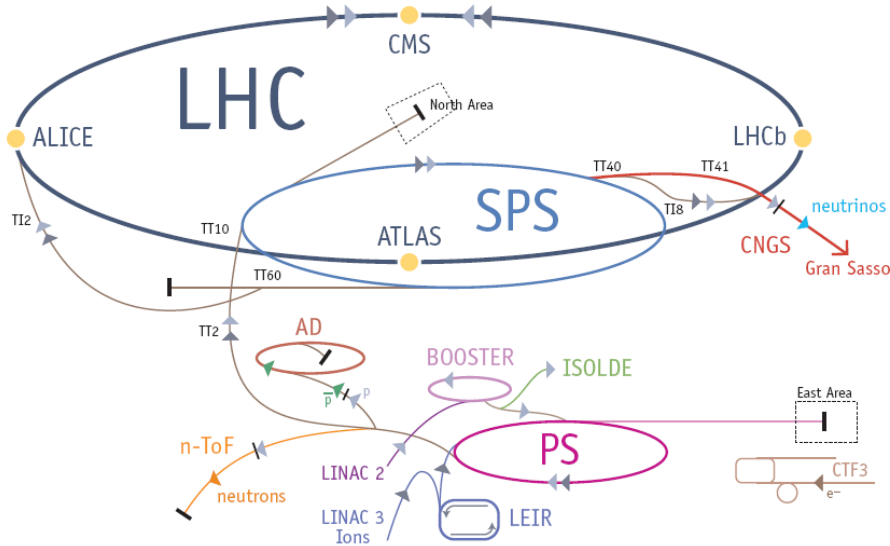


Figure 3.1: The accelerator complex at CERN [46].

The first LHC collisions happened with an energy of 450 GeV per proton beam, in 2009. The first $\sqrt{s} = 7$ TeV collisions were recorded in 2010. The Run-1 comprises the data taking period of 2011, with pp collisions with a center-of-mass energy of 7 TeV (3.5 for each beam), and 2012, with pp collisions with a center-of-mass energy of 8 TeV (4 TeV for each beam).

There are seven experiments placed along the LHC perimeter: the main four, ALICE, ATLAS, CMS and LHCb, and the three smaller, LHCf, MoEDAL and TOTEM. An illustration of the LHC and the four main experiments is shown in Figure 3.2.

ALICE (A Large Ion Collider Experiment) [47] is an experiment dedicated to Heavy Ion Physics. It is designed to address the physics of strongly interacting matter and the quark-gluon plasma at extreme values of energy density and temperature in nucleus-nucleus collisions.

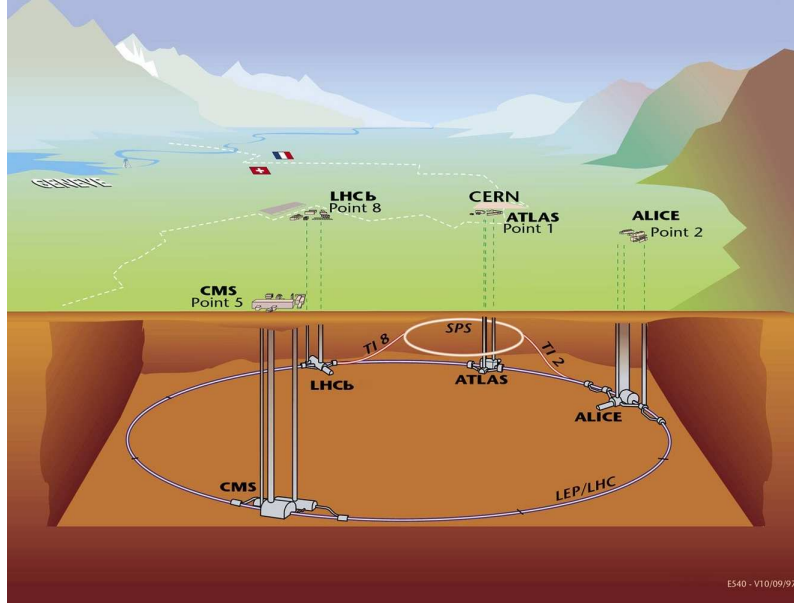


Figure 3.2: Illustration of the LHC and its main experiments.

ATLAS (A large Toroidal LHC ApparatuS) [48] and CMS (The Compact Muon Solenoid) [49] are the two general purpose experiments. Designed to cover a wide range of physics in the LHC, from the search to the Higgs Boson to supersymmetry (SUSY) and extra dimensions, they have different design and different technical solutions.

LHCb (Large Hadron Collider beauty experiment) [44] is an experiment dedicated to heavy flavour physics focused on the study of CP violation and rare decays of b and c-hadrons, as mentioned in the beginning of this chapter. It will be described in the following section.

LHCf (Large Hadron Collider forward) [50] is an experiment dedicated to the measurement of neutral particles emitted in the very forward regions of LHC collisions. The physics goal is to provide data for calibrating the hadron interaction models that are used in the study of Extremely High-Energy Cosmic-Rays. It is located near the ATLAS detector.

MoEDAL (Monopole and Exotics Detector at the LHC) [51] has as prime motivation direct searches for the Magnetic Monopole and other highly ionizing Stable (or

pseudo-stable) Massive Particles (SMPs) at the LHC. It is located near the LHCb detector.

TOTEM (TOTAl Elastic and diffractive cross section Measurement) [52] will measure the total pp cross-section with a luminosity-independent method and study elastic and diffractive scattering at the LHC. It is located near the CMS detector.

3.2 The LHCb detector

LHCb is a single-arm spectrometer with a forward angular coverage from approximately 10 mrad to 300 mrad in the horizontal plane and from approximately 10 mrad to 250 mrad in the vertical plane. The layout of the LHCb spectrometer is shown in Figure 3.3.

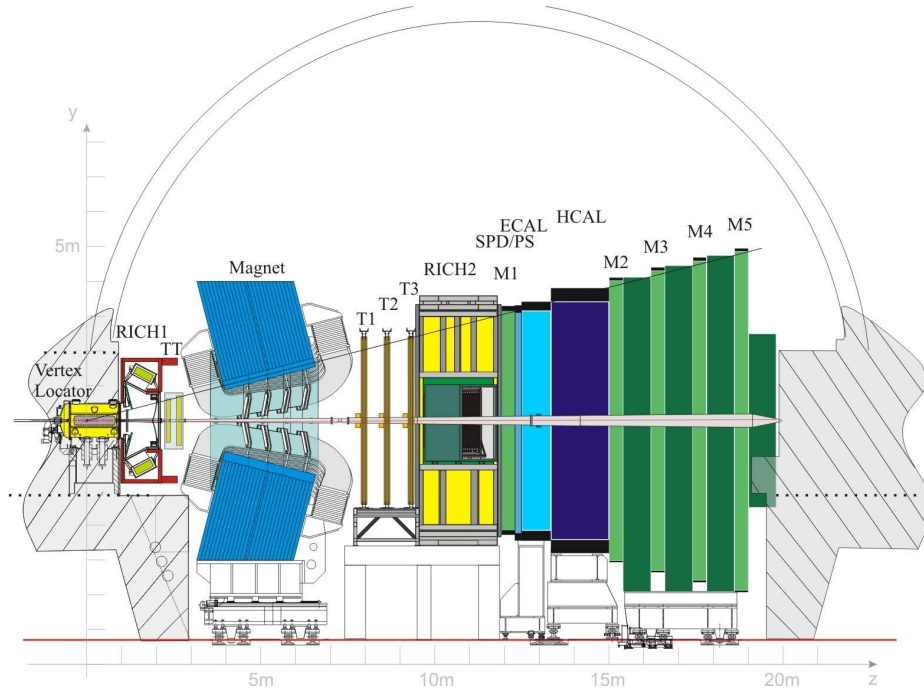


Figure 3.3: View of the LHCb detector.

The choice of the detector geometry is justified by the fact that at high energies both the b -e $\bar{b}$ -hadrons are predominantly produced in the same forward or backward

cone (see Figure 3.4). The right-handed coordinate system adopted has the z axis along the proton beam and the y axis along the vertical.

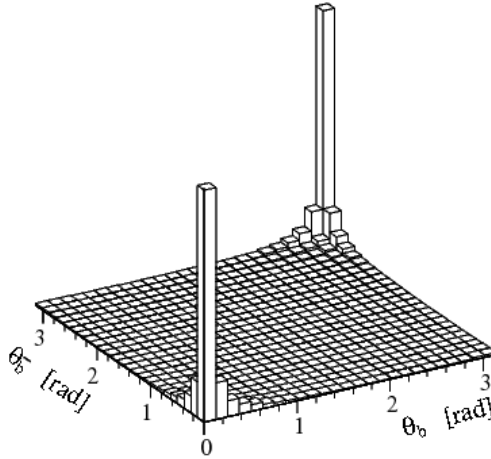


Figure 3.4: Polar angles of the b - and $\bar{b}$ -hadrons calculated by the PYTHIA event generator [53].

The LHCb detector is composed of several subdetectors, as can be seen in Figure 3.3. In the remaining of this chapter, an overview of these subsystems is given, with emphasis on aspects which are important for the analysis presented in this thesis.

3.2.1 The interface to the LHC machine

The beampipe design is particularly delicate since the LHCb experiment is frontal and its detectors are close to the beam, where the particle density is high. The critical aspect in the optimisation of design and choice of material is the minimization of secondary interactions between produced particles in the primary interaction and the beampipe. This is crucial, mainly in the regions close to the tracking stations and RICH detectors.

The beampipe, schematically represented in Figure 3.5, includes the forward window of the VELO, covering the full LHCb acceptance, and four main conical sections. The three sections closer to the interaction point are made of beryllium and the one further away are produced with stainless steel. Beryllium was chosen

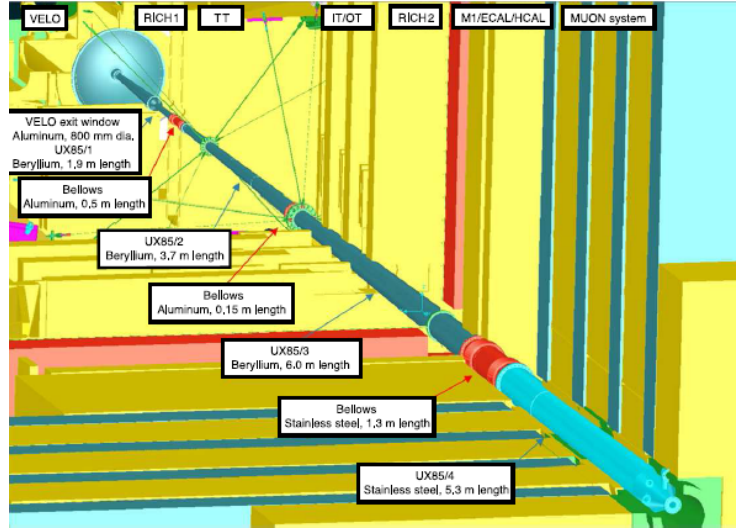


Figure 3.5: Beam pipe scheme. The 19 m long vacuum chamber inside the LHCb experiment is divided into four main sections. The first three are made of machined beryllium cones assembled by welding and the fourth of stainless steel. Bellows expansion joints provide interconnect flexibility in order to compensate for thermal expansions and mechanical tolerances [44].

as the material for 12 m out of the 19 m long beampipe for its transparency and elasticity. However, its toxicity, fragility and cost are drawbacks which had to be taken into account in the design, installation and operation phases. Flanges, bellows and the VELO exit window are made of high strength aluminium alloys. The remaining length, situated outside the critical zone in terms of transparency, is made of stainless steel, a material widely used in vacuum chambers because of its good mechanical and vacuum properties.

The experiment beam vacuum is isolated from the LHC vacuum with two sector valves, installed at the cavern entrances, which allow interventions and commissioning independently of the machine vacuum system.

In order to cope with possible adverse LHC beam conditions, particularly with hadronic showers caused by misaligned beams or failures of components upon particle injection into the LHC, the LHCb experiment is equipped with a Beam Conditions Monitor (BCM). This system monitors the particle flux at two locations in

the close vicinity of the vacuum chamber to protect the sensitive LHCb tracking devices. The BCM connects to the LHCb experiment control system and to the beam interlock controller of the LHC. More information can be found in [44].

3.2.2 Magnet

A dipole magnet is used in the LHCb experiment to allow the measurement of the momentum of charged particles. The magnet, shown in Figure 3.6, provides a magnetic field in the y direction of 4 Tm integrated along 10 m. It has saddle-shaped coils in a window-frame yoke with sloping poles.

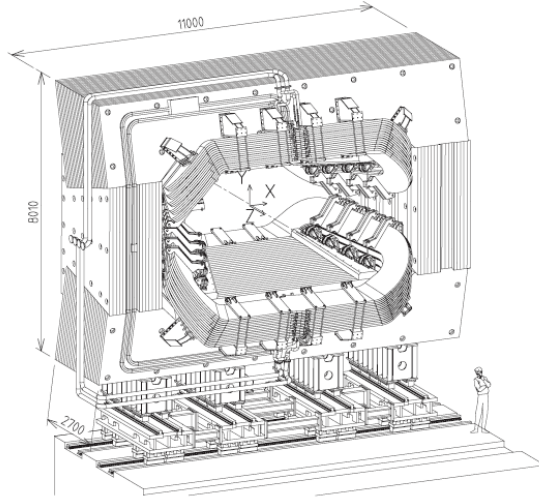


Figure 3.6: Perspective view of the LHCb dipole magnet with its current and water connections (units in mm). The interaction point lies behind the magnet. [44].

The magnet is operated via the Magnet Control System that controls the power supply and monitors a number of operational parameters (e.g. temperatures, voltages, water flow, mechanical movements, etc.). A second, fully independent system, the Magnet Safety System (MSS), ensures the safe operation and acts autonomously by enforcing a discharge of the magnet if critical parameters are outside the operating range.

To control the systematic effects of the detector, the direction of the magnetic field is periodically changed. This is important mainly for measurements of CP

asymmetries. In the analysis presented in this thesis, we analyze separately the data taken with the magnet field polarity directed towards the positive y axis (*MagUp*) and the data taken with magnet polarity directed towards the negative y axis (*MagDown*). The magnetic field along the z axis is shown in Figure 3.7.

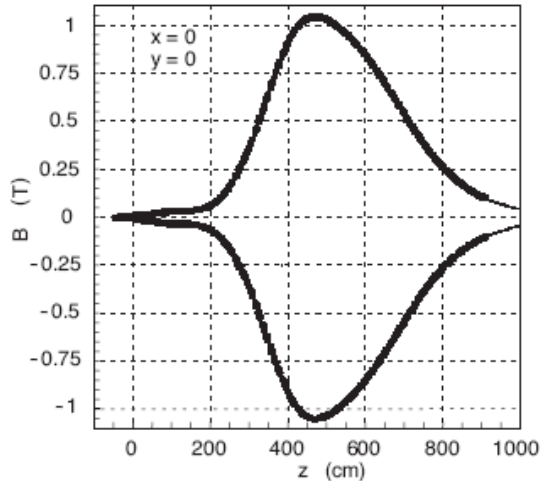


Figure 3.7: Magnetic field along the z axis [44].

Additional information about the magnet can be found in [44] and [54].

3.2.3 VELO

The VERtEX LOcator (VELO) [44, 55] provides precise measurements of track coordinates close to the interaction region, which are used to identify displaced secondary vertices, distinctive features of b and c -hadron decays. The VELO consists of a series of silicon modules, each providing a measure of the r and ϕ coordinates, arranged along the beam direction (Figure 3.8). To preserve the detector, the VELO has a retractable system which allows it to keep each of its halves in a distance of 3 cm away from the operating position during the injection and beam acceleration, and in a distance of 8 mm from the beam (VELO closed) when this is already collimated and stable. The detectors are mounted in a vessel that maintains vacuum around the sensors and is separated from the machine vacuum by a thin walled corrugated

aluminium sheet. This is done to minimize the material traversed by a charged particle before it crosses the sensors and the geometry is such that it allows the two halves of the VELO to overlap when in the closed position.

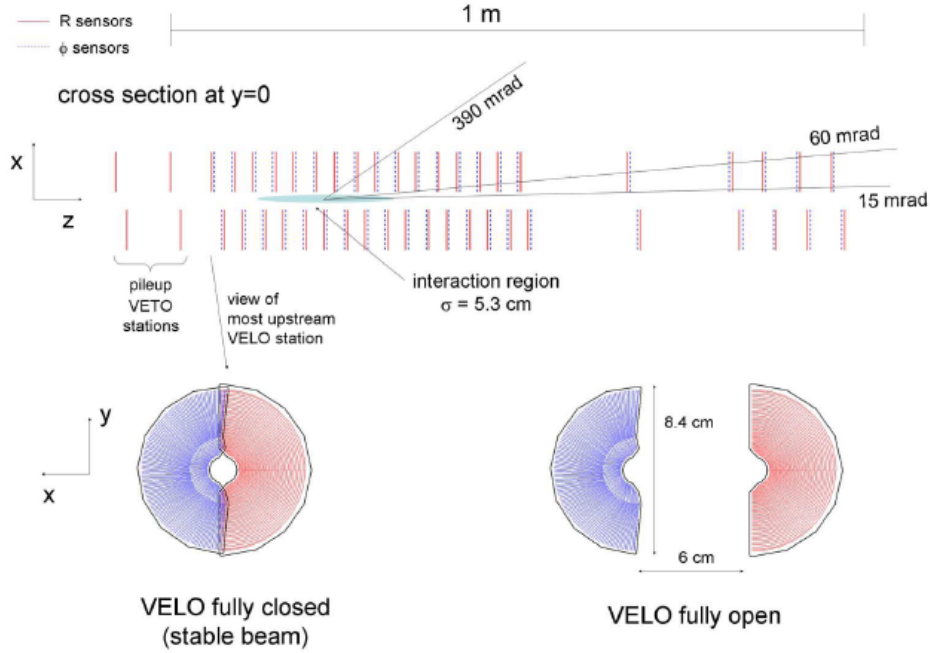


Figure 3.8: Cross section in the (x,z) plane of the VELO silicon sensors, at $y = 0$, with the detector in the fully closed position. The front face of the first modules is also illustrated in both the closed and open positions. The two pile-up veto stations are located upstream of the VELO sensors [44].

The measurement of the coordinates is performed by two kind of sensors: the R-sensor, which provides information on the radial distance r from the beam axis, and the ϕ -sensor, which provides information on the azimuthal coordinate ϕ . The third coordinate is provided by knowledge of the position of each sensor plane within the experiment. Both sensors use microstrip silicon detectors and are $300 \mu\text{m}$ thick. The R-sensor has azimuthal strips and the ϕ -sensor has radial strips. The sensors are shown in Figure 3.9. The use of cylindrical geometry ($r\phi$ coordinates) was chosen in order to enable fast reconstruction of tracks and vertices in the LHCb trigger¹.

¹The trigger will be described in Section 3.2.8

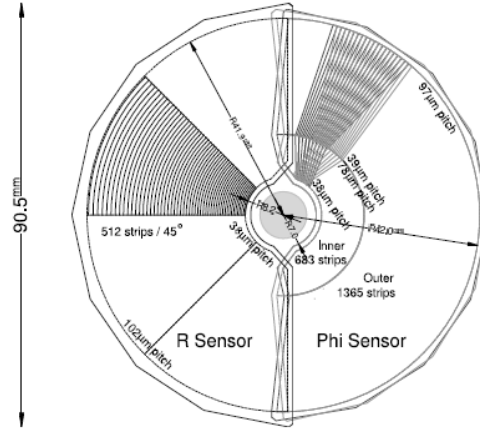


Figure 3.9: Sketch illustrating the $r\phi$ geometry of the VELO sensors. For clarity, only a portion of the strips are illustrated. [44].

Located close to the interaction region, the VELO is under high radiation doses. Protection against radiation and residual fields were designed taking into account the transparency level necessary to avoid additional interactions.

The VELO properties provide spacial resolution in the primary vertex reconstruction of $40\ \mu\text{m}$ in the z axis and $10\ \mu\text{m}$ in the direction perpendicular to the beam.

Two planes perpendicular to the beam-line and located upstream of the VELO sensors form the pile-up veto system, which helps in the trigger decision. Each plane consists of two R-sensors. The pile-up system estimates the number of primary pp interactions in each beam crossing.

3.2.4 Tracking Stations

Together with VELO, the tracking stations, TT (Tracker Turicensis), T1, T2 and T3, compose the LHCb tracking system. The stations TT and T1-T3, are separated by the magnet, as illustrated in Figure 3.3. The T1-T3 are divided in two parts: the region close to the beampipe (Inner Tracker, IT) and the outer region (Outer Tracker, OT). These two detector regions were built with different technologies. The

IT, as the TT, uses silicon microstrip detectors, whereas straw-tubes are employed in the OT. An illustration of the tracking stations can be seen in Figure 3.10.

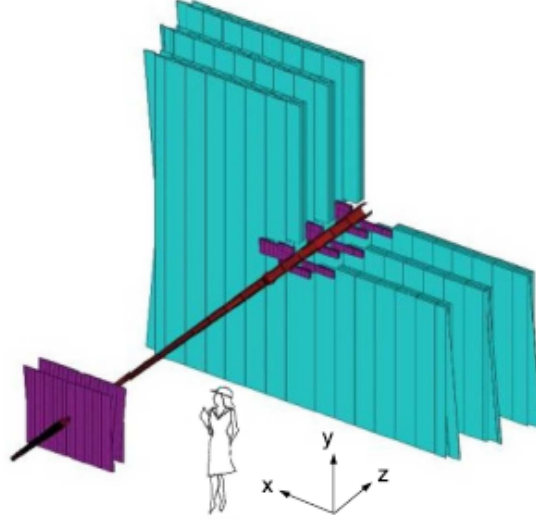


Figure 3.10: Tracking stations, TT, T1, T2 and T3. The IT, in purple, in the inner region of T's, and the OT, in blue, in the outer region [44].

The TT is a 150 cm wide and 130 cm high planar tracking station. It covers the full acceptance of the experiment. The IT covers a 120 cm wide and 40 cm high cross shaped region in the center of the three tracking stations. Both TT and IT have four detection layers in an $(x-u-v-x)$ arrangement with vertical strips in the first and last layers and strips rotated by a stereo angle of -5° and $+5^\circ$ in the second and third layers, respectively. The layout of the third TT detection layer is shown in Figure 3.11. The TT has an active area of about 8.4 m^2 and the IT has an active area of 4.0 m^2 .

Each of the three IT stations consists of four individual detector boxes that are arranged around the beampipe as shown in Figure 3.12. Each detector box contains four detection layers and each detection layer consists of seven detector modules. The resulting layout and dimensions of one of the IT detection layers are illustrated in Figure 3.13.

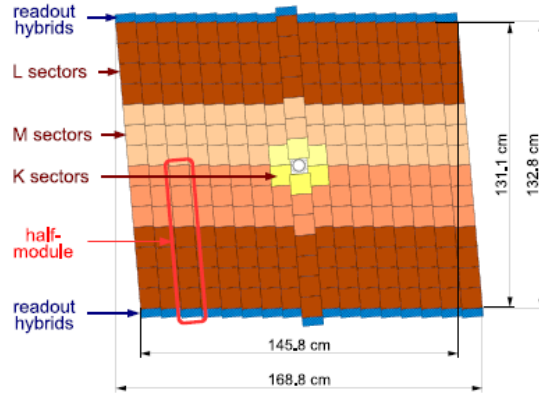


Figure 3.11: Layout of the third TT detection layer. Different readout sectors are indicated by different shadings [44].

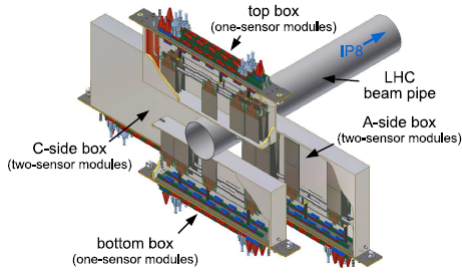


Figure 3.12: View of the four IT detector boxes arranged around the LHC beampipe [44].

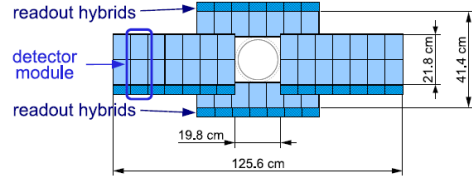


Figure 3.13: Layout of an x detection layer in the second IT station [44].

The OT is a drift-time detector designed as an array of individual, gas-tight straw-tube modules. The modules are composed of two staggered layers of 64 drift tubes each, as shown in Figure 3.14. The drift-tubes have an inner diameter of 4.9 mm and are filled by a mixture of Argon (70%) and CO_2 (30%), chosen in order to guarantee a fast drift time (below 50 ns) and a sufficient drift-coordinate resolution ($200 \mu\text{m}$). The total active area of a OT station is $5971 \times 4850 \text{ mm}^2$.

The trajectories of the charged particles traversing the tracking system are reconstructed from hits in the VELO, TT, IT and OT detectors. This is very important to identify the signatures of the decays. The average tracking efficiency is above 96% in the momentum range $5 \text{ GeV}/c < p < 200 \text{ GeV}/c$ and in the pseudorapidity

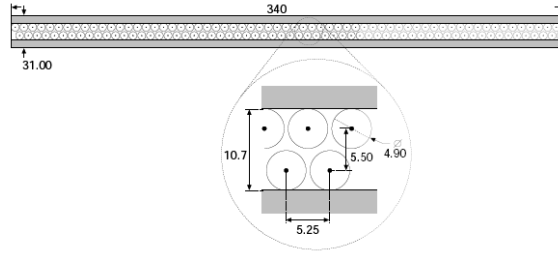


Figure 3.14: Cross section of a straw-tubes module of OT [44].

range $2 < \eta < 5$, which covers the phase space of LHCb [56].

More information about the tracking stations can be found in [44], [57] and [58].

3.2.5 RICH

Particle identification (PID) is a fundamental requirement for LHCb. To this purpose, LHCb has two RICH (Ring Imaging Cherenkov) detectors, mainly responsible for separating kaons from pions. The RICH is a detector which uses Cherenkov radiation, emitted when a particle traverses a medium, called radiator, with speed higher than speed of light in that medium. This radiation is emitted with a characteristic angle (θ_c) which depends on the speed of the particle. Measuring its momentum, it is possible to determine its mass. The radiator is chosen to provide a good distinction between particles in a given momentum range. The LHCb has two RICH detectors with different radiators to cover the full momentum range (see Figure 3.15).

The RICH 1 detector is located upstream of the LHCb dipole magnet, between the VELO and the TT. It identifies charged particles in the low momentum range (from 1 to 60 GeV/c, approximately), using as radiators aerogel and fluorobutane (C_4F_{10}) covering a wide acceptance: from ± 25 mrad to ± 300 mrad, in the horizontal, and from ± 25 mrad to ± 250 mrad, in the vertical direction. A scheme, a 3D model and a photo of the RICH 1 detector are shown in Figure 3.16.

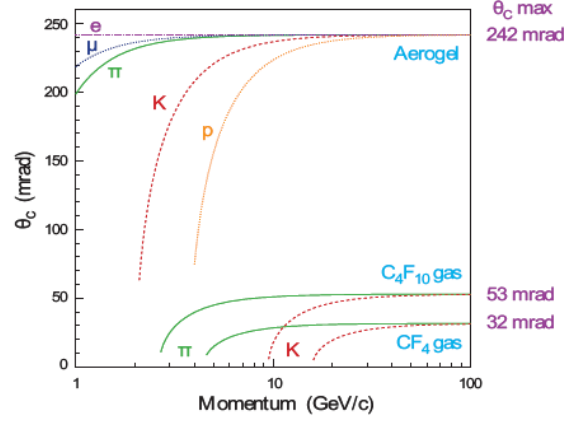


Figure 3.15: Cherenkov angle versus particle momentum for the RICH radiators [44].

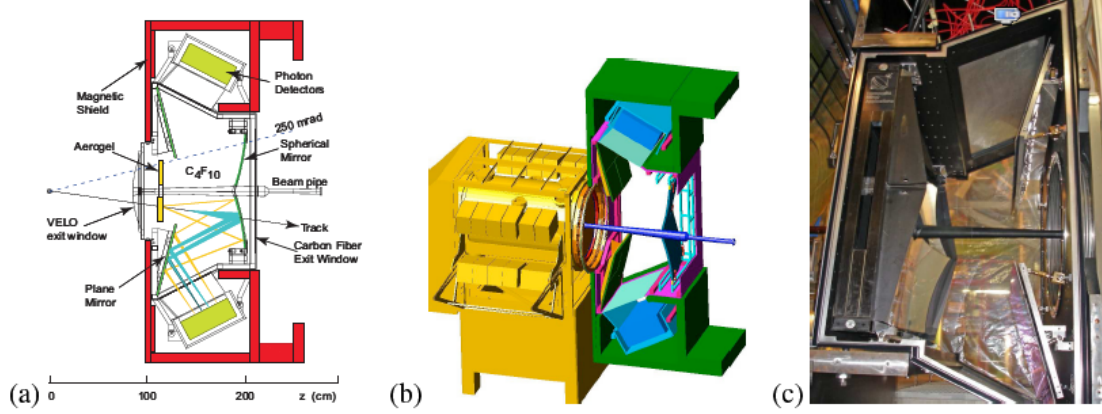


Figure 3.16: (a) Side view schematic layout of the RICH 1 detector. (b) Cut-away 3D model of the RICH 1 detector, shown attached by its gas-tight seal to the VELO tank. (c) Photo of the RICH1 gas enclosure containing the flat and spherical mirrors. Note that in (a) and (b) the interaction point is on the left, while in (c) is on the right [44].

The RICH 2 detector is located downstream of the magnet, between the last tracking station (T3) and the first muon station (M1)². It contains a CF_4 gas radiator, providing PID in the high momentum range from approximately 15 to 100 GeV/c and has a limited acceptance from ± 15 mrad to ± 120 mrad, in the horizontal, and from ± 15 mrad to ± 100 mrad, in the vertical direction, covering the region where the high momentum particles are produced. Two schematic layouts and a picture

²The muon system will be described in Section 3.2.7.

of the RICH 2 are shown in Figure 3.17.

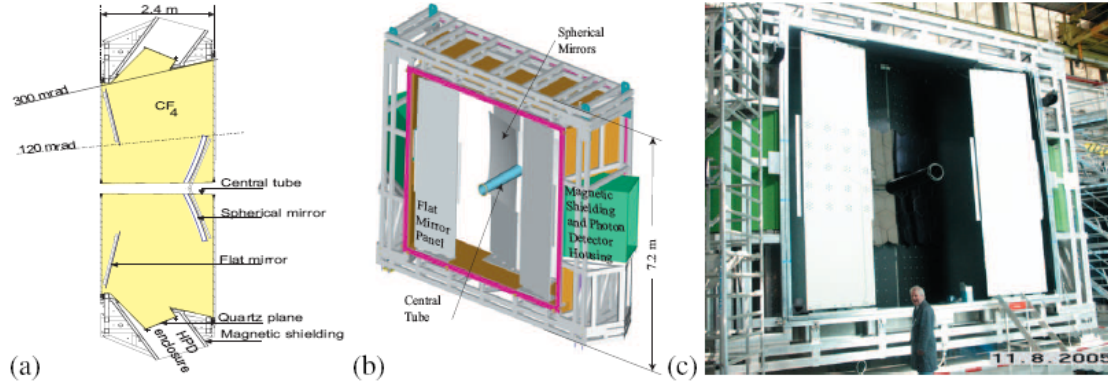


Figure 3.17: (a) Top view schematic of the RICH 2 detector. (b) A schematic layout of the RICH 2 detector. (c) A photograph of RICH 2 with the entrance window removed [44].

In both RICH detectors the focusing of the Cherenkov light is accomplished using a combination of spherical and flat mirrors to reflect the image out of the spectrometer acceptance. Hybrid Photon Detectors (HPD) are used to detect the Cherenkov photons in the wavelength range 200-600 nm. The pixel-HPD is shown in Figure 3.18.

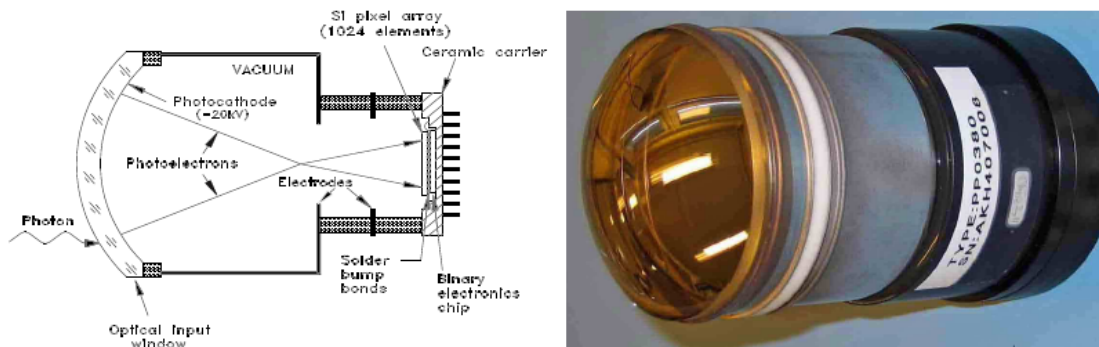


Figure 3.18: A schematic (left) and a photograph (right) of the pixel-HPD [44].

The Cherenkov angle information must be combined with the momentum measured by the tracking system to determine the particle species for each track [59].

An overall event log-likelihood algorithm is employed, where all tracks in the event and in both RICH detectors are considered simultaneously. At the starting point, all particles are assumed to be pions, since they are the most abundant particles in pp collisions. Then, for each track in turn, the mass hypothesis is changed to electron, muon, kaon and proton. The one which gives the largest increase in the event likelihood is set as preferred value of the mass hypothesis for that track. The differences in the log-likelihood values $\Delta \log \mathcal{L}$ are the final results of the particle identification. They give for each track the change in overall event log-likelihood when that track is changed from pion hypothesis to each of the electron, muon, kaon and proton hypotheses. These values are then used to identify particle types. In the decays of this analysis, there are kaons and pions in the final state then the difference between kaons and pions $\Delta \log \mathcal{L}(K - \pi)$ is used in the selection. The kaon efficiency (kaons identified as kaons) and pion misidentification (pions identified as kaons), as a function of particle momentum, obtained from imposing two different requirements on this distribution, are shown in Figure 3.19.

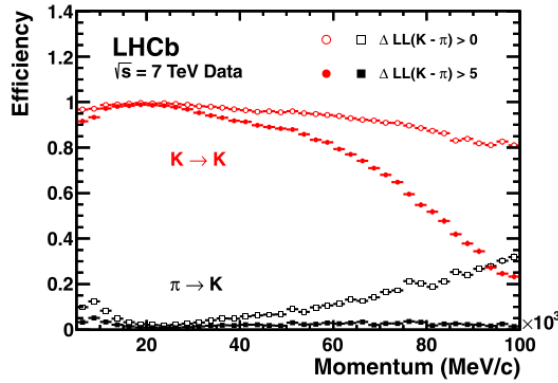


Figure 3.19: Kaon identification efficiency and pion misidentification rate measured on data as a function of track momentum. Two different $\Delta \log \mathcal{L}(K - \pi)$ requirements have been imposed on the samples, resulting in the open and filled marker distributions, respectively [59].

In this analysis, the ProbNN variables are also used. They combine the PID

information obtained separately from the muon, RICH and calorimeter systems³. It takes into account correlations between the detector systems. This is carried out using multivariate techniques, combining PID information from each sub-system into a single probability value for each particle hypothesis [56]. We use the variable related to the kaon hypothesis, the ProbNNk.

More information about the RICH detectors can be found in [44] and [60], and about their performance in [56] and [59].

3.2.6 Calorimeters

The calorimeter system [44, 61] has as main purposes to provide values of transverse energy⁴ (E_t) for the first trigger level⁵ (L0), and identify electrons, photons and hadrons, measuring their energy and position. This system is composed by an electromagnetic (ECAL) and a hadronic (HCAL) calorimeter, a Scintillator Pad Detector (SPD) and a PreShower (PS). The latter two components were included in the system to help the electron trigger in the rejection of background due to neutral and charged pions. PS/SPD, ECAL and HCAL adopt a variable lateral segmentation, shown in Figure 3.20, since the hit density varies over the calorimeter surface. ECAL and PS/SPD are divided in three different regions and the HCAL is divided in two regions. All calorimeters follow the same basic principle: scintillation light is transmitted to a Photo-Multiplier (PMT) by wavelength-shifting (WLS) fibers.

The SPD and the PS are placed before the ECAL and are separated by a 15 mm lead converter $2.5 X_0$ thick and have a sensitive area 7.6 m wide and 6.2 m high. The lead thickness is enough to generate electromagnetic showers but not hadronic showers. The three regions of the PS and SPD have 3072 cells in the inner section, 3584 cells in the middle section and 5376 cells in the outer section, with cell dimensions 4×4 , 6×6 and 12×12 cm², approximately.

³The muon and calorimeter systems will be described in the following sections.

⁴The transverse energy corresponds to the energy of the particle multiplied by the sine of the angle between the velocity of the particle and the beam direction.

⁵The LHCb trigger will be described in Section 3.2.8.

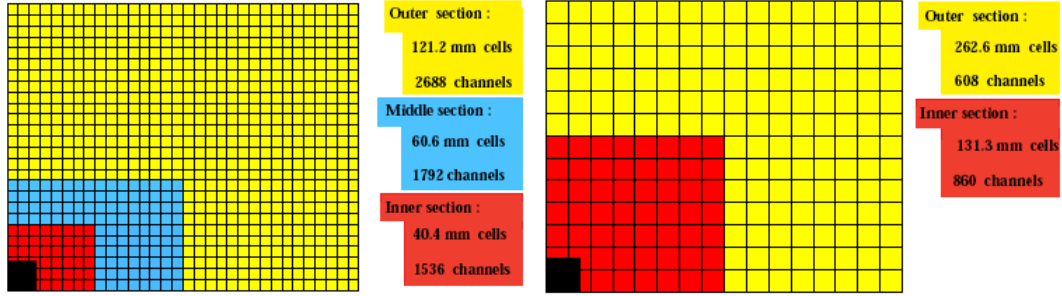


Figure 3.20: Lateral segmentation of the SPD/PS and ECAL (left) and the HCAL (right). One quarter of the detector front face is shown. In the left figure the cell dimensions are given for the ECAL [44].

The ECAL is built from alternating 2 mm thick lead and 4 mm thick scintillator tiles. It is used in the identification of electrons and photons. The energy resolution of ECAL is given by: $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$, with E in GeV.

The HCAL is a sampling device made of iron and scintillating tiles as absorber and active material, respectively. The scintillation tiles orientation runs parallel to the beam axis and, in the lateral direction, the tiles are interspersed with 1 cm iron. It measures the energy and helps in the identification of hadrons. The HCAL has an energy resolution given by: $\sigma_E/E = 69\%/\sqrt{E} \oplus 9\%$, with E in GeV.

3.2.7 Muon System

The selection and identification of muons are fundamental requirements of the LHCb experiment. Muons are present in the final states of many CP-sensitive B decays and of rare B and D decays that have the potential to reveal new physics. They also help in the tag of the initial state flavour of the accompanying neutral B mesons in CP asymmetry and oscillation measurements.

The LHCb muon system is composed of five stations (M1-M5), shown in Figure 3.21. The first station M1 is placed in front of the calorimeters and is used to improve the p_T measurement in the trigger. Stations M2 to M5 are placed downstream the calorimeters and are interleaved with iron absorbers 80 cm thick to select penetrating

muons. The muon stations are the last detectors of LHCb and ideally should be only traversed by muons⁶.

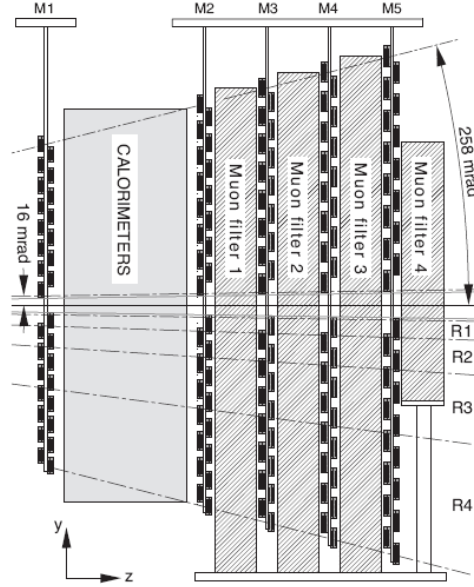


Figure 3.21: Side view of the muon system [44].

Each muon station is divided into four regions, R1 to R4, as shown in Figure 3.22. Multi Wire Proportional Chambers (MWPC) are used for all regions except the inner region of station M1 where the expected particle rate exceeds safety limits for ageing. In this regions, triple-GEM (Gas Electron Multiplier) detectors are used.

The MWPC are filled with a gas mixture of Ar (40%), CO₂ (55%) and CF₄ (5%) in layers 5 mm thick with a wire plane of gold-plated tungsten 30 μ m diameter, with 2 mm spacing between them. The triple GEM detectors consist of three gas electron multiplier (GEM) foils sandwiched between anode and cathode planes and are filled with a gas mixture of Ar (45%), CO₂ (15%) and CF₄ (40%).

The first step in the muon identification strategy is a binary selection of candidates based on the penetration of the tracks through the calorimeters and iron filters, called isMuon. This selection is defined according to the number of stations

⁶Neutrinos are also passing by but they are not detected.

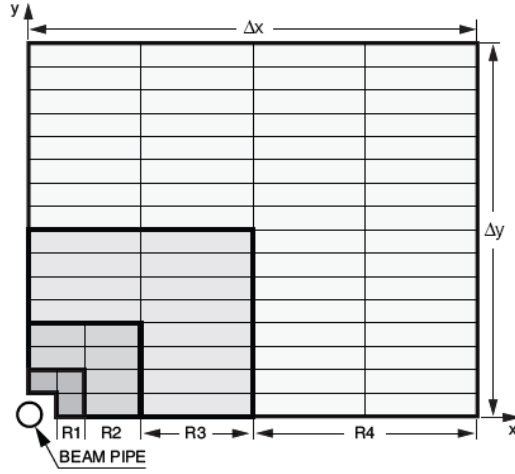


Figure 3.22: Front view of a quadrant of a muon station. Each rectangle represents one chamber. Each station contains 276 chambers [44].

where a hit is found within a field of interest defined along the track extrapolation. The number of stations required to have a muon signal is a function of the track momentum (p), as shown in Table 3.1 [62]. This selection is used in the analysis presented in this work to reduce the background contribution from decays with muons in their final state. For particles with p_T above 1.7 GeV/ c , the efficiency is above 97% in the whole momentum range, from 3 GeV/ c to 100 GeV/ c . The pion and kaon misidentification probabilities are within 0.2-5.6% and 0.6-4.5%, respectively.

Table 3.1: Muon stations required to trigger the isMuon decision as a function of momentum range [62].

Momentum range	Muon stations
$3 \text{ GeV}/c < p < 6 \text{ GeV}/c$	M2 and M3
$6 \text{ GeV}/c < p < 10 \text{ GeV}/c$	M2 and M3 and (M4 or M5)
$p > 10 \text{ GeV}/c$	M2 and M3 and M4 and M5

More information about the muon system can be found in [44] and [63], and about the performance of muon identification in [62].

3.2.8 Trigger

A large amount of data is generated by the pp collisions at the LHC and it is not possible to store all the generated data. The role of the trigger is to enrich the sample we are able to store with events which are interesting for the physics analyses. With a luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, the frequency of beam crossing with visible interactions⁷ in the LHCb is about 10 MHz. This rate must be reduced to approximately 2 kHz, rate at which the data are stored to be analyzed.

The trigger [44,64] is the system responsible for the selection of interesting events. The LHCb trigger is divided in two levels: L0 (Level 0 Trigger) and HLT (High Level Trigger), the latter subdivided in two stages: HLT1 and HLT2. The first level trigger is implemented in hardware and, the second, in software.

The L0 must reduce the data flow from 40 MHz⁸ to 1 MHz by selecting hadrons, electrons and photons with high E_t in the calorimeters and muons with high p_t in the muon system, characteristic of the decay products of b - or c -hadrons due to their large mass. The L0 also uses information from the pile-up system. The information from different subdetectors are collected by the L0 Decision Unit (L0DU) where the event is accepted or not.

The HLT must reduce the data flow from 1 MHz to about 2 kHz. It consists of a C++ application which runs on every CPU of the Event Filter Farm (EFF). It has access to all data in one event. The HLT1 performs a partial reconstruction of the physical properties of the particles using, besides the information from calorimeters and muon system, the information from the VELO and the tracking system, and confirms the L0 decision reducing the data flow to approximately 30 kHz. The HLT2 performs a full reconstruction of the event and executes a number of selection algorithms (called *lines*) which are sets of selection criteria used to identify exclusive or inclusive decays or signatures, reducing the data flow to about 2 kHz. The events

⁷An interaction is defined to be visible if it produces at least two charged particles with sufficient hits in the VELO and T1-T3 to allow them to be reconstructible.

⁸Corresponding to the beam crossing rate at the LHC.

selected by any of the lines are stored and it is possible to know if the candidate was selected by a certain line (**TOS** — Trigger On Signal), i.e., if it fulfilled the requirements of that line, or independent of it (**TIS** — Trigger Independent of the Signal), i.e., accepted by other lines or by being in the same event as a selected candidate. There are some dedicated lines used for this analysis. Details about the track reconstruction and requirements applied in the High Level Trigger are given in [65].

A scheme of the LHCb trigger is shown in Figure 3.23.

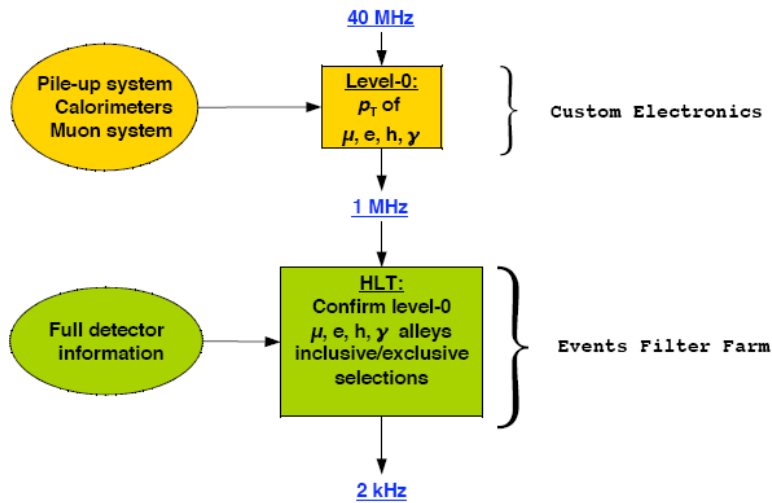


Figure 3.23: Scheme of the LHCb trigger [44].

3.2.9 Dataflow and Software

The events selected by the trigger are recorded as RAW data. The simulated data are recorded in a similar format containing, besides the hit information, extra “truth” information. The RAW data are reconstructed to provide physical quantities from the detector information. The event reconstruction results in the generation of new data, the Data Summary “Tape” (DST). Calibration and alignment data are used in the reconstruction. In the reconstructed data a set of pre-selection algorithms is applied, designed to select particular channels of interest. This is

called *Stripping*, and is a first step in the analysis process [66]. The output data are grouped by physical related processes in the so called *streams*. For this work, the CHARM stream is used as the starting point for the candidate selection. A schematic of the logical dataflow⁹ can be seen in Figure 3.24.

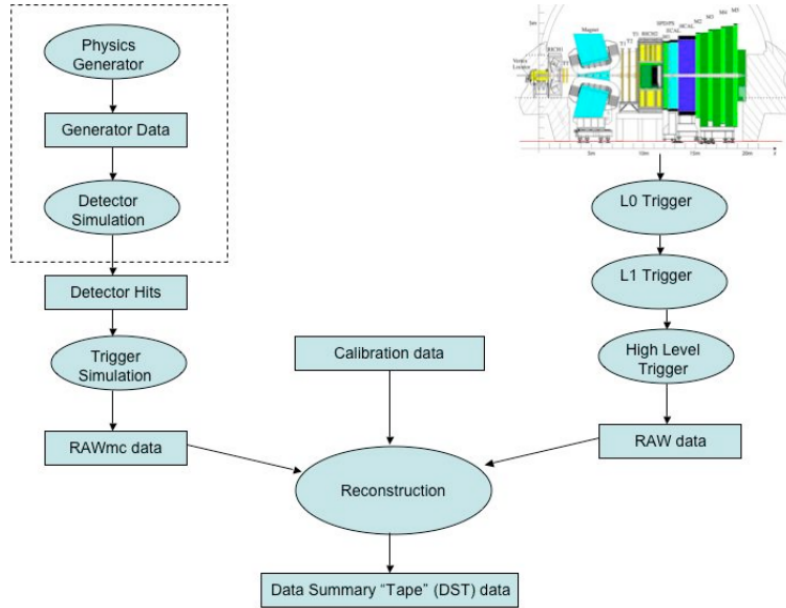


Figure 3.24: The LHCb computing logical dataflow model [67].

The LHCb collaboration has several applications used in the different steps of data processing and simulation. These applications are based on the Gaudi software framework.

The **Gauss** application [68] is used for the generation of simulated data, including the simulation of pp collisions, the decay of the particles and interaction with detectors. It uses some external packages. For the simulation of the pp collisions, it uses PYTHIA [69, 70] and, for the description of the decays of the particles generated in the collision, EVTGEN [71] is used. The simulation of the physics processes in the interaction of the generated particles with the LHCb detector uses the GEANT4 toolkit [72, 73].

⁹A Level-1(L1) trigger was included in the original project of the LHCb trigger but is not included in its current version.

Boole is the digitization application, the final stage of the LHCb detector simulation [66]. It applies the detector response to the hits generated by **Gauss**.

The **Moore** application is the software of the LHCb trigger, used for the implementation of the HLT algorithms.

Brunel is the reconstruction application. It uses the information from the LHCb subdetectors to reconstruct the event, including tracking and particle identification.

The **DaVinci** application is the analysis framework. It allows vertex reconstruction and selection of events from the reconstructed data. The selected events with their related parameters of interest can be recorded for further analysis.

These applications and dataflow are illustrated in Figure 3.25.

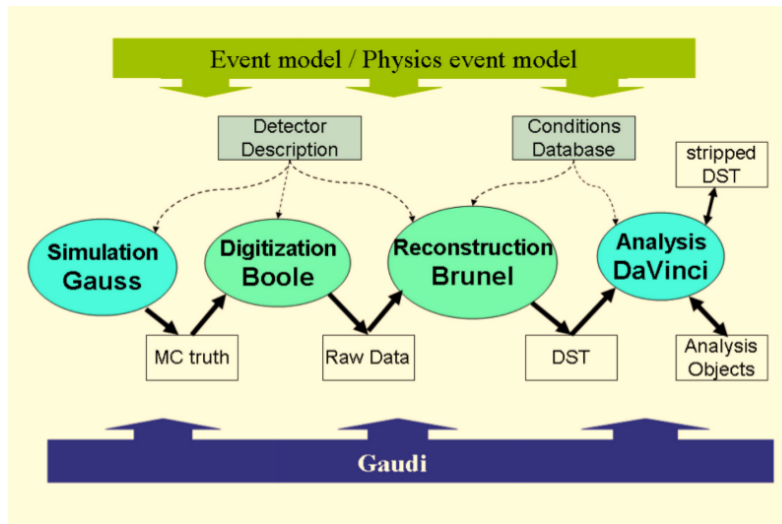


Figure 3.25: The LHCb data processing applications and data flow. Underlying all of the applications is the Gaudi framework and the event model describes the data expected. The arrows represent input/output data [66].

Chapter 4

Data Sample and Selection

The first step of any high energy physics analysis is the selection of the relevant decays among all the collected data. For the ΔA_{CP} measurement presented in this thesis, $D^+ \rightarrow K^- K^+ \pi^+$, $D^+ \rightarrow \pi^- \pi^+ \pi^+$, $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ decays are selected, the latter two to be used as control modes. In this chapter, the characteristics of the data and Monte Carlo (MC) simulated samples are given and the selection of the decays is described.

4.1 Data and Monte Carlo samples

The analysis is performed using the data collected in pp collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV by LHCb in 2011 and 2012, respectively, which in total correspond to 3.0 fb^{-1} of integrated luminosity. The versions of the data reconstruction algorithm and analysis software used are **Reco14** and **DaVinci v34r1**, respectively. For 2012, the CHARM data set is selected by **Stripping20** which corresponds to 2.0 fb^{-1} of integrated luminosity, divided in $1.000 \pm 0.012 \text{ fb}^{-1}$, taken with magnet polarity directed towards the positive y axis (MagUp), and $0.988 \pm 0.012 \text{ fb}^{-1}$, with magnet polarity directed towards the negative y axis (MagDown). For 2011, the CHARM data set is selected by **Stripping20r1** that corresponds to an integrated luminosity of 1.0 fb^{-1} , divided in $0.4222 \pm 0.0011 \text{ fb}^{-1}$ and $0.5636 \pm 0.0013 \text{ fb}^{-1}$, with magnet polarity directed towards the positive and negative y axis, respectively.

The MC simulated data are used to guide the selection criteria and to validate the mass probability density function (PDF) used in the fits to data. Fully simulated samples, centrally generated by the LHCb production team, are used. Events are generated with a flat distribution over the phase space, with **Gauss v45r3**, using MC12 configuration (Reco14a, Digi13, Nu2.5-Pythia8, Trig0x409f0045) and **DaVinci v34r1**. In order to generate large signal MC samples, the cuts shown in Table 4.1 are applied at generator level and a trigger filter (explained in section 4.2.1) is used.

Table 4.1: Cuts applied at generator level.

variable	cut
$D_{(s)}^+ p >$	14.0 GeV/ c
$D_{(s)}^+ p_T >$	2.1 GeV/ c
each daughter $p >$	2.0 GeV/ c
each daughter $p_T >$	0.25 GeV/ c

4.2 Selection

The D^+ and D_s^+ mesons have lifetimes of (1.040 ± 0.007) ps and (0.500 ± 0.007) ps [29], respectively, and travel a distance of the order of a centimeter in average, before decaying. Thus, the $D_{(s)}^+$ are not directly detected in the experiment and it is necessary to reconstruct them from the kaons and pions produced in their decay. The kaons and pions are identified using the PID variables defined in Section 3.2.5. To select the $D_{(s)}^+$, the trajectories of all reconstructed particles in the event are combined three by three and the candidates are selected exploiting the specific features of the decays of interest which discriminate them from the background.

We are looking for a decay into three charged particles whose trajectories form a secondary vertex (the $D_{(s)}^+$ decay vertex) away from the primary vertex (PV), or collision point. Two variables help to recognize this pattern: the impact parameter (IP) and the flight distance (FD). The impact parameter is the smallest distance

between the projected trajectory of the particle and the primary vertex, as illustrated in Figure 4.1(a). The flight distance is the distance traveled by the particle before decaying (distance between the primary and secondary vertices). Their chi squares (χ_{IP}^2 , χ_{FD}^2) can have even higher discriminating power. They are defined as the difference in the IP (FD) with respect to the PV reconstructed with and without this particle. Good quality tracks are required by cutting on the χ^2/DOF of the track fit. The reconstructed mass of the $D_{(s)}^+$ meson and the momenta of the particles also play an important role in the selection. Among the variables used for the selection, we also rely on the Distance of Closest Approach (DOCA) between two tracks and the cosine of the angle θ between the reconstructed $D_{(s)}^+$ momentum and the vector connecting the PV to the reconstructed $D_{(s)}^+$ decay vertex (DIRA). This angle is typically low and its cosine close to 1 (see Figure 4.1(b)) [74].

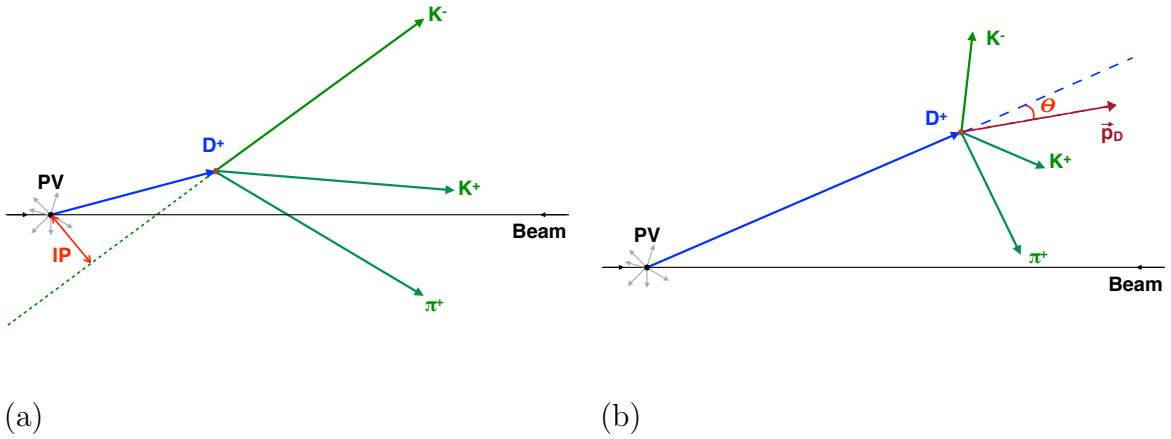


Figure 4.1: Illustration of some variables used in selection: (a) Impact Parameter (IP) representation (of the K^-); (b) Representation of the θ angle, used to calculate DIRA, shown in red [74].

4.2.1 Trigger Selection

Both D^+ and D_s^+ candidates are required to trigger the dedicated `Hlt1TrackAllL0` and `Hlt2CharmHadD2HHH` lines (HLT1 and HLT2 TOS). The biggest part of our data was taken with the requirements summarized in this section.

The single displaced-track line **Hlt1TrackAllL0** starts with a fast reconstruction of pp primary interaction vertices (PVs) and charged particle tracks. It is a simple selection based on the properties of one of these reconstructed tracks. **Hlt1TrackAllL0** accepts events selected by any L0 line with at least one track that satisfies a number of track quality criteria, that is displaced from every reconstructed PV in the event and has a relatively large estimated p_T [75]. The cuts of **Hlt1TrackAllL0** line are summarized in Table 4.2.

Table 4.2: Track requirements and global event cuts used in the **Hlt1TrackAllL0** line. The numbers in brackets correspond to 2012 cuts, when they are different from the ones used in 2011.

Number of VELO hits/Track	> 9
Number of missed VELO hits/Track	< 3
Track IP	> 0.1 mm
Number of OT + IT $\times$ hits/track	> 16
Track χ^2/ndf	< 2.5
Track momentum P	> 10 GeV/ c
Track transverse momentum p_T	> 1.7 (> 1.6) GeV/ c
Track χ^2_{IP}	> 16
Number of IT hits	< 3000
Number of OT hits	< 15000
Number of VELO hits	$< 3000(6000)$
L0.Decision.Physics	

The **Hlt2CharmHadD2HHH** line selects 3-body decays of D^+ and D_s^+ mesons. In 2011, the standard reconstruction of tracks in HLT2 required any track to have $p_T > 500$ MeV/ c and $p > 5000$ MeV/ c^2 . The efficiency of these criteria varies a factor of ~ 7 over the 3-body phase space, in particular in the edges of the kinematic limits of the Dalitz plot (DP). In order to avoid that, the algorithm of the **Hlt2CharmHadD2HHH** line was processed in two steps. The central idea was to form a 2-body object from the list of standard HLT2 tracks, apply certain requirements on it and then, when afforded by the lower rate, form the 3-body candidate by adding a third track. This track could come from the standard HLT2 track list but also from a list of low- p_T

tracks, that were reconstructed in a “second-loop” step to recover lost tracks in HLT2. By doing that, the efficiency variation across the DP is reduced to a factor ~ 2 . The requirements on both stages are shown in Table 4.3. In 2012, it was already possible to reconstruct tracks with lower p_T and this trigger stage could be defined in one step with the selection criteria presented in Table 4.4.

Concerning the hardware trigger, our samples consist of candidates selected either by a `D_LOHadron_TOS` decision or by a combination of specific TIS decisions (`D_LOHadron_TIS||D_LOMuon_TIS||D_LOElectron_TIS||D_LOPhoton_TIS`, henceforth called `L0TIS`), which account for the great majority of the data stored. After the HLT1, HLT2 and stripping requirements, about 30% of our candidates are `L0Hadron_TOS`, with a small variation among the four signal samples. The remaining candidates are selected through the `L0TIS` requirement. The `L0Hadron` trigger requires at least one E_T deposit in a 2×2 set of cells in the calorimeter with a minimum energy of 3.5 GeV in 2011 (3.62 GeV in 2012) and a total number of SPD hits smaller than 600 [76]. By adding the TIS candidates to the sample, the statistical significance is improved for all the signal and control modes by about 50% in average.

4.2.2 Stripping Selection

Data events are selected using the exclusive stripping lines `D2hhh_PPPLine` and `D2hhh_KKPLine`, with the `Stripping20(r1)` definitions listed in Table 4.5¹.

¹Since standard $D_{(s)}^+$ particles are used as input to the stripping, some cuts in this table are actually applied at the level of the standard particle selection.

Table 4.3: Selection criteria for HLT2CharmHadD2HHH on 2-body (first stage) and 3-body (second stage) combinations (2011 data).

	Cuts	2Body	3Body
GEC N_{FwdTrk}	$<$	110	–
p_T (MeV/c)	$>$	500	250
p (MeV/c)	$>$	5000	2000
$\sum p_T$ (MeV/c)	$>$	2000	2500
IP χ^2	$>$	10	5
track χ^2	$<$	3	3
FD (mm)	$>$	3	–
FD χ^2	$>$	40	150
min DOCA (mm)	$<$	0.1	0.08
Vertex χ^2	$<$	–	20
D χ^2_{IP}	$<$	–	15
MCor (MeV/c ²)	$<$	3500	3500
Invariant mass (MeV/c ²)		–	1800–2040
TOS in Hlt1A11L0Track or Hlt1TrackMuon			

Table 4.4: Selection criteria for HLT2CharmHadD2HHH in 2012.

	Cuts	Value
GEC N_{FwdTrk}	$<$	180
p_T (MeV/c)	$>$	300
p (MeV/c)	$>$	3000
$\sum p_T$ (MeV/c)	$>$	2800
IP χ^2	$>$	6
track χ^2	$<$	3
FD (mm)	$>$	3
FD χ^2	$>$	175
min DOCA (mm)	$<$	0.08
Vertex χ^2	$<$	20
D χ^2_{IP}	$<$	12
Invariant mass (MeV/c ²)		1800–2040
TOS in any Hlt1Track Line		

Table 4.5: **Stripping20** definition of the exclusive lines.

Daughter cuts	
Track χ^2/DOF	< 5
Transverse momentum (p_t)	$> 250 \text{ MeV}/c$
Momentum	$> 2000 \text{ MeV}/c$
χ^2 of Impact Parameter wrt PV	> 4
$\Delta \log \mathcal{L}(K - \pi)$ for kaons	> 7
$\Delta \log \mathcal{L}(K - \pi)$ for pions	< 3
Combination cuts	
$\sum p_t$	> 2800
χ^2 of Impact Parameter	> 10 (at least two tracks)
Mother cuts	
Track vertex χ^2/DOF	< 10
Transverse momentum (p_t)	> 1000
Invariant mass	$1800 \text{ MeV}/c^2 < m_D < 2040 \text{ MeV}/c^2$
χ^2 of Flight Distance	> 125
χ^2 of Impact Parameter	< 12
DIRA	> 0.98

4.2.3 Offline Selection

The $D_{(s)}^+$ candidates used in this analysis must satisfy the trigger and stripping requirements described in the previous section. The invariant mass distributions of the candidates selected by the stripping and trigger stages in 2012 and 2011 are shown in Figures 4.2 and 4.3, respectively. The black dashed line shows the candidates passing any trigger line while the blue and red solid lines show the candidates passing the L0TOS || L0TIS and the L0TIS requirements, respectively, as defined in the previous section. For these two latter distributions, the candidates are also required to trigger the dedicated `Hlt1TrackAllL0` and `Hlt2CharmHadD2HHH` lines. Purities are of the order of 77% (40%), for candidates passing any trigger line, and of the order of 88% (60%), for candidates passing L0TIS requirements, for the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ ($D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$) sample. Due to the differences between the behaviour of the individual raw asymmetries in the control and signal samples (see Appendix A), it was decided to use only the L0TIS sample for this analysis. With this requirement, the statistical precision of the combined MagUp+MagDown ΔA_{CP} result increases by 16%, but we expect to have a better control of the systematic uncertainties. From this point on, all the plots, numbers and results are shown for the L0TIS selected samples.

An additional set of offline selection criteria is defined in order to reduce the contribution of specific backgrounds to each channel. In addition, some kinematic cuts are defined to remove candidates which populate regions of the phase space with high asymmetry induced by instrumental sources. Whenever possible, equivalent cuts are applied to the $KK\pi$ and $\pi\pi\pi$ candidates, in both signal and control samples, in order to ensure an optimal cancellation of instrumental asymmetries and a good control of them.

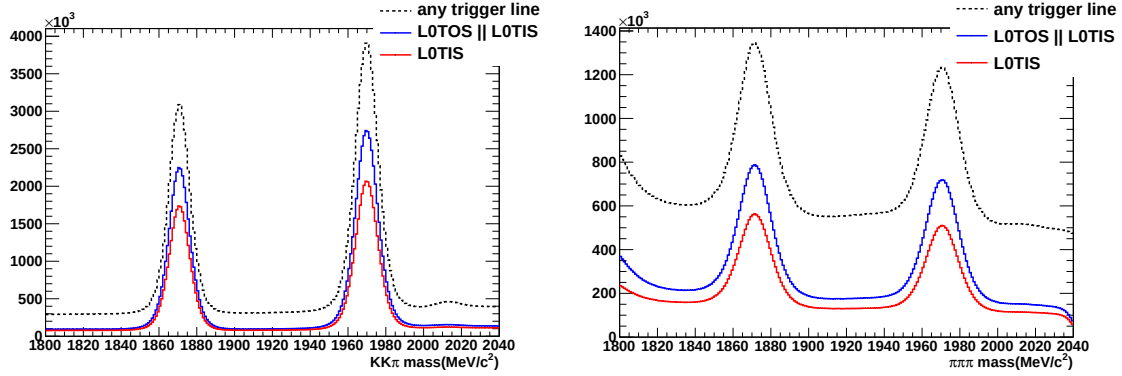


Figure 4.2: Invariant mass distributions for candidates from Stripping20 (2012 data).

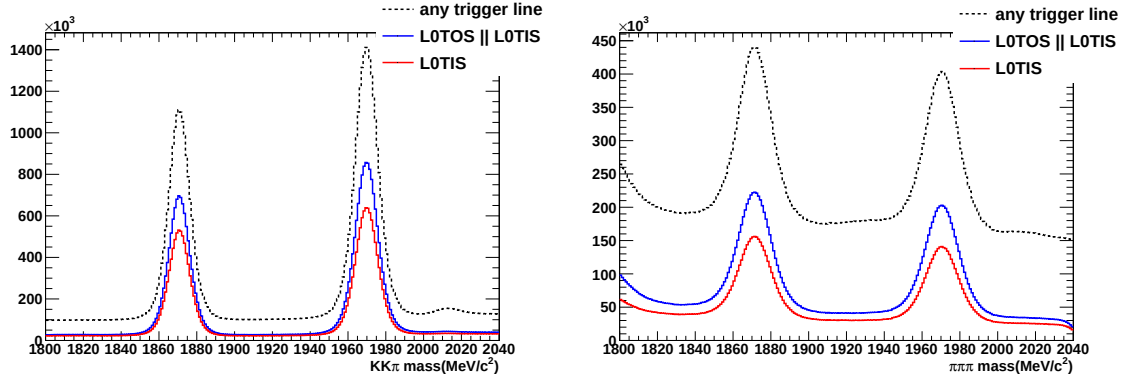


Figure 4.3: Invariant mass distributions for candidates from Stripping20r1 (2011 Data).

4.2.3.1 Fiducial cuts

Low momentum tracks may be driven away from or to the detector acceptance by the magnetic field, depending on their electric charge, what may induce a charge asymmetry. The control channels are used to study this effect. More specifically, the distribution of the raw asymmetry in the $p_z \times p_x$ plane is plotted for each daughter and a cut is defined to exclude regions with high asymmetry. Candidates with any of the daughters (p_x, p_z) in the regions defined by these cuts are then rejected from our samples.

The distributions of the raw asymmetry in the daughters $p_z \times p_x$ planes for $D_s^+ \rightarrow K^- K^+ \pi^+$ ($D_s^+ \rightarrow \pi^- \pi^+ \pi^+$) are shown in Figure 4.4 (4.5). The left most

plots show the raw asymmetry as a function of the $K^-(\pi^-)$ (p_x, p_z), the middle plots, as a function of the $K^+(\pi^+)$ (p_x, p_z), and the ones on the right, of the bachelor pion (p_x, p_z). The plots on the top are obtained with the MagUp sample, while the ones in the bottom correspond to the MagDown sample.

To eliminate the regions with high asymmetry, the cut illustrated by the black line ($p_z > 3.3 * |p_x| + 2500$) is applied. Studies comparing how the ΔA_{CP} changes when these fiducial cuts are applied are presented in Appendix E.

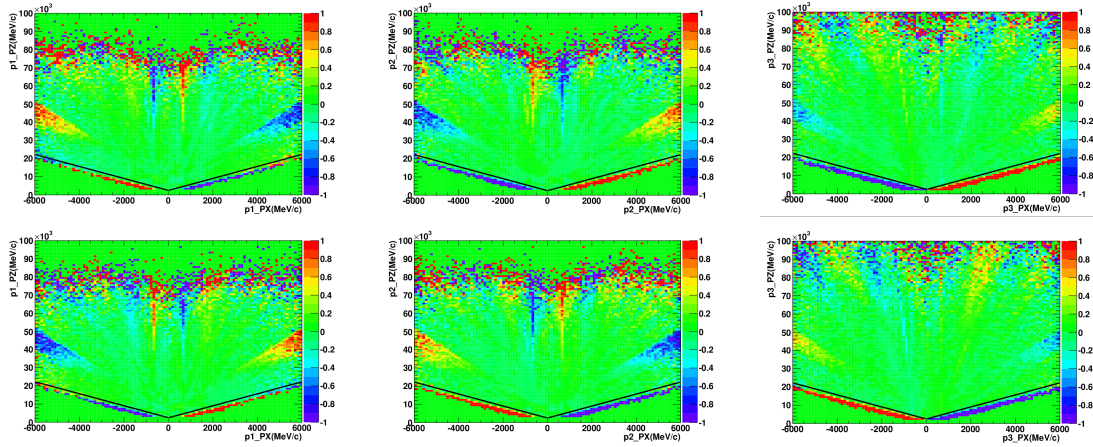


Figure 4.4: Asymmetries for $D_s^+ \rightarrow K^- K^+ \pi^+$ (MagUp — top plots — and MagDown — bottom plots) with respect to the distribution of $p_x \times p_z$ for the daughters. The black line indicates the cut chosen: $p_z > 3.3 * |p_x| + 2500$.

It is also known that the presence of the beam pipe causes a left-right asymmetry for low momentum tracks. Rightward-moving tracks are swept back to the left and reach the beam pipe instead of a T-station. This affects tracks with p_y/p_z close to zero. To handle this effect we include the cut used in the LHCb measurement of the ΔA_{CP} of $D^0 \rightarrow K^- K^+, \pi^- \pi^+$ analysis [77], given by $p_1 - \beta_1 p_z < |p_x| < p_2 + \beta_2 p_z$, where $p_1 = 418$ MeV/c, $p_2 = 497$ MeV/c, $\beta_1 = 0.01397$, $\beta_2 = 0.01605$ and p_x and p_z are the x and z momentum components of the bachelor pion. This cut is only applied to candidates with $|p_y/p_z| < 0.02$ and is illustrated in the asymmetries of the control channels with respect to the distributions of $p_x(\pi^+) \times p_z(\pi^+)$ of the bachelor pions, shown in Figure 4.6.

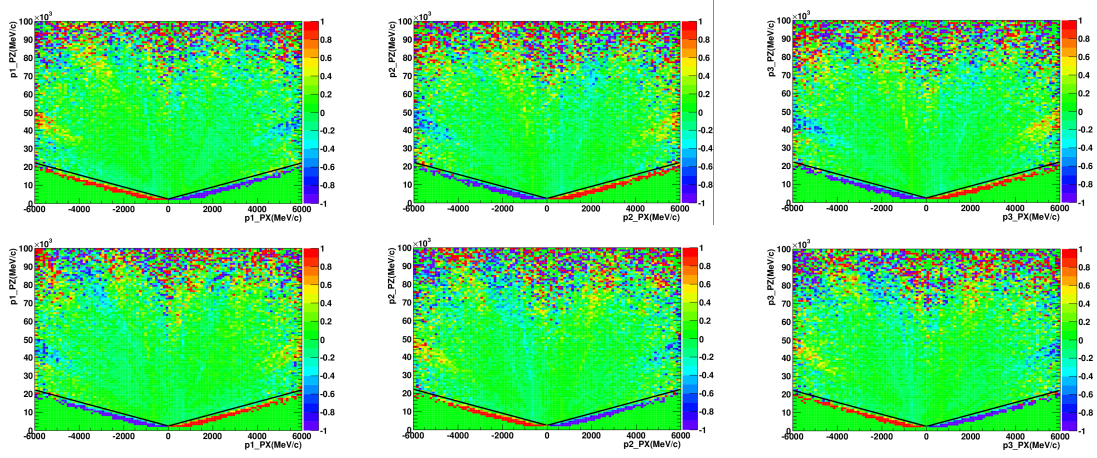


Figure 4.5: Asymmetries for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (MagUp — top plots — and MagDown — bottom plots) with respect to the distribution of $p_x \times p_z$ for the daughters. The black line indicates the cut chosen: $p_z > 3.3 * |p_x| + 2500$.

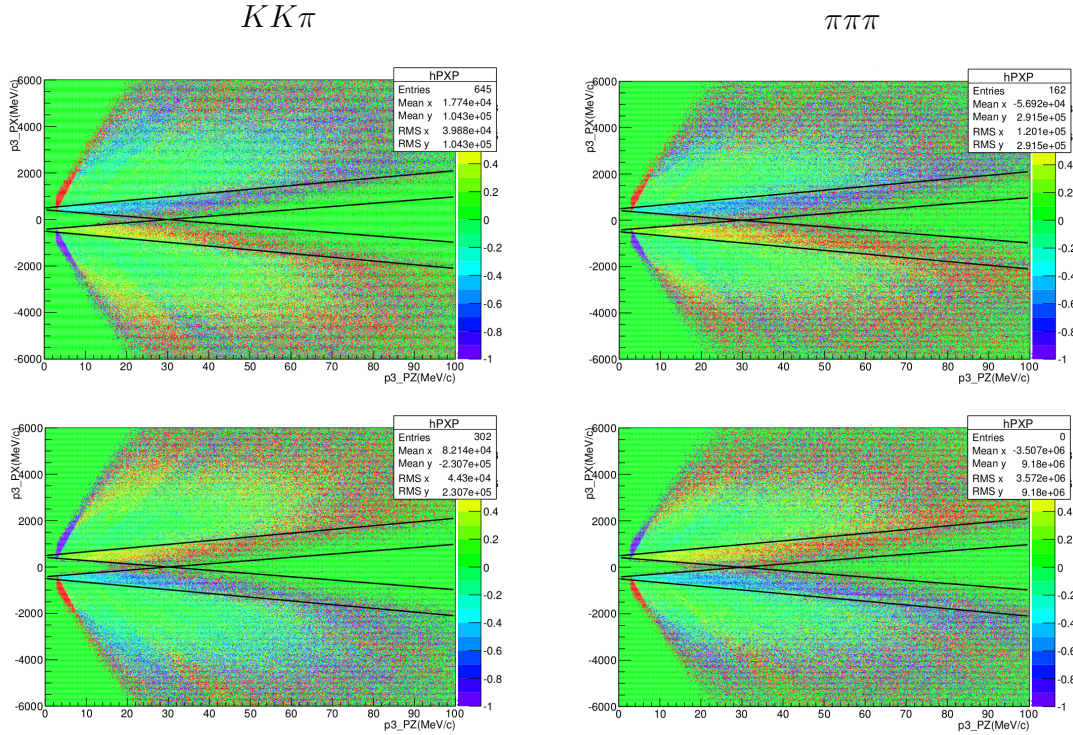


Figure 4.6: Asymmetries for control channels with respect to $p_x(\pi^+) \times p_z(\pi^+)$ distribution for bachelor pions with $|p_y/p_z| < 0.02$. The black lines show the cut applied to remove the asymmetry due to tracks traversing the beam pipe.

Figure 4.7 shows the number of candidates for the control channels with respect to $p_x(\pi^+) \times p_z(\pi^+)$ distribution for bachelor pions with $|p_y/p_z| < 0.02$. It can be seen that this is a region of low statistics and this cut has high efficiency.

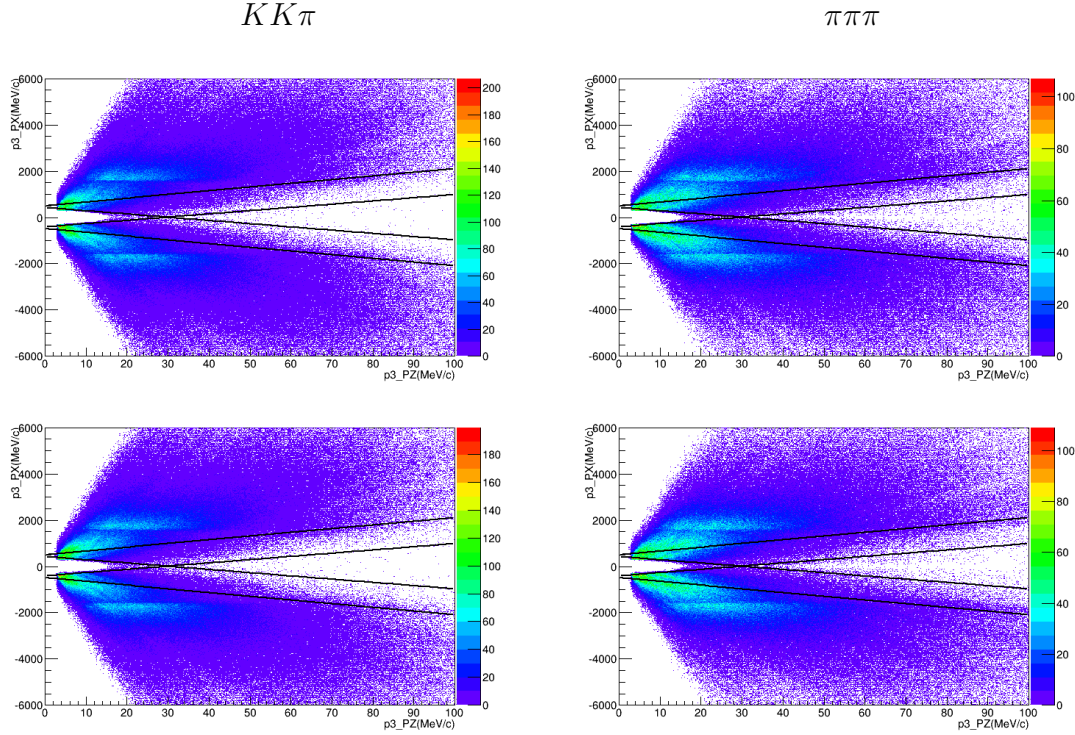


Figure 4.7: Number of candidates for the control channels with respect to $p_x(\pi^+) \times p_z(\pi^+)$ distribution for bachelor pions with $|p_y/p_z| < 0.02$. The black lines show the cut applied to remove the asymmetry due to tracks traversing the beam pipe.

4.2.3.2 Removal of specific background contributions

One of the purposes of the offline selection is to reduce some specific contributions of the background to a negligible level. To suppress the contribution from $D_{(s)}^+$ candidates originating from b -hadron decays, a $D^+ \chi_{\text{IP}}^2 < 8$ cut is applied. Semileptonic decays ($D^+ \rightarrow \pi^+ \pi^- \mu^+ \nu$, for instance) are rejected by a muon veto² (isMuon=0) for all daughters. Backgrounds from fully or partially reconstructed D^{*+} decays are reduced by requiring the π^+ of lowest p_T to satisfy $\chi_{\text{IP}}^2 > 30$. The effect of this cut

²The isMuon variable is defined according to the number of hits a particle leaves when traversing the muon stations (M1-M5), as explained in Section 3.2.7.

is illustrated with $D^{*+} \rightarrow D^0(\rightarrow \pi^+\pi^-)\pi^+$ decays reconstructed as $D^+ \rightarrow \pi^-\pi^+\pi^+$, as shown in Figure 4.8. In this plot, the difference $m_{\pi\pi\pi} - m_{\pi\pi} - m_\pi$ is shown for $D_{(s)}^+ \rightarrow \pi^-\pi^+\pi^+$ candidates passing the stripping and trigger cuts (with $m_{\pi\pi\pi}$ in the interval $[1800, 2040]$ MeV/ c^2). A clear peak close to zero shows the contribution from the $D^{*+} \rightarrow D^0(\rightarrow \pi^+\pi^-)\pi^+$ background, which is almost fully removed after the χ_{IP}^2 cut.

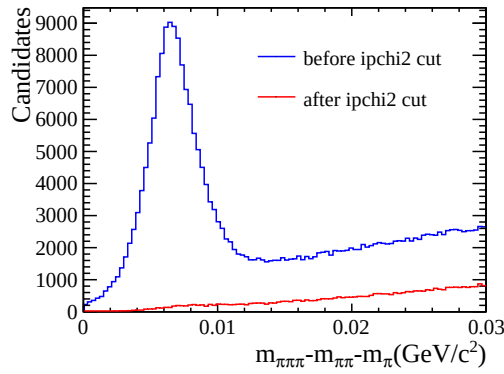


Figure 4.8: Distribution of the mass difference $m_{\pi\pi\pi} - m_{\pi\pi} - m_\pi$ for candidates passing stripping and trigger requirements in the $D^+ \rightarrow \pi^-\pi^+\pi^+$ data sample. A clear peak due to $D^* \rightarrow D^0(\rightarrow \pi\pi)\pi$ decays is observed (blue line) and removed by a $\chi_{\text{IP}}^2 > 30$ (for π^+ of lowest p_T) cut (red line).

An important background is the $D^+ \rightarrow K^-\pi^+\pi^+$ feedthrough, a contamination that arises due to the misidentification of only one daughter (a π^+ misidentified as a kaon for $D_{(s)}^+ \rightarrow K^-K^+\pi^+$ or a K^- misidentified as a π^- in $D_{(s)}^+ \rightarrow \pi^-\pi^+\pi^+$). Tight PID cuts are chosen to handle this background in both $D_{(s)}^+ \rightarrow K^-K^+\pi^+$ and $D_{(s)}^+ \rightarrow \pi^-\pi^+\pi^+$ samples. For the $D_{(s)}^+ \rightarrow K^-K^+\pi^+$, the same PID cut is applied to both kaons, in order to avoid asymmetries arising from different PID cuts, ensuring a cancellation between the $D_{(s)}^+$ and $D_{(s)}^-$ candidates.

The performance of the two available PID variables in rejecting the $D^+ \rightarrow K^-\pi^+\pi^+$ contamination was checked for both decays. ProbNNk is more efficient in the high momentum range, whereas $\Delta \log \mathcal{L}(K - \pi)$ has better efficiency at low momentum. We found that the $\Delta \log \mathcal{L}(K - \pi)$ variable is more efficient for

the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$, where the kaons have typically low momentum. For the $D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$, ProbNNk is more efficient, since most of the $K - \pi$ misID occurs at higher momentum.

The performance of the two PID variables for the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ is illustrated in Figure 4.9. In the left panel, the pion mass is assigned to the K^+ daughter from the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ candidates, whose $m_{KK\pi}$ distribution is shown in the right plot. In black, all candidates passing stripping and trigger cuts are shown, while in red (blue), only candidates satisfying $\Delta \log \mathcal{L}(K - \pi) > 15$ (ProbNNk > 0.7) are shown. It is important to note that, for all kaon candidates, a stripping cut $\Delta \log \mathcal{L}(K - \pi) > 7$ is already applied. It is clear that the $\Delta \log \mathcal{L}(K - \pi) > 15$ is more efficient, while providing a quite similar $D^+ \rightarrow K^- \pi^+ \pi^+$ rejection power.

Similar plots are shown in Fig. 4.10, for the $D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$. On the left plot, the kaon mass is assigned to the π^- daughter of $D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$ candidates. The $\pi^- \pi^+ \pi^+$ invariant mass distribution is shown in the right side. The green and red lines show the distributions for $\Delta \log \mathcal{L}(K - \pi) < -2$ and ProbNNk < 0.08 , respectively (there is a $\Delta \log \mathcal{L}(K - \pi) < 3$ stripping cut already applied to all daughters). The pions from $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ are, therefore, required to satisfy a ProbNNk < 0.08 cut, which reduces the $D^+ \rightarrow K^- \pi^+ \pi^+$ contamination to a negligible level. Since the bachelor pion for this final state is randomly chosen, the same PID cut is applied for all three daughters. In order to ensure that any asymmetry arising from this requirement is canceled between the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ and $D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$ samples, the same cut on the pion ID is applied to the pion from the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ candidates. By using the same PID cuts for daughters from the D_s^+ and D^+ decays, we are confident that the D_s^+ decays provide a good control of the instrumental asymmetries in the D^+ channel.

Due to a proton to kaon misidentification, the $\Lambda_c^+ \rightarrow K^- p \pi^+$ decay appears as a contamination to the $K^- K^+ \pi^+$ sample. To deal with this contribution, a mass

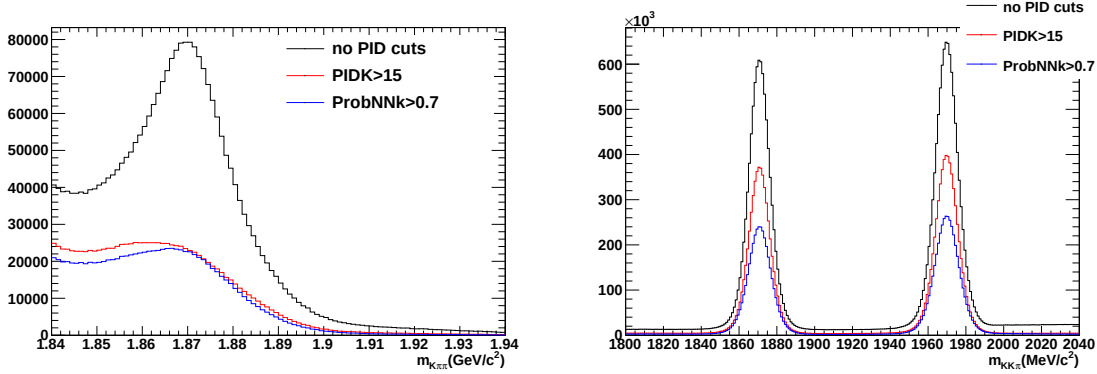


Figure 4.9: Comparison between the performance of ProbNNk and $\Delta \log \mathcal{L}(K - \pi)$ for the rejection of $D^+ \rightarrow K^- \pi^+ \pi^+$ decays in the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ sample. The mass distribution shown in the left (right) side is plotted for $D_s^+ \rightarrow K^- K^+ \pi^+$ candidates, assigning the pion (kaon) mass to the K^+ daughter. The red and blue lines are used to show the mass distributions with $\Delta \log \mathcal{L}(K - \pi) > 15$ and ProbNNk > 0.7 cuts applied to both kaon candidates, respectively.

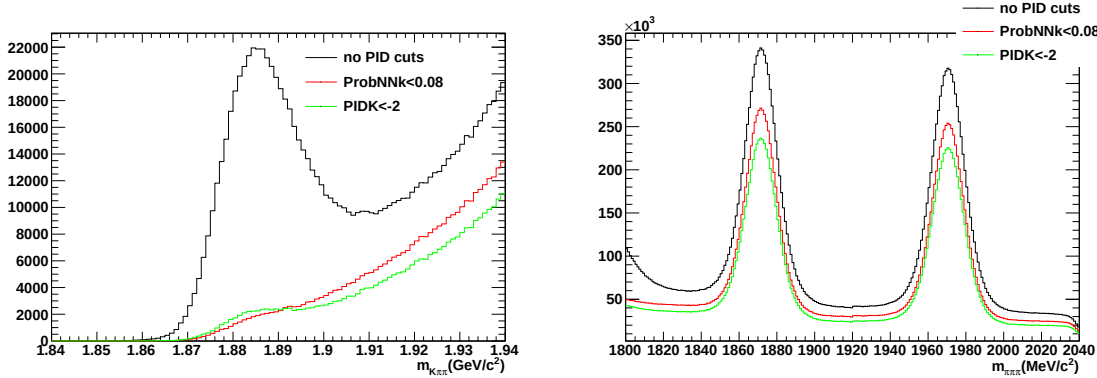


Figure 4.10: Comparison between ProbNNk and $\Delta \log \mathcal{L}(K - \pi)$ performances for the rejection of $D^+ \rightarrow K^- \pi^+ \pi^+$ decays in the $D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$ data sample. The invariant mass $m_{K\pi\pi}$ is built by assigning the kaon mass to the π^- candidates (left). The distribution of the $m_{\pi\pi\pi}$ for the same candidates is shown in the right plot. In green and red, the same distributions are shown for candidates passing the cuts $\Delta \log \mathcal{L}(K - \pi) < -2$ and ProbNNk < 0.08 , respectively.

veto was found to be more efficient than a PID cut. This invariant mass veto ($|m_{Kp\pi} - 2288.5 \text{ MeV}/c^2| > 12 \text{ MeV}/c^2$) is illustrated in Figure 4.11.

In the $\pi^- \pi^+ \pi^+$ sample, there is also a $D^+ \rightarrow K_S^0 \pi^+$ contamination, where the K_S^0 decays to $\pi^- \pi^+$. PID cuts here are of no help. To remove this contribution, a

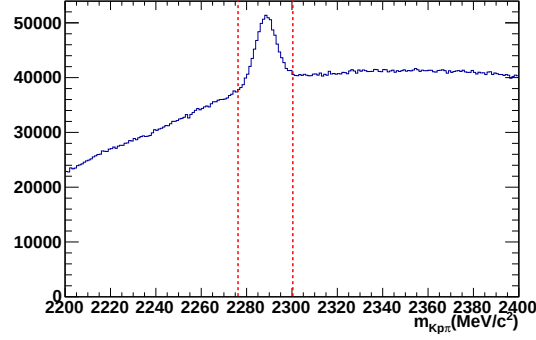


Figure 4.11: Distribution of $m_{Kp\pi}$ (assigning the proton mass to the K^+ daughter), for $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ candidates. The cut applied to reject the $\Lambda_c \rightarrow K p \pi$ contribution is illustrated in red.

cut is applied to the $\pi^- \pi^+$ invariant mass of lowest value between the two possible $\pi^- \pi^+$ combinations, as shown in Figure 4.12. For each candidate in the signal $D^+ \rightarrow \pi^- \pi^+ \pi^+$ region, ($m_{\pi\pi\pi}$ within the interval $[1850, 1890]$ MeV/c^2), the π^- is combined with the two π^+ and the invariant mass $m_{\pi^- \pi^+}$ of lowest value is plotted, showing a peak on the K_s^0 mass. Since this distribution also contains random K_s^0 combined with an extra π^+ , it is subtracted from the same distribution for candidates in the signal sidebands ($m_{\pi\pi\pi}$ within the interval $[1820, 1840]$ or $[1900, 1920]$ MeV/c^2). The veto is defined as $|m_{\pi^- \pi^+}(\text{low}) - 0.497 \text{ GeV}/c^2| > 0.012 \text{ GeV}/c^2$.

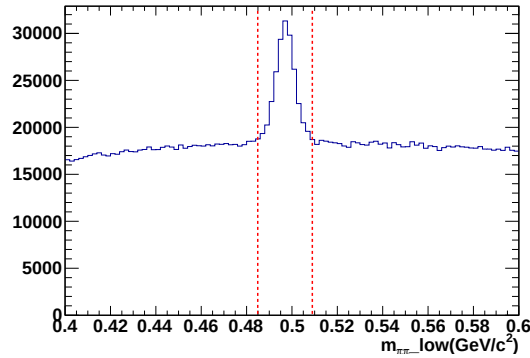


Figure 4.12: Distribution of minimum $m_{\pi^- \pi^+}$, for candidates with invariant mass $m_{\pi\pi\pi}$ in the signal range, subtracted from the background in the sidebands. The red line shows the cut applied to reject the K_s^0 contribution.

After all the above cuts, there is still a small background contribution from the combination of a $D^0 \rightarrow \pi^- \pi^+$ or a $D^0 \rightarrow K^- K^+$ with a π^+ to the $D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$ and $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ samples, respectively. The invariant mass distributions of the $\pi^- \pi^+$ and $K^- K^+$ are shown in Fig. 4.13, in the region close to the D^0 mass. For $D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$ candidates the π^- is combined with the two π^+ . The combination with the higher invariant mass is plotted. A cut on the 2-body invariant mass (m_{KK} , $m_{\pi\pi}$ less than $1.85 \text{ GeV}/c^2$), removes completely this background keeping essentially 100% of the signal candidates.

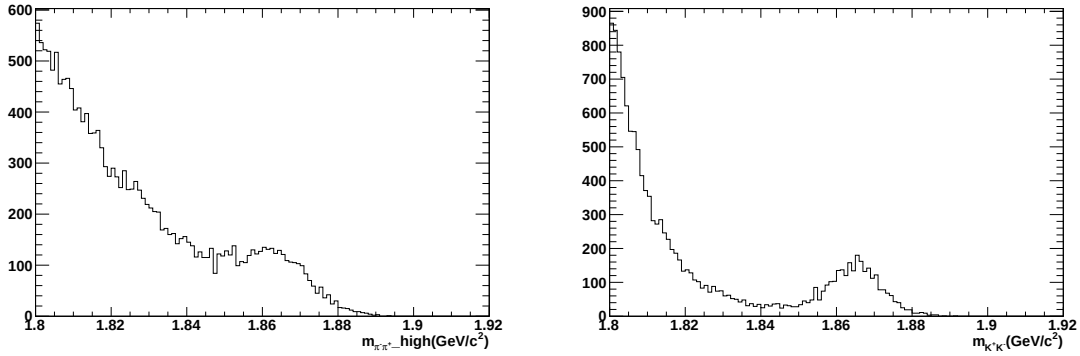


Figure 4.13: Two-body invariant masses $m_{\pi^- \pi^+}$ ($D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$ sample) on the left and $m_{K^- K^+}$ ($D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ sample) on the right.

Specific background contributions remaining in the samples after the selection criteria presented above, in particular partially or fully reconstructed charm decays that could require the inclusion of a specific model in the mass PDF, are studied using full LHCb MC samples. Examples of such decays besides those already mentioned in the previous section are $D_s^+ \rightarrow \eta' \pi^+$ with $\eta' \rightarrow \pi^+ \pi^- \gamma$, $D_s^+ \rightarrow \phi \pi^+ \pi^0$ with $\phi \rightarrow K^- K^+$, $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$, etc. The expected yield for each studied channel was estimated using the ratio of efficiencies, branching ratios and cross-sections with respect to the signal decay and the PID variables from the MC. The most important contributions are shown together with the final 2012 data distributions in Figures 4.14 and 4.15. As can be seen from these figures, after applying cuts for

removing feedthrough from other charm decays, the remaining background is essentially due to combinatorics. The $D_s^+ \rightarrow \eta'\pi$ decay is the most important specific contribution to the $\pi^-\pi^+\pi^+$ spectrum, in particular in the D^+ mass range, while $D^+ \rightarrow K^-\pi^+\pi^+$ is the most important contamination to the $K^-K^+\pi^+$ spectrum. They represent, however, a small fraction of the signal yields for $\pi^-\pi^+\pi^+$ ($K^-K^+\pi^+$) in the fit range with a smooth shape that can be safely incorporated to the combinatorial background. The $D_s^+ \rightarrow \eta'\pi$ decay corresponds to about 8% of the signal in the $D^+ \rightarrow \pi^-\pi^+\pi^+$ and less than 1% of the signal in the $D_s^+ \rightarrow \pi^-\pi^+\pi^+$. The $D^+ \rightarrow K^-\pi^+\pi^+$ decay corresponds to about 1.4% of the signal in $D_s^+ \rightarrow K^-K^+\pi^+$. The sum of all these remaining specific contributions to the background shown in Figures 4.14 and 4.15 account for approximately 0.5%, 1.4%, 9.6% and 1.1% of the signal yields of $D^+ \rightarrow K^-K^+\pi^+$, $D_s^+ \rightarrow K^-K^+\pi^+$, $D^+ \rightarrow \pi^-\pi^+\pi^+$ and $D_s^+ \rightarrow \pi^-\pi^+\pi^+$, respectively.

Further improvements in the statistical significance of the $D^+ \rightarrow \pi^-\pi^+\pi^+$ yield, which dominates the statistical uncertainty of the ΔA_{CP} measurement, are attempted using both a multivariate analysis and linear cuts on the usual track/vertex quality, pointing and detachment variables, but no significant improvement is found. The full set of cuts applied in the offline selection is listed in Table 4.6 with the relative efficiencies with respect to the previous cut. The final signal yields are approximately 5.2×10^6 $D^+ \rightarrow \pi^-\pi^+\pi^+$, 5.1×10^6 $D_s^+ \rightarrow \pi^-\pi^+\pi^+$, 11×10^6 $D^+ \rightarrow K^-K^+\pi^+$ and 13×10^6 $D_s^+ \rightarrow K^-K^+\pi^+$ for 2012. For the 2011 data set, approximately 1.5×10^6 $D^+ \rightarrow \pi^-\pi^+\pi^+$, 1.5×10^6 $D_s^+ \rightarrow \pi^-\pi^+\pi^+$, 3.5×10^6 $D^+ \rightarrow K^-K^+\pi^+$ and 4.2×10^6 $D_s^+ \rightarrow K^-K^+\pi^+$ are observed.

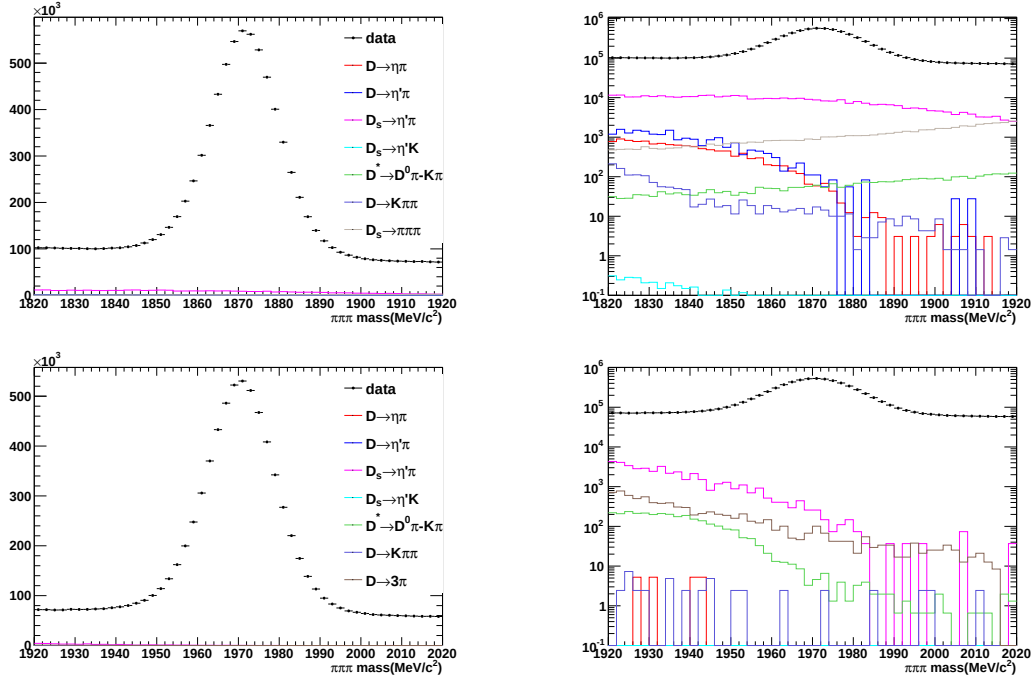


Figure 4.14: $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (top) and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (bottom) mass distributions for the 2012 data sample, with signal and background MC distributions superimposed, in linear (left) and logarithmic (right) scales after all the selection criteria.

Table 4.6: Summary of cuts applied in the offline selection. The total efficiency is given with respect to the stripping selection, for the candidates selected by L0TIS, Hlt1TrackAllL0 and Hlt2CharmHadD2HHH criteria.

Selection		Efficiencies	
		$D^+ \rightarrow K^- K^+ \pi^+$	$D^+ \rightarrow \pi^- \pi^+ \pi^+$
Specific Background Contributions			
isMuon	= 0 (all daughters in both decays)	94%	94%
ProbNNk	< 0.08 (all pions in both decays)	61%	79%
$\Delta \log \mathcal{L}(K - \pi)$	> 15 (kaons of $KK\pi$)		
$D^+ \chi_{\text{IP}}^2$	< 8	94%	94%
$\pi^+ \chi_{\text{IP}}^2$	> 30 (for π^+ of lowest p_T)	95%	91%
$ m_{Kp\pi} - 2288.5 \text{ MeV}/c^2 $	> 12 MeV}/c^2 (for $KK\pi$)	93%	-
$ m_{\pi^-\pi^+}(\text{low}) - 0.497 \text{ GeV}/c^2 $	> 0.012 GeV}/c^2 (for 3π)	-	95%
m_{K-K^+}	< 1.85 GeV}/c^2 (for $KK\pi$)	100%	-
$m_{\pi^-\pi^+}(\text{high})$	< 1.85 GeV}/c^2 (for 3π)	-	100%
Fiducial			
$p_z > 3.3 * p_x + 2500$ (all tracks)			
$1.5 \leq \eta \leq 5.0$ and $3 \leq p \leq 100 \text{ GeV}/c$ (all tracks)		93%	89%
<i>Beam pipe veto</i>			
Total efficiency		45%	53%

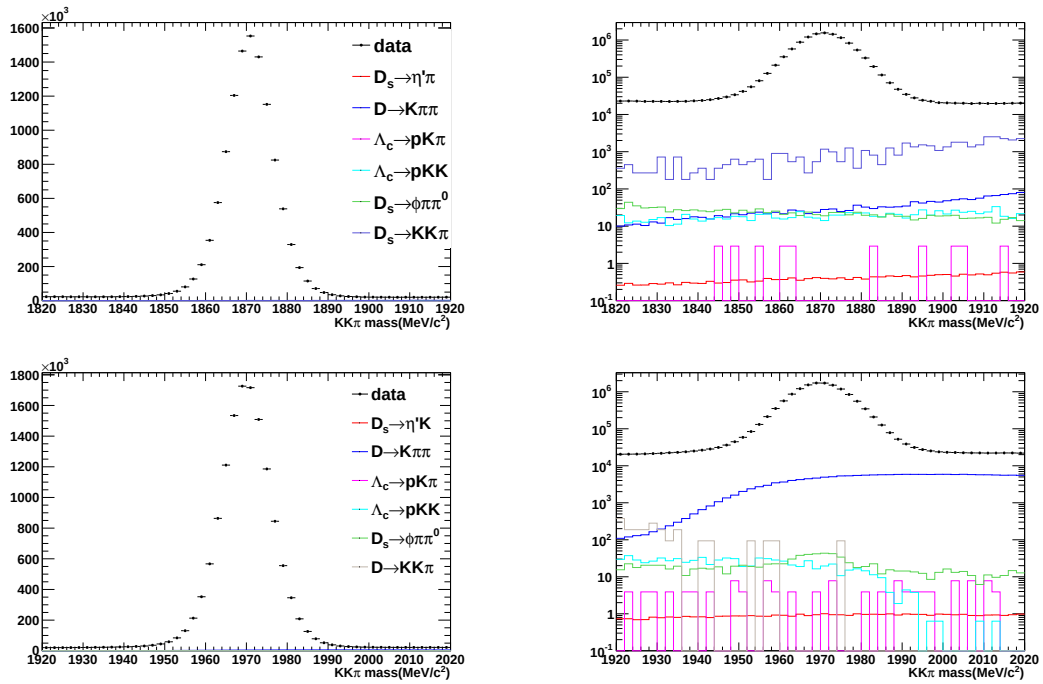


Figure 4.15: $D^+ \rightarrow K^- K^+ \pi^+$ (top) and $D_s^+ \rightarrow K^- K^+ \pi^+$ (bottom) mass distributions for the 2012 data sample, with signal and background MC distributions superimposed, in linear (left) and logarithmic (right) scales after all the selection criteria.

Chapter 5

Analysis Strategy

After selecting the decays, it is necessary to define the strategy to extract the asymmetries from data. This strategy is described in this chapter.

In the first section, the formalism relating the observed asymmetry to the physical one is presented. Control channels where no CPV is expected are used to perform further tests, as shown in Section 5.2. To not bias the ΔA_{CP} measurement, this analysis is performed in a *blind way* and the actual values of the D^+ asymmetries are only known in the final stage of analysis, as explained in Section 5.3. The sample is divided in kinematic bins and in each of them the observed asymmetry is obtained from a simultaneous fit to the invariant mass distributions using the model described in Section 5.4. The kinematic binning is described in Section 5.5.

5.1 Formalism

The charge asymmetry for the decays $D^+ \rightarrow h^- h^+ h'^+$ is defined as

$$A = \frac{N^+ - N^-}{N^+ + N^-} \quad (5.1)$$

where N^+ and N^- are the number of D^+ and D^- decays observed.

Equation 5.1 can be rewritten as

$$\frac{N^+}{N^-} = \frac{1 + A}{1 - A} \quad (5.2)$$

If the asymmetry is small ($\mathcal{O}(1\%)$) we can expand it in Taylor series,

$$f(x) = f(a) + f'(a)x + f''(a)\frac{x^2}{2} + \dots \quad (5.3)$$

Considering $x = A$ and $a = 0$, we obtain

$$\frac{1+A}{1-A} = 1 + 2A + 2A^2 + \dots \quad (5.4)$$

The number of observed decays is given by

$$N^\pm = \mathcal{B}(D^\pm \rightarrow h^\mp h^\pm h'^\pm) \varepsilon_\pm N_P^\pm \quad (5.5)$$

where $\mathcal{B}(D^\pm \rightarrow h^\mp h^\pm h'^\pm)$ is the decay branching fraction, $\varepsilon_\pm$ is the detection efficiency and $N_P^\pm$ is the number of $D^\pm$ produced in the experiment. Therefore

$$\frac{N^+}{N^-} = \frac{\mathcal{B}(D^+ \rightarrow h^- h^+ h'^+) \varepsilon_+ N_P^+}{\mathcal{B}(D^- \rightarrow h^+ h^- h'^-) \varepsilon_- N_P^-} \quad (5.6)$$

and, defining the decay rate asymmetry $A_{\mathcal{B}} = \frac{\mathcal{B}(D^+ \rightarrow h^- h^+ h'^+) - \mathcal{B}(D^- \rightarrow h^+ h^- h'^-)}{\mathcal{B}(D^+ \rightarrow h^- h^+ h'^+) + \mathcal{B}(D^- \rightarrow h^+ h^- h'^-)}$ and the detection and production asymmetries A_ε and A_P , in analog ways, we have:

$$\frac{1+A}{1-A} = \left(\frac{1+A_{\mathcal{B}}}{1-A_{\mathcal{B}}} \right) \left(\frac{1+A_\varepsilon}{1-A_\varepsilon} \right) \left(\frac{1+A_P}{1-A_P} \right) \quad (5.7)$$

Replacing Eq. 5.7 in Eq. 5.4 and considering only terms up to second order:

$$1 + 2A + 2A^2 \simeq (1 + 2A_{\mathcal{B}} + 2A_{\mathcal{B}}^2)(1 + 2A_\varepsilon + 2A_\varepsilon^2)(1 + 2A_P + 2A_P^2) \quad (5.8)$$

CP violation leads to a difference in the decay rate between particle and antiparticle therefore we associate $A_{\mathcal{B}} = A_{CP}$. To first order approximation,

$$A_{\text{raw}} \simeq A_{CP} + A_\varepsilon + A_P \quad (5.9)$$

The term A_ε includes the asymmetry induced by any instrumental effect which leads to a difference in the probability to observe a $D^+ \rightarrow h^- h^+ h'^+$ compared to a $D^- \rightarrow h^+ h^- h'^-$ decay: selection, trigger, reconstruction, differences in the detection performance, differences between π^+ , K^+ and π^- , K^- interaction cross sections, etc.

Assuming that the production asymmetry does not depend on the decay mode and that the net detection asymmetry is entirely due to the bachelor pion and for this reason is the same for $D^+ \rightarrow K^- K^+ \pi^+$ and $D^+ \rightarrow \pi^- \pi^+ \pi^+$, the observable

$$\Delta A_{\text{raw}}(D^+) = A_{\text{raw}}(KK\pi) - A_{\text{raw}}(\pi\pi\pi) = A_{CP}(KK\pi) - A_{CP}(\pi\pi\pi) \quad (5.10)$$

is equivalent to the CP asymmetry difference between the two decay modes $\Delta A_{CP}(D^+)$.

The major part of the analysis is dedicated to verify that:

- the terms A_ε and A_P do cancel between the two decay modes;
- second-order effects in the expansion are negligible;
- the background does not produce any residual asymmetry.

5.2 Control channels

The Cabibbo favoured decays $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ are chosen as control channels for this analysis, since they have the same final states as the signal modes, with similar topology. In the Standard Model these decays are not expected to present CP violation ($\Delta A_{CP}(D_s^+) = 0$). If the production and detection asymmetries cancel between the two final states, the $\Delta A_{\text{raw}}(D_s^+) = A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+) - A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+)$ is null. Although the D_s^+ has a higher mass than the D^+ and a lifetime which is two times smaller, the measurement of a null $\Delta A_{\text{raw}}(D_s^+)$ provides a good control of the elimination of production and instrumental asymmetries from the difference $\Delta A_{\text{raw}}(D^+)$ measured with the signal modes. Since D_s^+ and D^+ samples are of similar size, it can be anticipated that the raw asymmetries will have comparable statistical uncertainties and sensitivities to instrumental effects.

5.3 Blind analysis

At this stage the analysis is blind, meaning that we do not look at the actual values of asymmetries for the signal channels in order not to bias the measurement. Asymmetries are measured either from mass fits to the D_s^+ control samples or including random unknown offsets to the A_{raw} parameters of the fits to the mass distributions of the signal D^+ samples. The RooFit class `RooUnblindUniform` is used to insert the offsets, with `AcpDBlindKKP` as blind string for $D^+ \rightarrow K^- K^+ \pi^+$ and `AcpDBlindPPP` as blind string for $D^+ \rightarrow \pi^- \pi^+ \pi^+$. These offsets are different for each mode, but they are common to the MagUp and MagDown data or to any kind of split samples, so that systematic uncertainties can already be studied without unblinding the actual value of the asymmetries or of the ΔA_{CP} . Once the analysis is approved by the LHCb collaboration, the fits to the signal samples will be performed without the offsets.

5.4 Fit model

To obtain the raw asymmetries, a simultaneous maximum likelihood fit to the binned $D_{(s)}^+$ and $D_{(s)}^-$ reconstructed invariant mass distributions is performed, using the following probability density function (PDF):

$$\mathcal{P}^\pm(m) = \frac{1}{2(N_{sig}^\pm + N_{bkg}^\pm)} [(1 \pm A_{\text{raw}}) N_{sig} \mathcal{P}_{sig}^\pm(m) + (1 \pm A_{bkg}) N_{bkg} \mathcal{P}_{bkg}^\pm(m)], \quad (5.11)$$

where $\mathcal{P}_{sig}^\pm$ and $\mathcal{P}_{bkg}^\pm$ are the signal and background PDFs, N_{sig} and N_{bkg} are the total numbers of signal and background candidates and A_{raw} and A_{bkg} are their respective charge asymmetries.

The nominal signal PDF for $D_{(s)}^+$ and $D_{(s)}^-$ candidates is defined as a sum of a Gaussian (G) and a Crystal Ball (CB) function [78] with common most probable values $\mu \pm \Delta\mu$. Their widths are σ and $\sigma * R_\sigma$, respectively, where the R_σ is the

ratio between the Crystal Ball and Gaussian widths:

$$\mathcal{P}_{sig}^{\pm}(m) = f_G G(m, \mu \pm \Delta\mu, \sigma) + (1 - f_G) \text{CB}(m, \mu \pm \Delta\mu, \sigma * R_\sigma, \alpha, n). \quad (5.12)$$

The Gaussian is defined as

$$G(m, \mu \pm \Delta\mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\{-[m - (\mu \pm \Delta\mu)]^2\}. \quad (5.13)$$

The Crystal Ball function is given by

$$\text{CB} = \begin{cases} N \cdot \exp\left(-\frac{[m - (\mu \pm \Delta\mu)]^2}{2(\sigma * R_\sigma)^2}\right) & \text{for } \frac{m - (\mu \pm \Delta\mu)}{\sigma * R_\sigma} \geq -\alpha \\ N \cdot \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right) \cdot \left(\frac{n}{|\alpha|} - |\alpha| - \frac{m - (\mu \pm \Delta\mu)}{\sigma * R_\sigma}\right)^{-n} & \text{for } \frac{m - (\mu \pm \Delta\mu)}{\sigma * R_\sigma} < -\alpha \end{cases} \quad (5.14)$$

where N is a normalization factor given by

$$N = \frac{1}{\sigma * R_\sigma \left[\frac{n}{|\alpha|} \cdot \frac{1}{n-1} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right) + \sqrt{\frac{\pi}{2}} \left(1 + \text{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right)\right) \right]}$$

The shift parameter $\Delta\mu$ is included to allow differences between the most probable values of the $D_{(s)}^+$ and $D_{(s)}^-$ masses. The CB tail parameters are n and α . In this model, the values of σ , R_σ , n and α are shared between the D^+ and D^- PDFs and the signal yields for the $D_{(s)}^+$ and $D_{(s)}^-$ samples are given by:

$$N_{sig}^{\pm} = \frac{N_{sig}(1 \pm A_{\text{raw}})}{2}. \quad (5.15)$$

The background PDF, $\mathcal{P}_{bkg}^{\pm}$, is an exponential function with a shared decay constant between the candidates reconstructed as $D_{(s)}^+$ or $D_{(s)}^-$:

$$\mathcal{P}_{bkg}^{\pm}(m) = \exp(\tau m) \quad (5.16)$$

The background yields are defined in a way similar to the signal yields:

$$N_{bkg}^{\pm} = \frac{N_{bkg}(1 \pm A_{bkg})}{2}. \quad (5.17)$$

5.4.1 Fit procedure

The raw asymmetries are obtained from a simultaneous log likelihood fit to the $D_{(s)}^+$ and $D_{(s)}^-$ binned mass distributions using the PDFs described above. For the baseline results, the fits to the data are performed with all the PDF parameters floating. As cross-checks, we also obtain the raw asymmetries fixing some of the shape parameters of the PDF: fixing R_σ , f_G , α and n , or fixing f_G , α and n , or just α and n to their values obtained from simulation. The 2011 and 2012 data samples are analyzed independently and these data sets are further subdivided by magnet polarity (MagUp and MagDown) and according to the kinematic binning, which is described in the following section. The value of ΔA_{raw} is obtained independently in these subsamples.

5.4.2 Model validation with MC

To validate the signal PDF, we fit the MC distributions of the four decay channels (signal and control) candidates which satisfy all the selection criteria and are matched to the true decay.

The parameters obtained from the mass fit of the MC samples are given in Table 5.1 and the mass distributions with the PDF fits are shown in Fig. 5.1 and Fig. 5.2. The signal PDF is fit to the whole sample of MC data available split by magnet polarity, MagUp and MagDown, with a simultaneous fit to the $D_{(s)}^+$ and $D_{(s)}^-$ candidate mass distributions. Results are similar for both polarities and the parameters from the MagDown fit were used in the fit to data, when fixing parameters.

Table 5.1: Parameters obtained from the mass fit of the MC samples.

$D_s^+ \rightarrow \pi^- \pi^+ \pi^+$		
Parameter	MagUp	MagDown
μ	$(1969.400 \pm 0.033) \text{ MeV}/c^2$	$(1969.500 \pm 0.033) \text{ MeV}/c^2$
$\Delta\mu$	$(0.010 \pm 0.033) \text{ MeV}/c^2$	$(0.039 \pm 0.033) \text{ MeV}/c^2$
σ	$(14.03 \pm 0.33) \text{ MeV}/c^2$	$(13.83 \pm 0.27) \text{ MeV}/c^2$
R_σ	0.5348 ± 0.0091	0.5349 ± 0.0078
f_G	0.183 ± 0.016	0.199 ± 0.014
α	3.51 ± 0.11	3.521 ± 0.036
n	0.011 ± 0.082	0.0000 ± 0.0011
$D^+ \rightarrow \pi^- \pi^+ \pi^+$		
Parameter	MagUp	MagDown
μ	$(1870.300 \pm 0.027) \text{ MeV}/c^2$	$(1870.300 \pm 0.027) \text{ MeV}/c^2$
$\Delta\mu$	$(-0.004 \pm 0.027) \text{ MeV}/c^2$	$(-0.017 \pm 0.027) \text{ MeV}/c^2$
σ	$(14.06 \pm 0.30) \text{ MeV}/c^2$	$(13.28 \pm 0.28) \text{ MeV}/c^2$
R_σ	0.5217 ± 0.0086	0.5420 ± 0.0086
f_G	0.151 ± 0.011	0.181 ± 0.014
α	3.520 ± 0.080	3.270 ± 0.037
n	0.009 ± 0.081	0.221 ± 0.046
$D_s^+ \rightarrow K^- K^+ \pi^+$		
Parameter	MagUp	MagDown
μ	$(1969.300 \pm 0.027) \text{ MeV}/c^2$	$(1969.300 \pm 0.027) \text{ MeV}/c^2$
$\Delta\mu$	$(0.010 \pm 0.027) \text{ MeV}/c^2$	$(-0.013 \pm 0.027) \text{ MeV}/c^2$
σ	$(10.89 \pm 0.27) \text{ MeV}/c^2$	$(11.12 \pm 0.28) \text{ MeV}/c^2$
R_σ	0.4999 ± 0.0098	0.491 ± 0.010
f_G	0.129 ± 0.011	0.121 ± 0.011
α	3.846 ± 0.045	3.887 ± 0.055
n	0.000180 ± 0.000015	0.00 ± 0.41
$D^+ \rightarrow K^- K^+ \pi^+$		
Parameter	MagUp	MagDown
μ	$(1870.200 \pm 0.021) \text{ MeV}/c^2$	$(1870.200 \pm 0.021) \text{ MeV}/c^2$
$\Delta\mu$	$(-0.003 \pm 0.021) \text{ MeV}/c^2$	$(-0.009 \pm 0.021) \text{ MeV}/c^2$
σ	$(10.89 \pm 0.24) \text{ MeV}/c^2$	$(10.76 \pm 0.23) \text{ MeV}/c^2$
R_σ	0.4796 ± 0.0087	0.4836 ± 0.0082
f_G	0.1107 ± 0.0085	0.11868 ± 0.00863
α	3.98 ± 0.21	3.895 ± 0.040
n	0.00 ± 0.10	0.0000785 ± 0.0000062

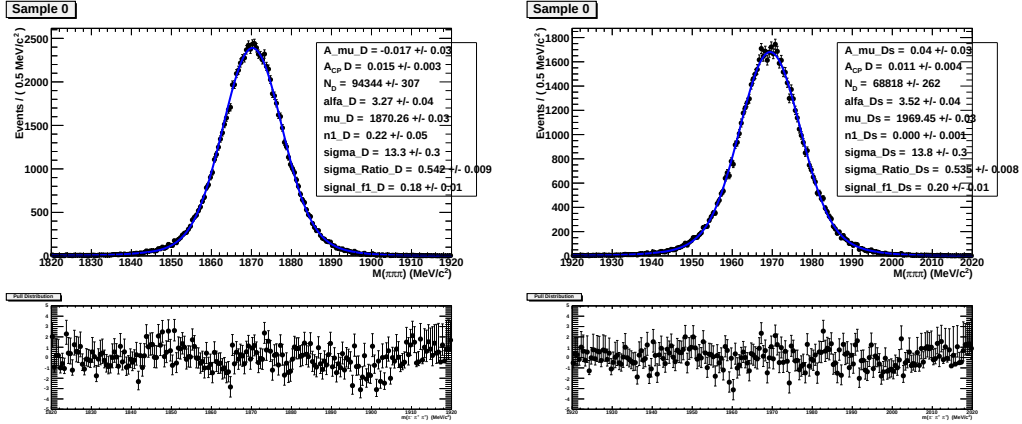


Figure 5.1: Fits to the MC mass distributions of $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (left) and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (right).

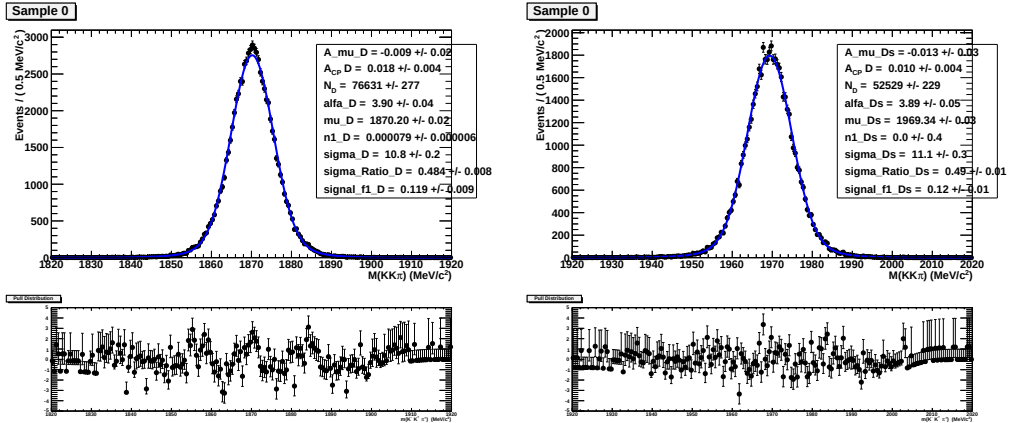


Figure 5.2: Fits to the MC mass distribution of $D^+ \rightarrow K^- K^+ \pi^+$ (left) and $D_s^+ \rightarrow K^- K^+ \pi^+$ (right).

5.5 Kinematic Binning

The cancellation of production and detection asymmetries is assumed to hold to first order when computing ΔA_{CP} . These asymmetries, however, may vary as a function of kinematic variables. Due to differences between kinematic distributions of the bachelor pion in the $KK\pi$ and $\pi\pi\pi$ final states, second order effects may remain. Cancellation of these effects may be reinforced by dividing the samples in different kinematic regions and computing ΔA_{CP} in each region. Two binning schemes are considered for this study and described in this section. Both are based on our smallest samples, the $D_{(s)}^+ \rightarrow \pi^-\pi^+\pi^+$ samples, one being based on the D_s^+ control channel, whereas the other is based on the D^+ signal. The latter one, based on the signal channel, is considered our baseline choice for the determination of the asymmetries in both the signal and control modes.

For both D^+ and D_s^+ decays to $\pi^-\pi^+\pi^+$, the bachelor pion is defined randomly between the 2 pions of same charge. This choice is made once at the beginning of the analysis, just after stripping selection, and then everything onwards is done respecting this choice. We see that, by defining this way the bachelor pions for both D^+ and D_s^+ , we have a better agreement between the global distributions of p and p_T for the π^- and the π^+ in the $D_{(s)}^+ \rightarrow \pi^-\pi^+\pi^+$ decays and also for the bachelor pions when comparing $\pi^-\pi^+\pi^+$ and $K^-K^+\pi^+$ modes (see Figure 5.3).

As can be seen from these plots, there are remaining differences between the distributions. Therefore, for our baseline result, the asymmetries and ΔA_{CP} are obtained separately in bins of the bachelor momentum and pseudorapidity and then combined in one single result. The combined measurement M (A_{raw} or ΔA_{CP}) and its error σ are given by

$$M = \sum_i \left(\frac{M_i}{\sigma_i^2} \right) / \sum_i \left(\frac{1}{\sigma_i^2} \right), \quad \frac{1}{\sigma^2} = \sum_i \left(\frac{1}{\sigma_i^2} \right), \quad (5.18)$$

where M_i and σ_i are the asymmetries and their respective errors measured in each bin.

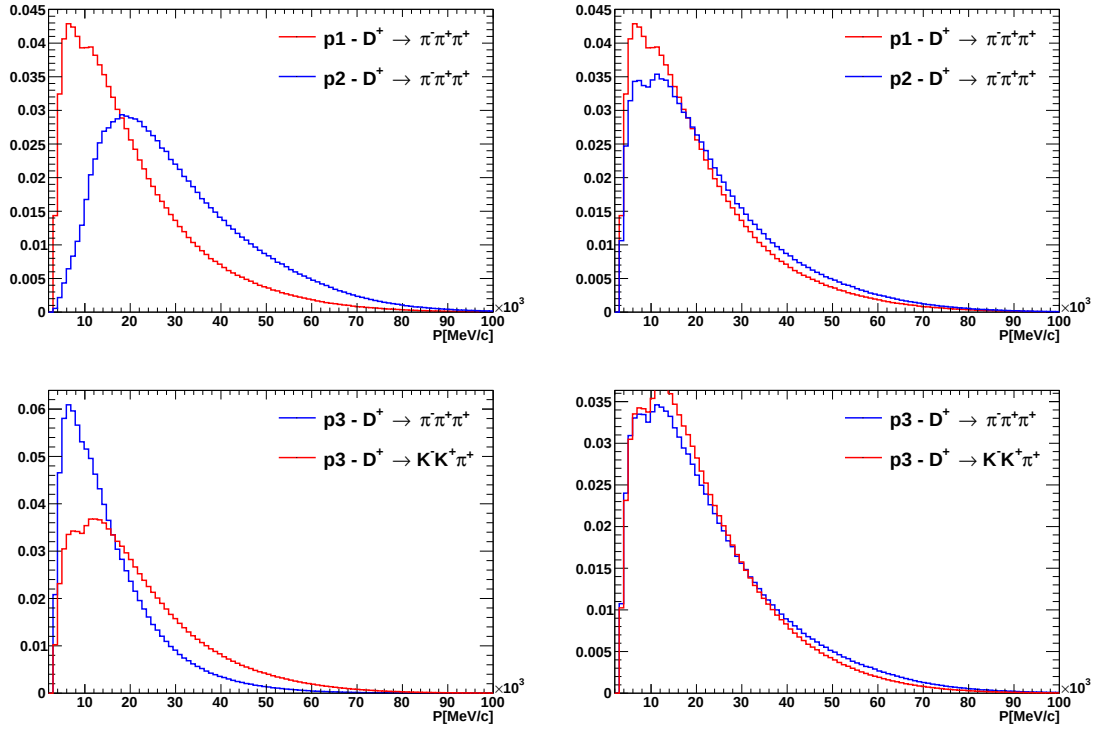
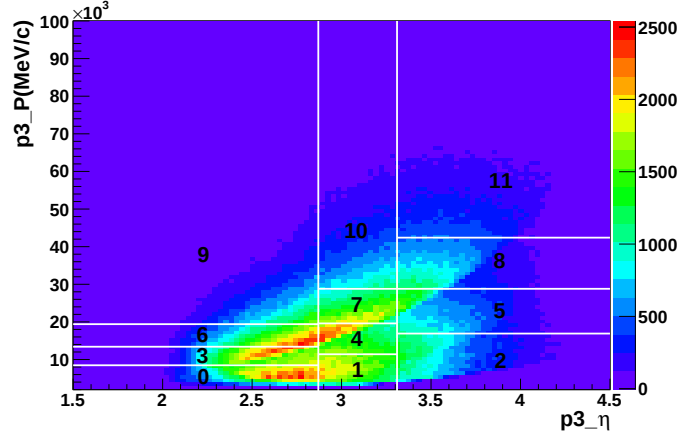


Figure 5.3: Comparison of momentum distributions of daughters with different choices of the bachelor pion π^+ (p3) for the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decay. In the left plots, the bachelor pion is the π^+ with lowest p_T . In the right plot, the bachelor is randomly chosen between the two π^+ . The top plots are the comparison between the distributions of the pair of opposite charge ($\pi^- \pi^+$ - p1p2) and the bottom plots are the comparison between the bachelor pions of $D^+ \rightarrow \pi^- \pi^+ \pi^+$ and $D^+ \rightarrow K^- K^+ \pi^+$.

5.5.1 $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning

This binning scheme is defined aiming at an approximately uniform bin population of $D^+ \rightarrow \pi^- \pi^+ \pi^+$ candidates from 2012 data. This is done in two steps. First, the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ sample is divided into three bins of $\eta(\pi^+)$. For each $\eta(\pi^+)$ bin four bins of π^+ momentum are defined, yielding a total of twelve bins. The bin division is illustrated in Figure 5.4 and the intervals of η and P for each bin are listed in Table 5.2.

Since the kinematics of the bachelor pion are different in the two final states, the bin population of $D^+ \rightarrow K^- K^+ \pi^+$ candidates is not uniform. The asymmetry

Figure 5.4: Illustration of the D^+ binning.Table 5.2: Bin limits in the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning.

Bin index	$\eta(\pi^+)$	$P(\pi^+)$
0	1.50-2.87	3000-8470 MeV
1	2.87-3.31	3000-11400 MeV
2	3.31-5.00	3000-16900 MeV
3	1.50-2.87	8470-13400 MeV
4	2.87-3.31	11400-19600 MeV
5	3.31-5.00	16900-28800 MeV
6	1.50-2.87	13400-19400 MeV
7	2.87-3.31	19600-28800 MeV
8	3.31-5.00	28800-42400 MeV
9	1.50-2.87	19400-100000 MeV
10	2.87-3.31	28800-100000 MeV
11	3.31-5.00	42400-100000 MeV

defined by Eq. 5.19 is used to compare the number of candidates of each final state in each bin.

$$A_{\text{bin}} \equiv \frac{N_{D^+ \rightarrow \pi^- \pi^+ \pi^+} - N_{D^+ \rightarrow K^- K^+ \pi^+}}{N_{D^+ \rightarrow \pi^- \pi^+ \pi^+} + N_{D^+ \rightarrow K^- K^+ \pi^+}} \quad (5.19)$$

The values of A_{bin} , computed for each bin, are shown in Figure 5.5. The asymmetries vary between 20 and 50% but are not significantly different from the global asymmetry between the two samples, $\sim 37\%$, illustrated by the solid lines in the plot.

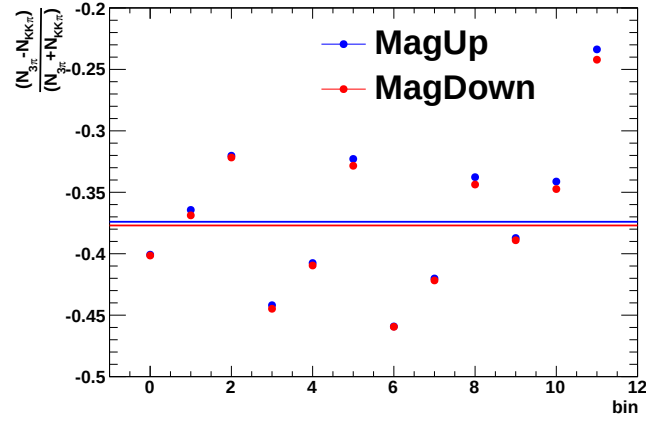


Figure 5.5: Asymmetry between the number of $D^+ \rightarrow K^- K^+ \pi^+$ and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ candidates in each kinematic bin, for the binning scheme based on the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decay. The blue and red solid lines represent the global asymmetry (no binning) for MagUp and MagDown, respectively.

The invariant mass distributions for both final states and magnet polarities, in each of the twelve bins are shown in Figures 5.6 and 5.7. In each $\eta(\pi^+)$ bin the invariant mass distributions for the four pion momentum bins are superimposed.

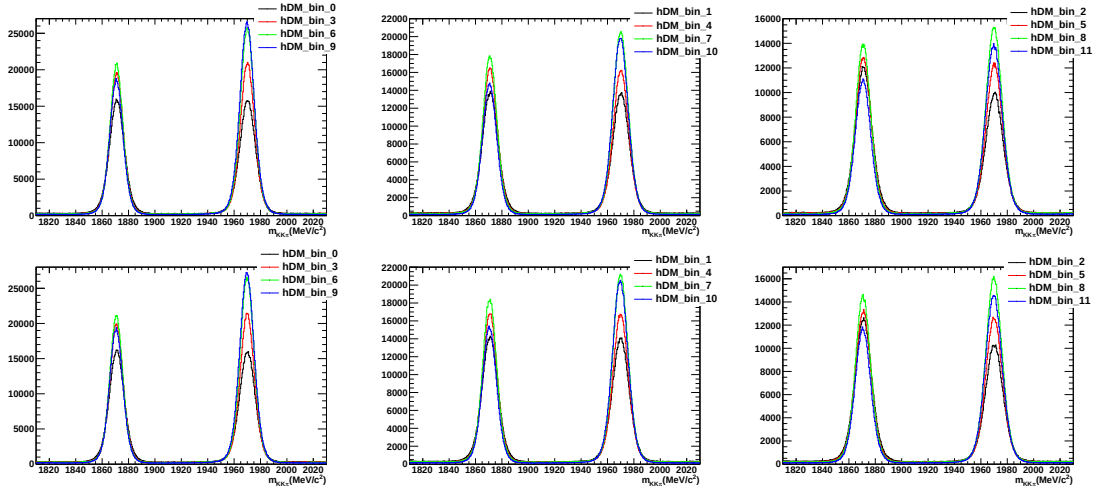


Figure 5.6: Distribution of $K^- K^+ \pi^+$ invariant mass in bins of $\eta(\pi^+)$ for MagUp (top) and MagDown (bottom) data ($D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning). The mass distributions for the four momentum bins of each $\eta(\pi^+)$ bin are superimposed.

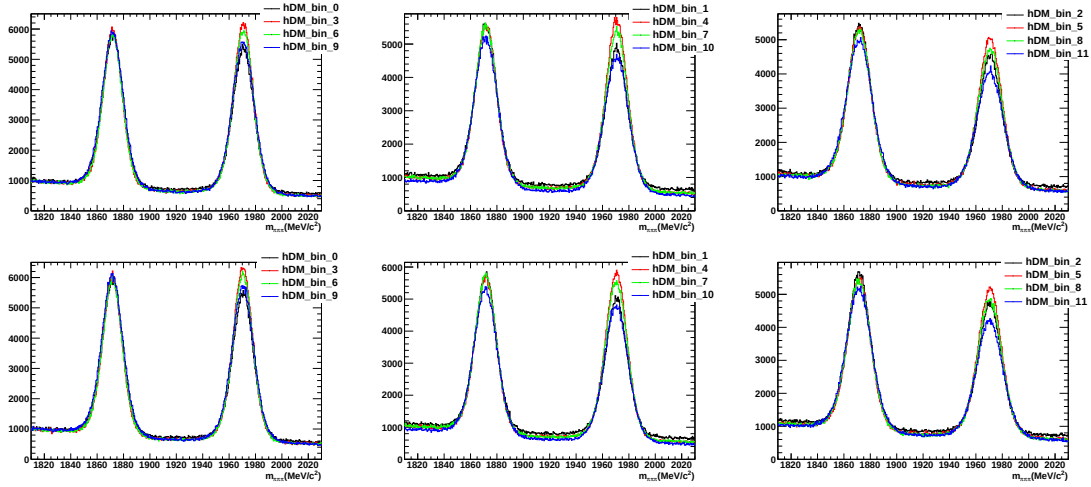


Figure 5.7: Distribution of $\pi^-\pi^+\pi^+$ invariant mass in bins of $\eta(\pi^+)$ for MagUp (top) and MagDown (bottom) data ($D^+ \rightarrow \pi^-\pi^+\pi^+$ driven binning). The mass distributions for the four momentum bins of each $\eta(\pi^+)$ bin are superimposed.

5.5.2 $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ driven binning

Using a procedure similar to the one used for the previous bin division, the goal now is to have a scheme in which the number of $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ candidates from 2012 data is approximately the same in each bin. Again, this is done in two steps: first, the sample is divided into three bins of $\eta(\pi^+)$ and for each of these, four bins of π^+ momentum are defined. The binning is illustrated in Figure 5.8 and the intervals of $\eta(\pi^+)$ and pion momentum of each bin are listed in Table 5.3.

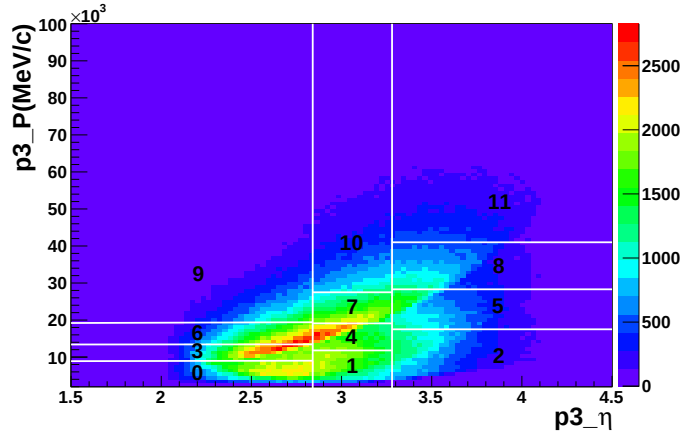


Figure 5.8: Illustration of the binning scheme based on $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ candidates.

Table 5.3: Bin limits in the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning.

Bin index	$\eta(\pi^+)$	$P(\pi^+)$
0	1.50-2.84	3000-8900 MeV
1	2.84-3.28	3000-11800 MeV
2	3.28-5.00	3000-17500 MeV
3	1.50-2.84	8900-13400 MeV
4	2.84-3.28	11800-19100 MeV
5	3.28-5.00	17500-28300 MeV
6	1.50-2.84	13400-19200 MeV
7	2.84-3.28	19100-27500 MeV
8	3.28-5.00	28300-41000 MeV
9	1.50-2.84	19200-100000 MeV
10	2.84-3.28	27500-100000 MeV
11	3.28-5.00	41000-100000 MeV

As before, the asymmetry defined by eq. 5.20,

$$A_{\text{bin}} \equiv \frac{N_{D_s^+ \rightarrow \pi^- \pi^+ \pi^+} - N_{D_s^+ \rightarrow K^- K^+ \pi^+}}{N_{D_s^+ \rightarrow \pi^- \pi^+ \pi^+} + N_{D_s^+ \rightarrow K^- K^+ \pi^+}} \quad (5.20)$$

is shown in Figure 5.9. The asymmetries between the different channels for the signal modes, defined in 5.5, are also shown for this binning scheme. The asymmetries vary between 30 and 60%, for D_s^+ decays, and between 20 and 50%, for D^+ decays, but they are not significantly different from the global asymmetries, illustrated by the solid lines in the plot, which are about 45% and 37%, for D_s^+ and D^+ decays, respectively.

The invariant mass distributions for both final states and magnet polarities, in each of the twelve bins are shown in Figures 5.10 and 5.11. In each $\eta(\pi^+)$ bin, the invariant mass distributions for the four pion momentum bins are superimposed.

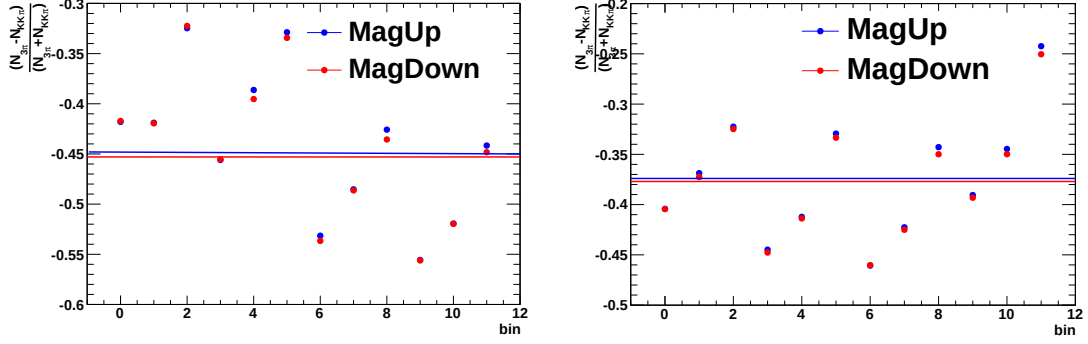


Figure 5.9: Asymmetry between the number of $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ candidates, in the left plot, and the number of $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$, in the right plot, in each kinematic bin, for the binning scheme based on the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ decay. The blue and red solid lines represent the global asymmetry (no binning) for MagUp and MagDown, respectively.

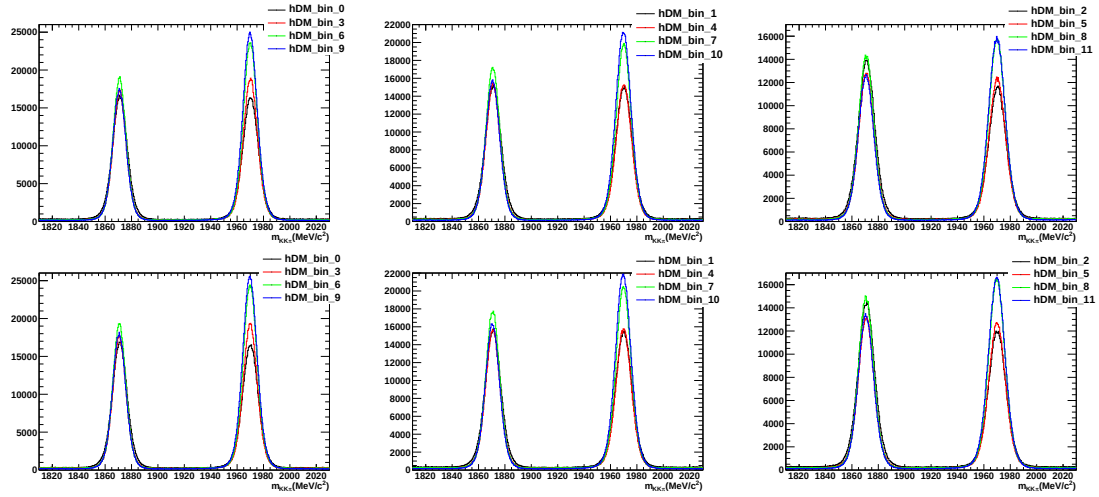


Figure 5.10: Distribution of $K^- K^+ \pi^+$ invariant mass in bins of $\eta(\pi^+)$ for MagUp (top) and MagDown (bottom) data ($D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning). The mass distributions for the four momentum bins of each $\eta(\pi^+)$ bin are superimposed.

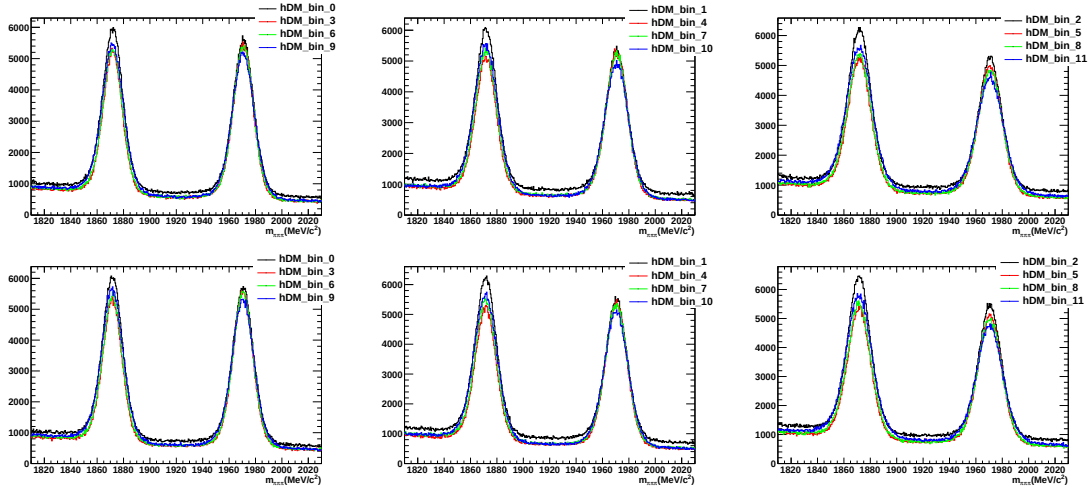


Figure 5.11: Distribution of $\pi^-\pi^+\pi^+$ invariant mass in bins of $\eta(\pi^+)$ for MagUp (top) and MagDown (bottom) data ($D_s^+ \rightarrow \pi^-\pi^+\pi^+$ driven binning). The mass distributions for the four momentum bins of each $\eta(\pi^+)$ bin are superimposed.

Chapter 6

Results

The measurement is performed using the data sample and strategy described in the previous chapters. To obtain the ΔA_{CP} for control and signal modes, the raw asymmetries are extracted from the fits to the invariant mass distributions of $D_s^+ \rightarrow K^- K^+ \pi^+$, $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$, $D^+ \rightarrow K^- K^+ \pi^+$ and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decays using the model described in Section 5.4. In these fits, all the PDF parameters are floated. The samples are split by magnet polarity (MagUp and MagDown) and by data taking year (2011 and 2012). Each of these subsamples is further divided according to the kinematic binning defined in Section 5.5.1 to account for the differences in the π^+ kinematic distributions.

6.1 Results for control modes

6.1.1 Asymmetries for the 2012 data

Using the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven kinematic binning, the mass fits are performed for each bin in the $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ 2012 samples, split by magnet polarity. The raw asymmetries are extracted from these fits. The fits, superimposed to the mass distributions, are shown for each bin for the MagUp and MagDown polarities in Figures 6.1 and 6.2.

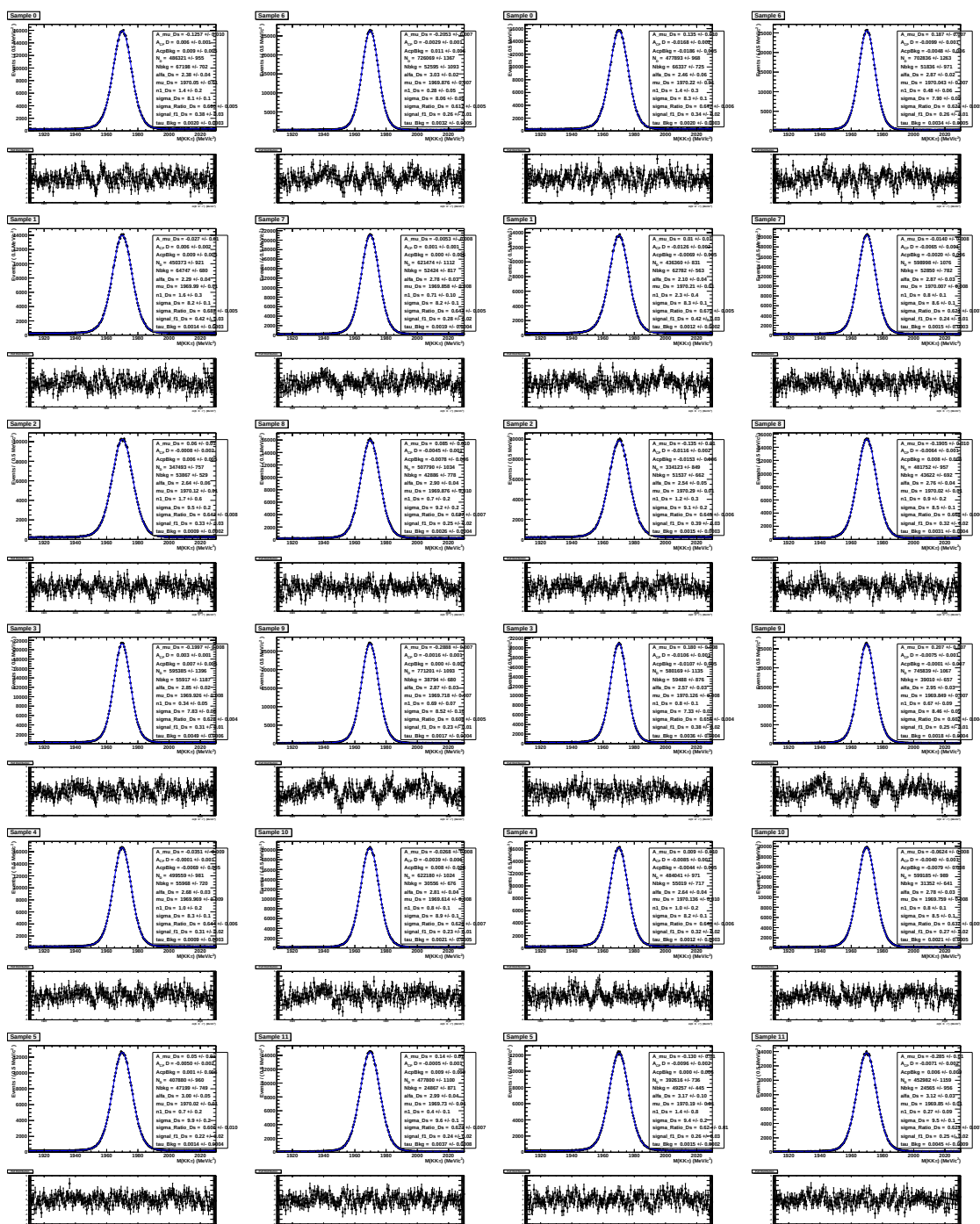


Figure 6.1: Invariant mass distributions for $D_s^+ \rightarrow K^- K^+ \pi^+$ decays and fits for the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2012 data (MagUp, in first two columns; MagDown in the last two ones).

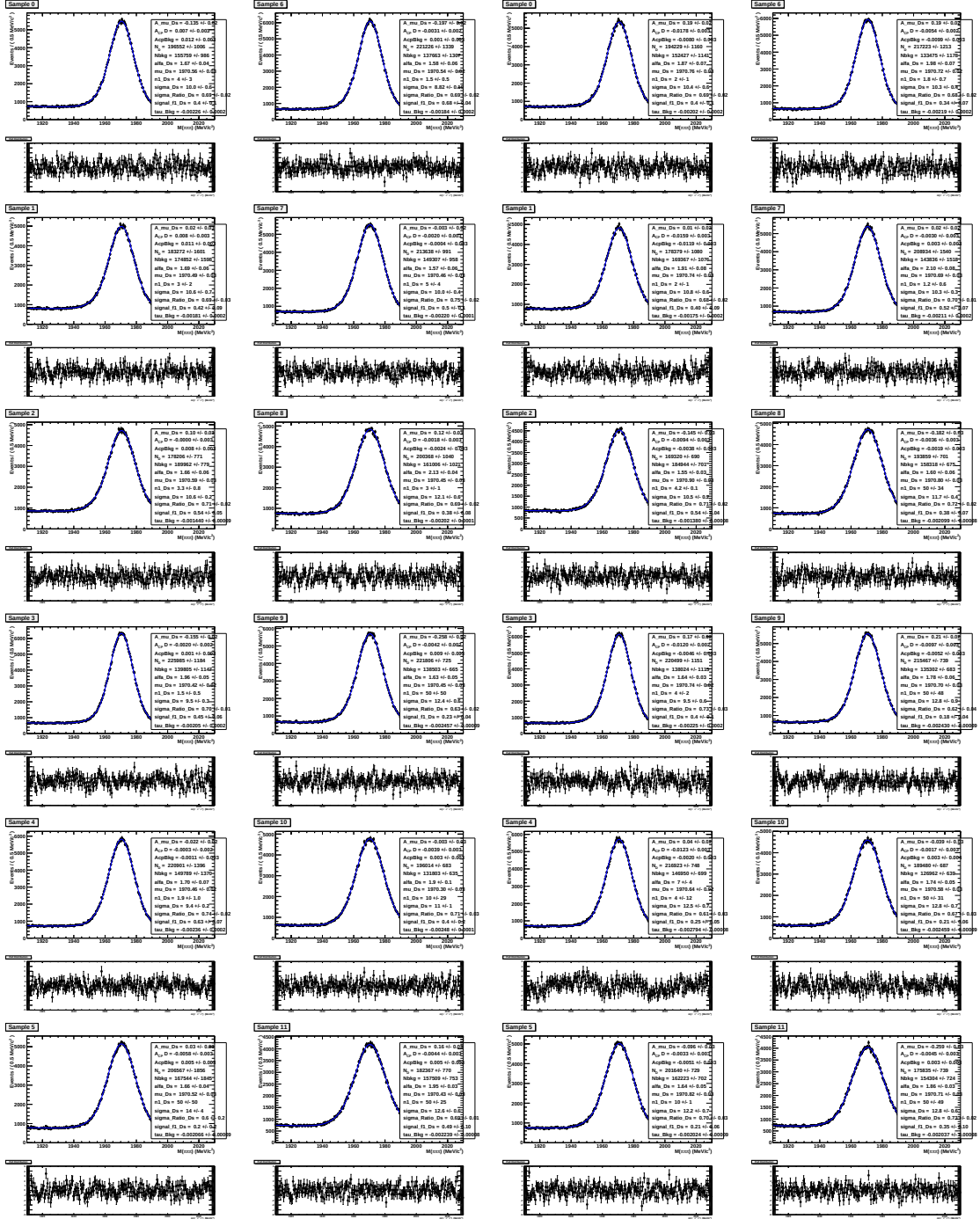


Figure 6.2: Invariant mass distributions for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ decays and fits for the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2012 data (MagUp, in first two columns; MagDown in the last two ones).

The asymmetries as a function of the kinematic bin are shown in Figure 6.3 and are also given in Table 6.1. Clearly the MagUp/MagDown individual asymmetries are larger in absolute value for the bins of low π^+ momentum, but the combination of MagUp+MagDown presents a much more stable behavior. A similar pattern is observed in both final states.

The raw asymmetries are not expected to be null because there are contributions from the instrumental and production asymmetries. The $D_s^+ - D_s^-$ production asymmetry in pp collisions at $\sqrt{s} = 7$ TeV is measured to be $A_P = (-0.33 \pm 0.22 \pm 0.10)\%$ [79].

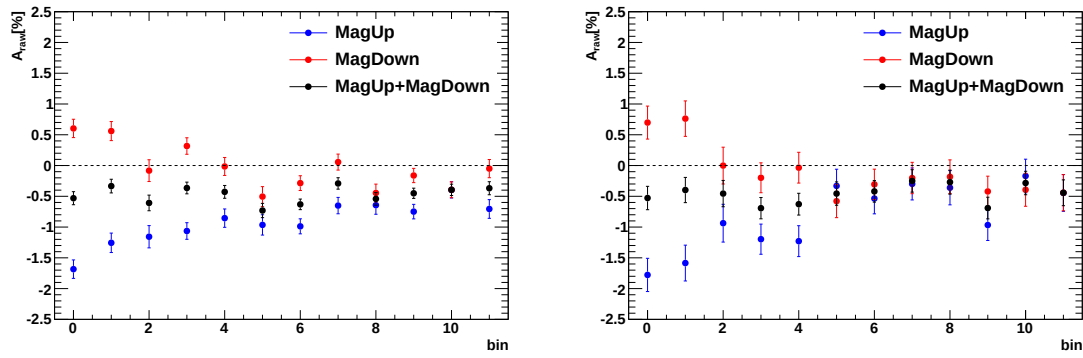


Figure 6.3: Raw asymmetries for $D_s^+ \rightarrow K^- K^+ \pi^+$ (left) and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (right) with 2012 data using the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning.

Table 6.1: Asymmetries of control channels for the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2012 data.

Bin	$A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+) (\%)$			$A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$		
	MagUp	MagDown	Up+Down	MagUp	MagDown	Up+Down
0	-1.68 ± 0.15	0.60 ± 0.15	-0.53 ± 0.11	-1.78 ± 0.27	0.70 ± 0.27	-0.53 ± 0.19
1	-1.26 ± 0.16	0.56 ± 0.16	-0.33 ± 0.11	-1.58 ± 0.29	0.76 ± 0.29	-0.40 ± 0.20
2	-1.16 ± 0.18	-0.08 ± 0.18	-0.61 ± 0.13	-0.94 ± 0.31	-0.00 ± 0.30	-0.46 ± 0.21
3	-1.06 ± 0.14	0.32 ± 0.13	-0.36 ± 0.10	-1.20 ± 0.24	-0.20 ± 0.24	-0.69 ± 0.17
4	-0.86 ± 0.15	-0.02 ± 0.15	-0.43 ± 0.10	-1.23 ± 0.25	-0.04 ± 0.25	-0.63 ± 0.18
5	-0.96 ± 0.16	-0.50 ± 0.16	-0.73 ± 0.12	-0.33 ± 0.27	-0.58 ± 0.27	-0.46 ± 0.19
6	-0.99 ± 0.12	-0.29 ± 0.12	-0.63 ± 0.09	-0.54 ± 0.25	-0.31 ± 0.25	-0.42 ± 0.18
7	-0.65 ± 0.13	0.06 ± 0.13	-0.29 ± 0.09	-0.30 ± 0.26	-0.20 ± 0.26	-0.25 ± 0.18
8	-0.64 ± 0.15	-0.45 ± 0.14	-0.54 ± 0.10	-0.36 ± 0.28	-0.18 ± 0.27	-0.27 ± 0.20
9	-0.75 ± 0.12	-0.16 ± 0.12	-0.45 ± 0.08	-0.97 ± 0.25	-0.42 ± 0.25	-0.69 ± 0.18
10	-0.40 ± 0.13	-0.39 ± 0.13	-0.40 ± 0.09	-0.17 ± 0.27	-0.39 ± 0.27	-0.28 ± 0.19
11	-0.71 ± 0.15	-0.05 ± 0.15	-0.37 ± 0.11	-0.44 ± 0.30	-0.44 ± 0.29	-0.44 ± 0.21

6.1.2 Asymmetries for the 2011 data

Using the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven kinematic binning, the mass fit is performed for each bin in the $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ 2011 sample, split by magnet polarity. The raw asymmetries are extracted from these fits. The fits superimposed to the mass distributions are shown for each bin for the MagUp and MagDown polarities in Figures 6.4 and 6.5.

The asymmetries as a function of the kinematic bin are shown in Figure 6.6 and are also given in Table 6.2.

Table 6.2: Asymmetries of control channels for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2011 data.

Bin	$A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+) (\%)$			$A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$		
	MagUp	MagDown	Up+Down	MagUp	MagDown	Up+Down
0	-1.98 ± 0.34	0.45 ± 0.28	-0.53 ± 0.22	-1.60 ± 0.62	1.16 ± 0.52	0.02 ± 0.40
1	-1.14 ± 0.31	0.99 ± 0.26	0.11 ± 0.20	-1.28 ± 0.58	0.53 ± 0.49	-0.22 ± 0.37
2	-0.42 ± 0.35	0.18 ± 0.29	-0.07 ± 0.22	-1.79 ± 0.59	0.76 ± 0.49	-0.29 ± 0.38
3	-1.21 ± 0.28	-0.59 ± 0.23	-0.84 ± 0.18	-1.19 ± 0.52	-0.81 ± 0.43	-0.96 ± 0.33
4	-0.78 ± 0.28	0.28 ± 0.24	-0.16 ± 0.18	-1.84 ± 0.49	-1.16 ± 0.41	-1.44 ± 0.31
5	-0.50 ± 0.31	-0.38 ± 0.26	-0.43 ± 0.20	-0.72 ± 0.51	-0.22 ± 0.43	-0.43 ± 0.33
6	-0.57 ± 0.24	-0.17 ± 0.20	-0.33 ± 0.15	-0.98 ± 0.50	-0.95 ± 0.41	-0.96 ± 0.31
7	-1.09 ± 0.24	0.04 ± 0.20	-0.43 ± 0.16	-0.99 ± 0.49	-0.30 ± 0.41	-0.58 ± 0.31
8	-1.07 ± 0.26	0.01 ± 0.22	-0.44 ± 0.17	-0.48 ± 0.51	0.21 ± 0.43	-0.08 ± 0.33
9	-0.73 ± 0.22	-0.24 ± 0.19	-0.44 ± 0.14	-1.48 ± 0.49	-0.17 ± 0.40	-0.70 ± 0.31
10	-1.04 ± 0.24	0.15 ± 0.20	-0.34 ± 0.15	-0.66 ± 0.50	-0.87 ± 0.42	-0.79 ± 0.32
11	-0.70 ± 0.26	-0.01 ± 0.22	-0.30 ± 0.17	-0.82 ± 0.52	0.17 ± 0.44	-0.24 ± 0.34

6.1.3 ΔA_{CP} for the control channels

Using the raw asymmetries extracted from the fits and shown in previous sections, the difference ΔA_{CP} is obtained for each bin and further combined in one final ΔA_{CP} value, according to Equation 5.18. The dependence of the ΔA_{CP} with kinematic binning is shown in Figure 6.7.

By combining the 2011 and 2012 results, we have $\Delta A_{CP}(D_s^+) = (0.055 \pm 0.054)\%$, which is compatible with zero within about one standard deviation. A constant fitted to the MagUp+MagDown distribution of ΔA_{CP} values in Figure 6.7 leads to

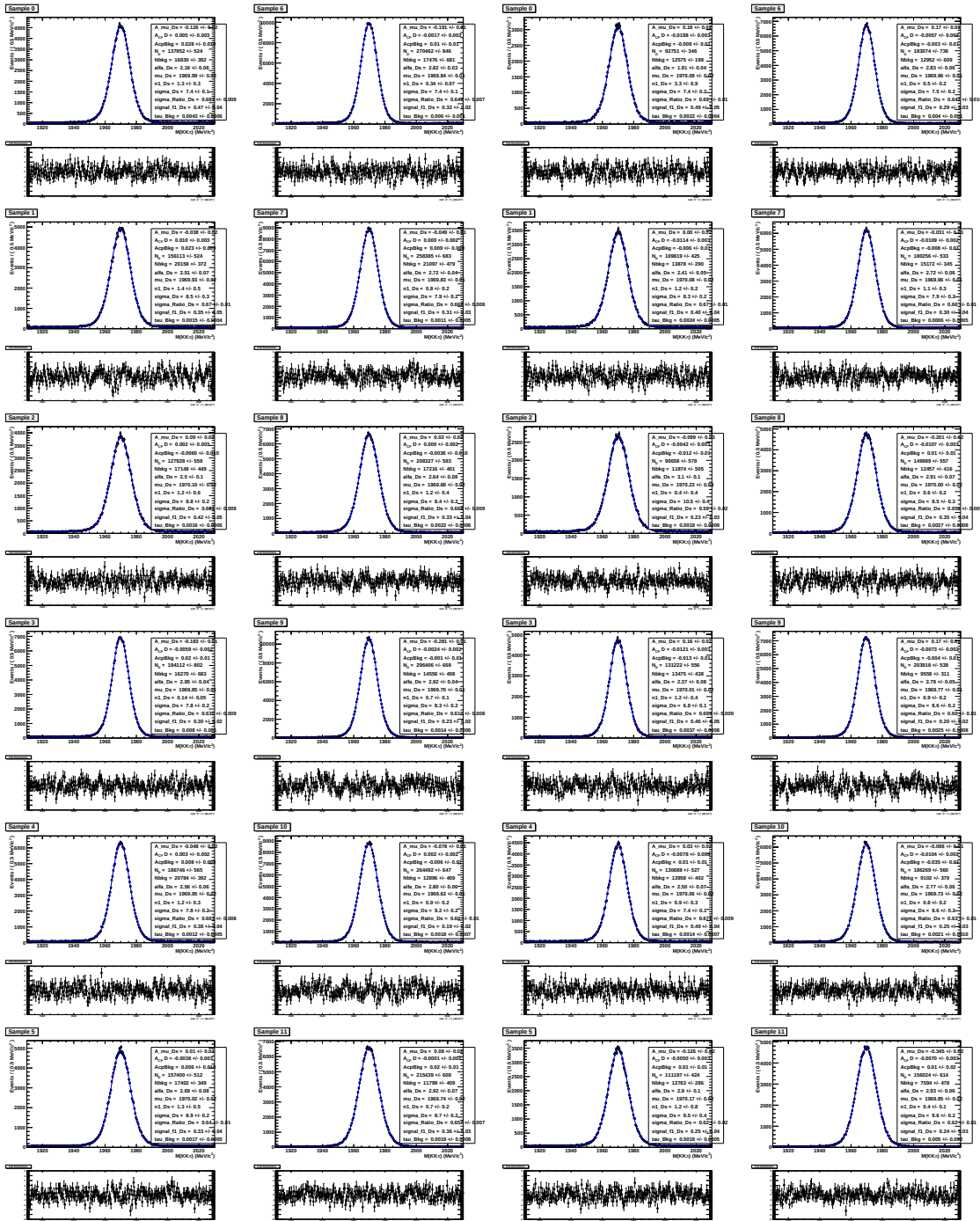


Figure 6.4: Invariant mass distribution for $D_s^+ \rightarrow K^- K^+ \pi^+$ with fitted PDF superimposed for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2011 data. (MagUp, in first two columns; MagDown in the last two ones)

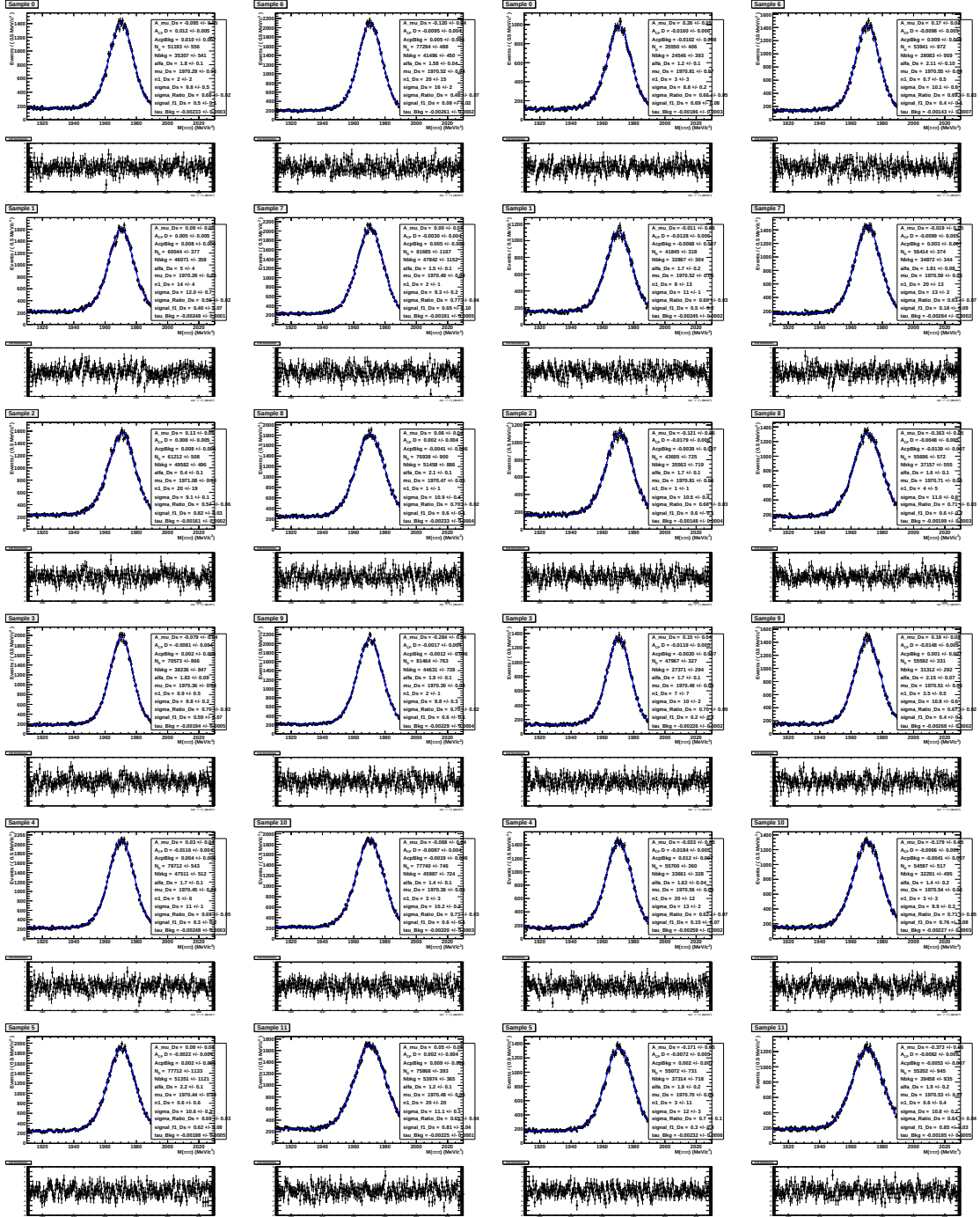


Figure 6.5: Invariant mass distribution for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ with fitted PDF superimposed for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2011 data (MagUp, in first two columns; MagDown in the last two ones).

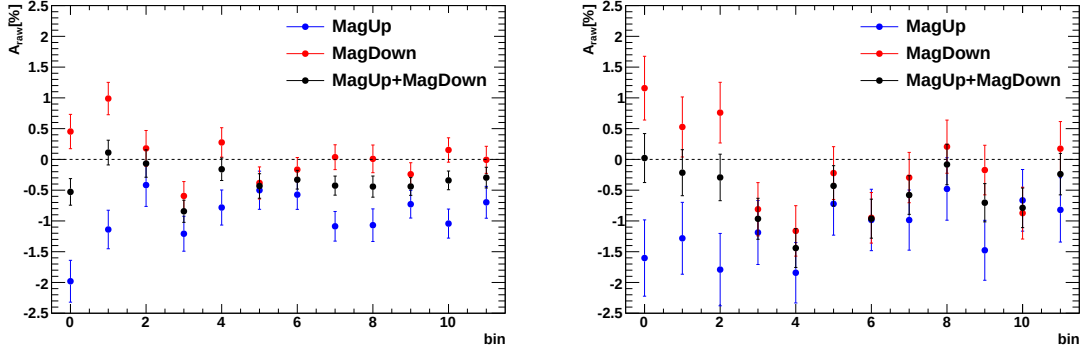


Figure 6.6: Raw asymmetries for $D_s^+ \rightarrow K^- K^+ \pi^+$ (left) and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (right) with 2011 data using the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning.

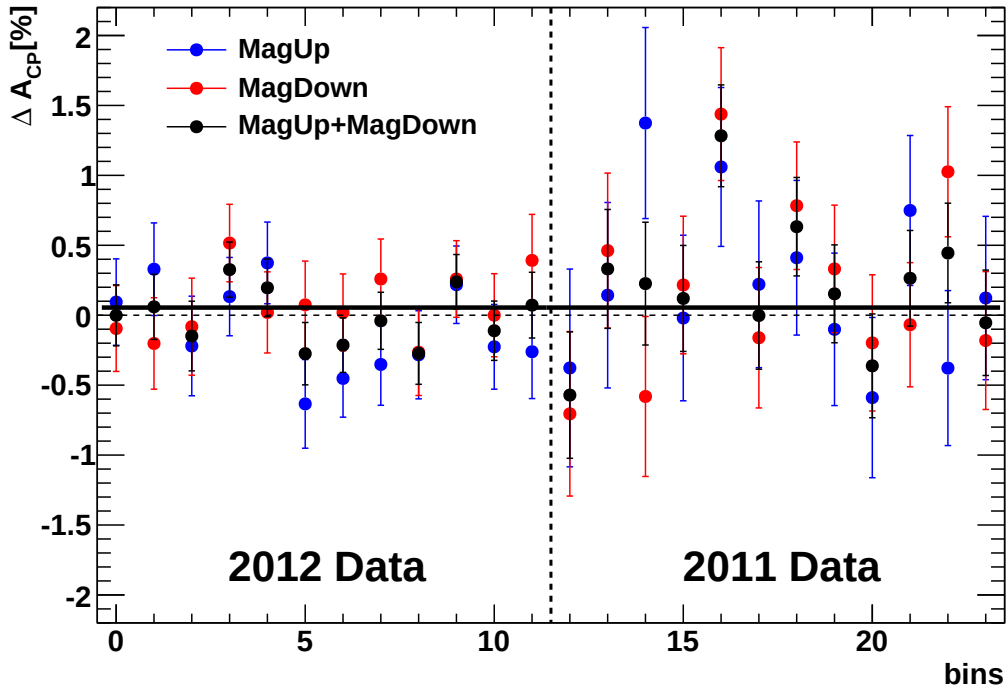


Figure 6.7: $\Delta A_{CP}(D_s^+)$ as a function of the kinematic bin with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2012 and 2011 data). The solid black line shows the value of a constant fit to the combined MagUp+MagDown data at $(0.055 \pm 0.054)\%$ with a p-value of 13%.

the same result. The χ^2/dof of the fit is 1.3 with a p-value for the consistency to the hypothesis of a common constant value of 13%.

The asymmetries of the background, assumed to be essentially combinatorial, are also obtained from the fits and, after combining the results for different polarities, the individual bins and combining 2011+2012, we have $\Delta A_{CP}^{\text{bkg}} = (-0.05 \pm 0.12)\%$, compatible with zero within one standard deviation.

6.2 Results for signal modes

6.2.1 Asymmetries obtained with 2012 data

The raw asymmetries are also computed for the D^+ decays as a function of the kinematic bins defined in Section 5.5.1. However, at the present stage of the analysis, the central values are kept blinded with the addition of random offsets to the asymmetry values obtained for the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ and the $D^+ \rightarrow K^- K^+ \pi^+$ decays (different offsets for each final state so that $\Delta A_{CP}(D^+)$ is also blind). Here again the raw asymmetries are extracted from the mass fits split by magnet polarity in each kinematic bin. The fits, superimposed to the mass distributions, are shown for each bin for the MagUp and MagDown polarities in Figures 6.8 and 6.9.

The asymmetries as a function of the kinematic bin are shown in Figure 6.10 and are also given in Table 6.3. The individual asymmetries behave in a similar manner as the control channels, being larger in absolute value for bins of low pion momentum and tending to zero at higher momentum. The combined MagUp+MagDown asymmetries are also more independent of the kinematics of the pion momentum than are the individual MagUp and MagDown values.

6.2.2 Asymmetries obtained with 2011 data

The raw asymmetries are also extracted from the 2011 data. The mass distributions superimposed with the fitted function for each of the subsamples defined according to the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning for the MagUp and MagDown signal are shown in Figures 6.11 and 6.12.

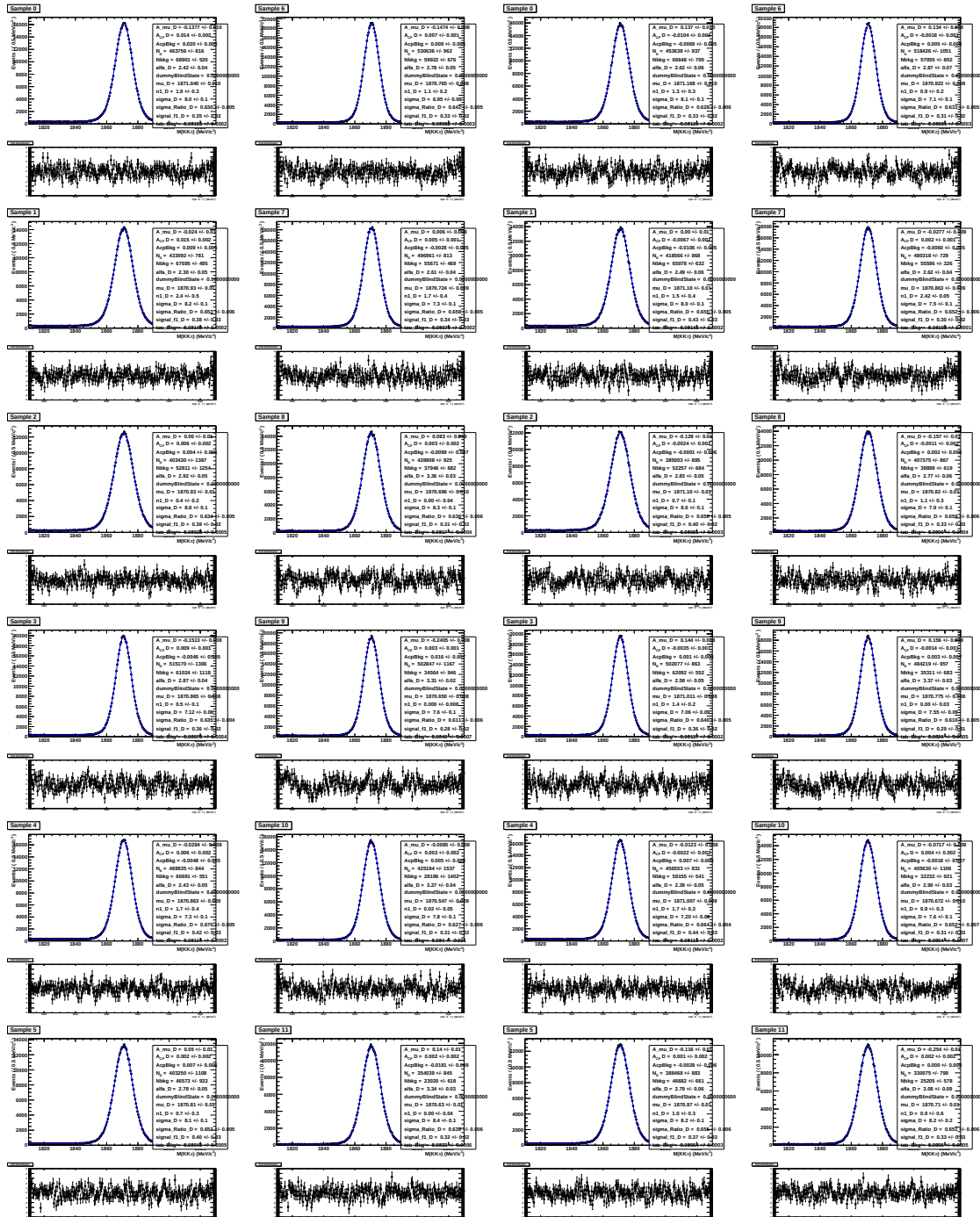


Figure 6.8: Invariant mass distribution for $D^+ \rightarrow K^- K^+ \pi^+$ with fitted PDF superimposed for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2012 data (MagUp on the left, MagDown on the right).

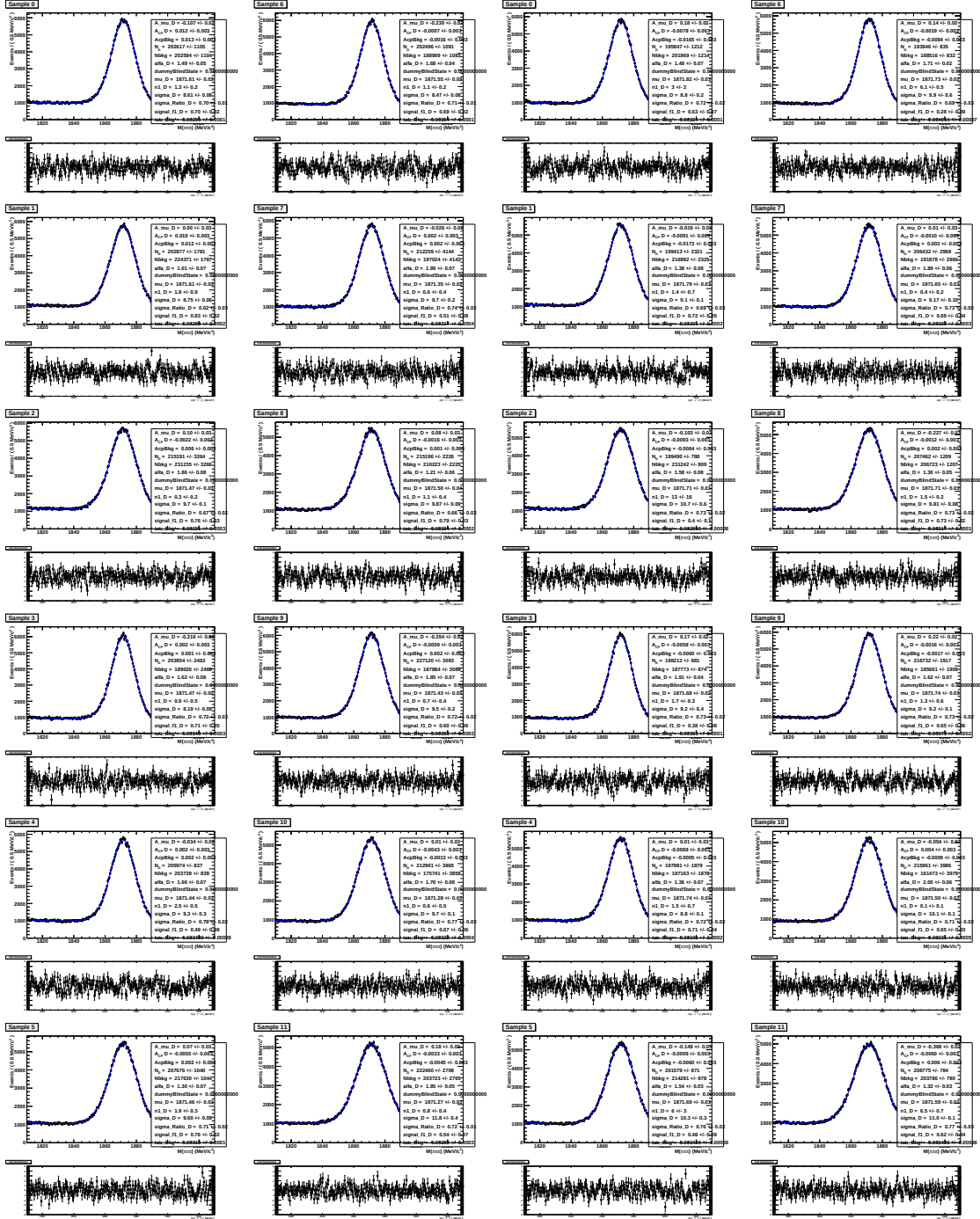


Figure 6.9: Invariant mass distribution for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ with fitted PDF superimposed for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2012 data (MagUp on the left, MagDown on the right).

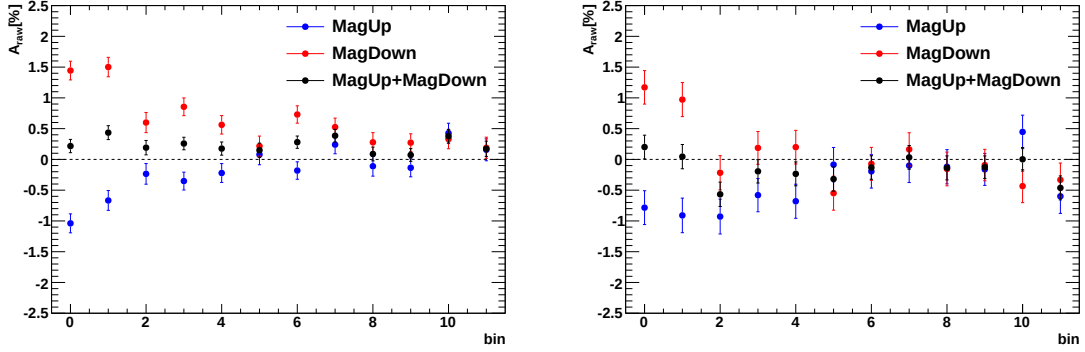


Figure 6.10: Raw asymmetries for $D^+ \rightarrow K^- K^+ \pi^+$ (left) and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (right) with 2012 data using the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning.

Table 6.3: Blind asymmetries of the signal channels for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2012 MagDown data.

Bin	$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+) (\%)$			$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$		
	MagUp	MagDown	Up+Down	MagUp	MagDown	Up+Down
0	-1.04 ± 0.15	1.44 ± 0.15	0.22 ± 0.11	-0.78 ± 0.28	1.17 ± 0.27	0.20 ± 0.19
1	-0.67 ± 0.16	1.50 ± 0.16	0.43 ± 0.11	-0.91 ± 0.28	0.97 ± 0.28	0.04 ± 0.20
2	-0.23 ± 0.17	0.60 ± 0.16	0.19 ± 0.12	-0.93 ± 0.28	-0.22 ± 0.28	-0.57 ± 0.20
3	-0.35 ± 0.14	0.86 ± 0.14	0.26 ± 0.10	-0.58 ± 0.27	0.19 ± 0.27	-0.19 ± 0.19
4	-0.22 ± 0.15	0.56 ± 0.15	0.18 ± 0.11	-0.68 ± 0.28	0.20 ± 0.27	-0.23 ± 0.19
5	0.08 ± 0.17	0.22 ± 0.16	0.15 ± 0.12	-0.08 ± 0.28	-0.55 ± 0.28	-0.32 ± 0.20
6	-0.18 ± 0.14	0.73 ± 0.14	0.28 ± 0.10	-0.19 ± 0.27	-0.07 ± 0.27	-0.13 ± 0.19
7	0.24 ± 0.15	0.52 ± 0.15	0.38 ± 0.10	-0.10 ± 0.28	0.16 ± 0.27	0.03 ± 0.19
8	-0.11 ± 0.16	0.28 ± 0.16	0.09 ± 0.11	-0.12 ± 0.28	-0.16 ± 0.27	-0.14 ± 0.20
9	-0.14 ± 0.15	0.27 ± 0.14	0.07 ± 0.10	-0.16 ± 0.26	-0.09 ± 0.26	-0.13 ± 0.18
10	0.43 ± 0.16	0.33 ± 0.16	0.38 ± 0.11	0.45 ± 0.27	-0.43 ± 0.27	0.00 ± 0.19
11	0.16 ± 0.18	0.19 ± 0.17	0.17 ± 0.12	-0.60 ± 0.28	-0.33 ± 0.27	-0.46 ± 0.20

The asymmetries as a function of the kinematic bin for 2011 data are shown in Figure 6.13 and are also given in Table 6.4.

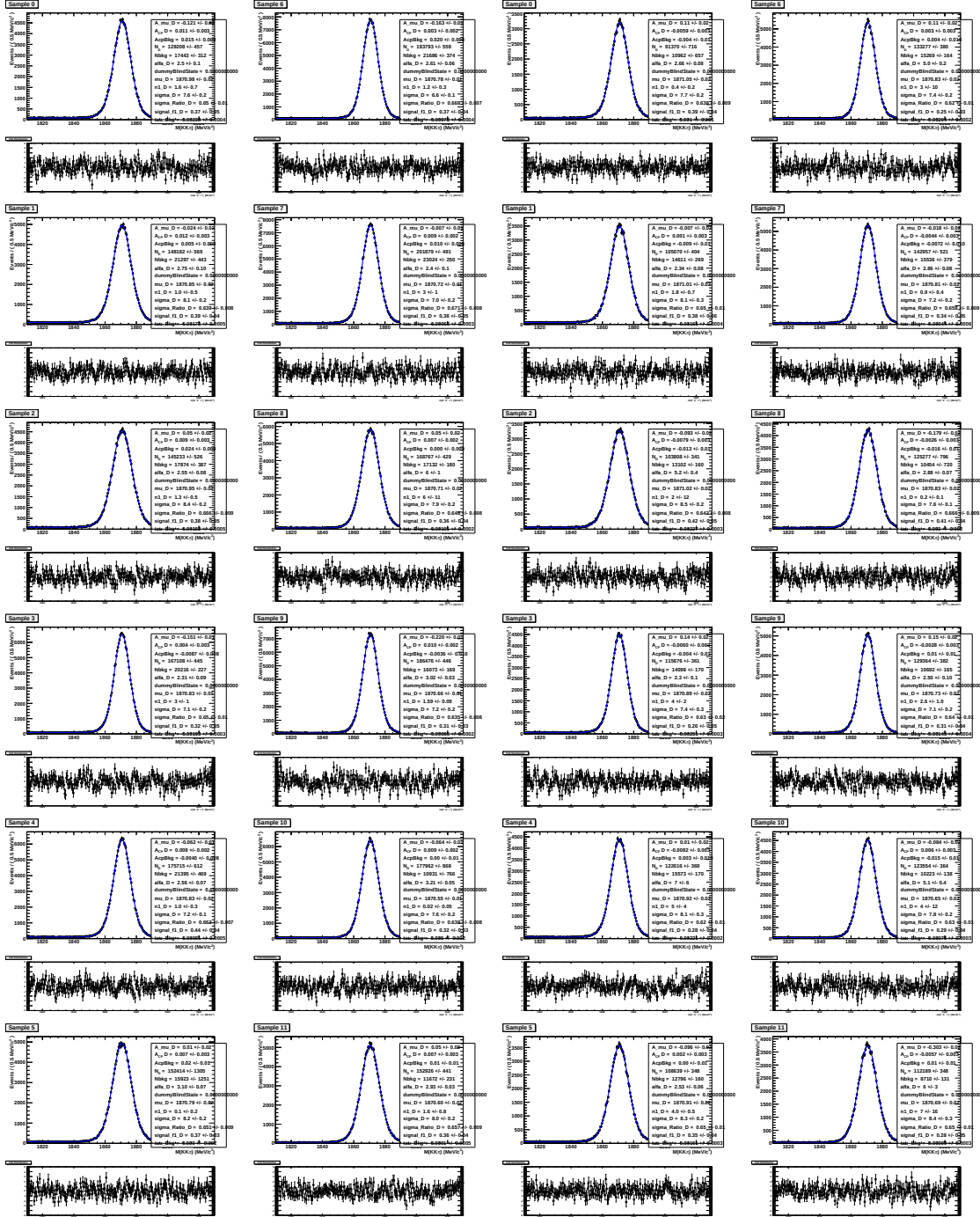


Figure 6.11: Invariant mass distribution for $D^+ \rightarrow K^- K^+ \pi^+$ with fitted PDF superimposed for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2011 data (MagUp on the left, MagDown on the right).

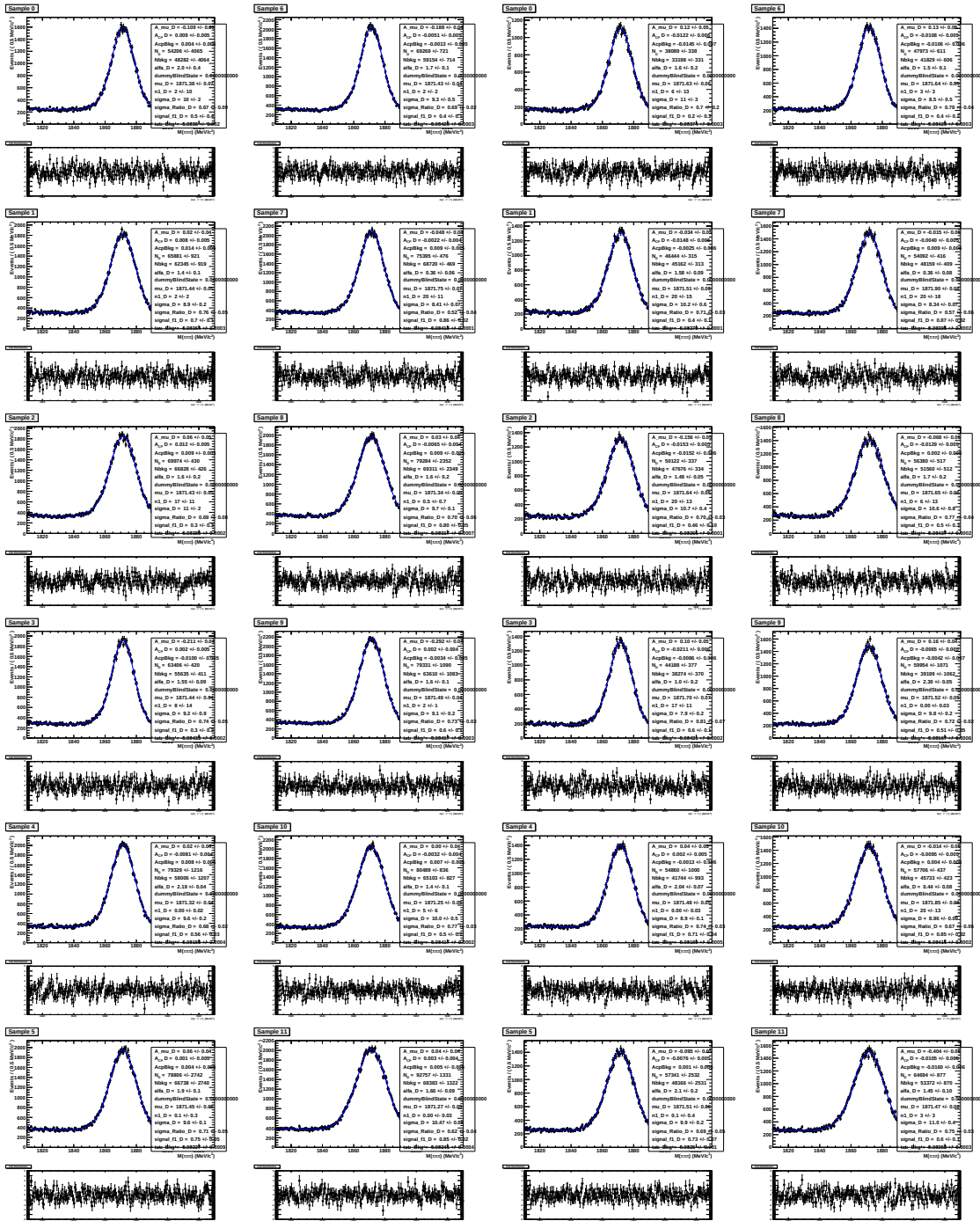


Figure 6.12: Invariant mass distribution for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ with fitted PDF superimposed for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2011 data (MagUp on the left, MagDown on the right).

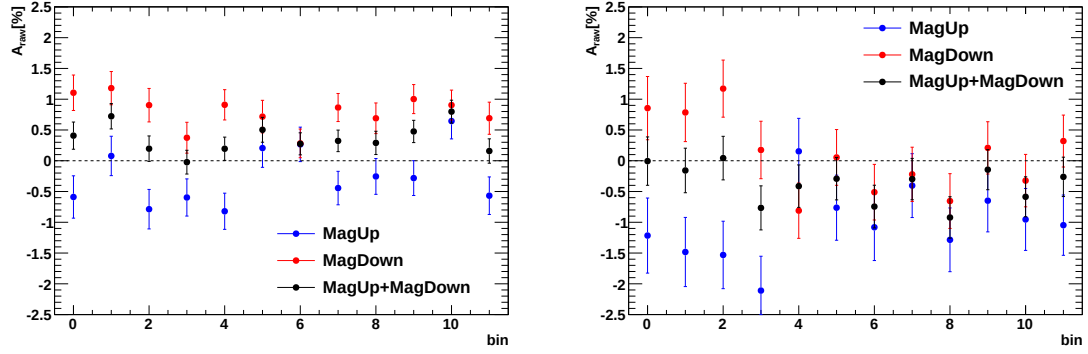


Figure 6.13: Raw asymmetries for $D^+ \rightarrow K^- K^+ \pi^+$ (left) and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (right) with 2011 data using the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning.

Table 6.4: Blind asymmetries of signal channels for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2011 MagDown data.

Bin	$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+) (\%)$			$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$		
	MagUp	MagDown	Up+Down	MagUp	MagDown	Up+Down
0	-0.59 ± 0.34	1.10 ± 0.29	0.41 ± 0.22	-1.22 ± 0.61	0.86 ± 0.51	-0.01 ± 0.39
1	0.08 ± 0.32	1.18 ± 0.27	0.72 ± 0.21	-1.48 ± 0.56	0.78 ± 0.47	-0.16 ± 0.36
2	-0.79 ± 0.32	0.90 ± 0.27	0.20 ± 0.21	-1.53 ± 0.55	1.17 ± 0.46	0.04 ± 0.35
3	-0.60 ± 0.30	0.37 ± 0.25	-0.02 ± 0.19	-2.11 ± 0.56	0.17 ± 0.47	-0.77 ± 0.36
4	-0.82 ± 0.29	0.91 ± 0.25	0.20 ± 0.19	0.15 ± 0.54	-0.81 ± 0.45	-0.41 ± 0.34
5	0.21 ± 0.31	0.72 ± 0.26	0.50 ± 0.20	-0.76 ± 0.53	0.05 ± 0.45	-0.29 ± 0.34
6	0.27 ± 0.28	0.28 ± 0.23	0.28 ± 0.18	-1.08 ± 0.54	-0.51 ± 0.45	-0.74 ± 0.35
7	-0.44 ± 0.27	0.86 ± 0.23	0.32 ± 0.18	-0.40 ± 0.52	-0.22 ± 0.44	-0.30 ± 0.34
8	-0.26 ± 0.29	0.69 ± 0.25	0.29 ± 0.19	-1.28 ± 0.52	-0.66 ± 0.44	-0.92 ± 0.34
9	-0.28 ± 0.28	1.00 ± 0.24	0.48 ± 0.18	-0.65 ± 0.51	0.21 ± 0.42	-0.14 ± 0.33
10	0.64 ± 0.29	0.90 ± 0.24	0.80 ± 0.19	-0.95 ± 0.50	-0.32 ± 0.43	-0.59 ± 0.32
11	-0.57 ± 0.30	0.70 ± 0.26	0.16 ± 0.20	-1.05 ± 0.49	0.32 ± 0.42	-0.26 ± 0.32

6.2.3 ΔA_{CP} for signal channels

Using the raw asymmetries extracted from the fits and shown in previous sections, the difference ΔA_{CP} is obtained for each bin and further combined in one final ΔA_{CP} value. The ΔA_{CP} results for the signal modes are still blind, but it is already possible to see their behaviour as a function of the bachelor π^+ kinematics. The dependence of the ΔA_{CP} with kinematic binning is shown in Figure 6.14.

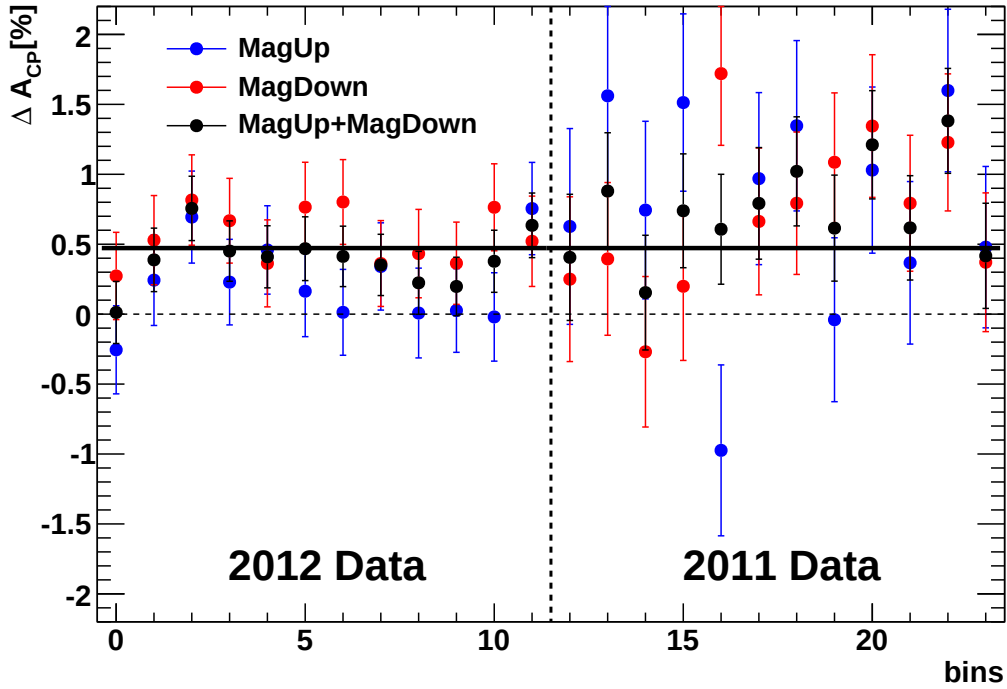


Figure 6.14: $\Delta A_{CP}(D^+)$ with 2012 and 2011 data using $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning. The solid black line shows the value of a constant fit to the combined MagUp+MagDown data at $(0.472 \pm 0.056)\%$ with a p-value of 37%.

By combining the 2011 and 2012 results, we have $\Delta A_{CP}(D^+) = (0.472 \pm 0.056)\%$. The combined value has a precision of $\sim 0.056\%$, of the same order of the control channels, as already anticipated. The χ^2/dof of the fit of the 24 ΔA_{CP} values to a single number is 1.1, so the p-value for the consistency with the average is 37%.

The asymmetries of the background, assumed to be essentially combinatorial, are

also obtained from the fits and, after combining the results for different polarities, the individual bins and combining 2011+2012, we have $\Delta A_{CP}^{\text{bkg}} = (0.22 \pm 0.11)\%$, compatible with zero within two standard deviations.

Chapter 7

Systematics Studies

An important step of a measurement is the estimation of systematic uncertainties. Systematic uncertainties arise from uncertainties associated with the nature of the measurement apparatus, assumptions made by the experimenter, or the model used to make inferences based on the observed data [80].

Studies were performed to identify relevant sources of systematic uncertainties and estimate their contributions. These studies are presented in this chapter: in the first section, the impact of changing the kinematic binning used; in the second section, the impact of the changes in the trigger configuration during the data taking; in the third section, the effect of changing the fit model; and, in the last section, we check the validity of the assumption that the only remaining instrumental asymmetry is related to the bachelor pion, which can be cancelled in the difference between the two decay modes.

7.1 Dependence on kinematic binning

The baseline result is the combination of the ΔA_{CP} values obtained in the individual kinematic bins defined in Section 5.5.1, further combining the results for both magnet polarities and different years (2011 and 2012). We also obtain results with an alternative binning, the D_s^+ based binning defined in Section 5.5.2, and, in order to access the impact of the binning, for the global samples without any

kinematic binning. The global fits are performed to the data samples split only by year (2011/2012) and by magnet polarity (Up/Down), as shown in Figures B.1 and B.2 of Appendix B, for the control modes.

The final ΔA_{CP} obtained with these global, unbinned, fits and with the fits performed in bins with approximately equal populations of $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ candidates are shown in Table 7.1, for 2012 and 2011 data and the combined result, with the control modes. The $\Delta A_{CP}(D_s^+)$ results as a function of the kinematic bins are shown in Figure 7.1. The individual asymmetries as a function of the kinematic bin can be found in Appendix B, Figures B.7 and B.8, together with the mass fits for both polarities and 12 bins in Figures B.3, B.4, B.5 and B.6.

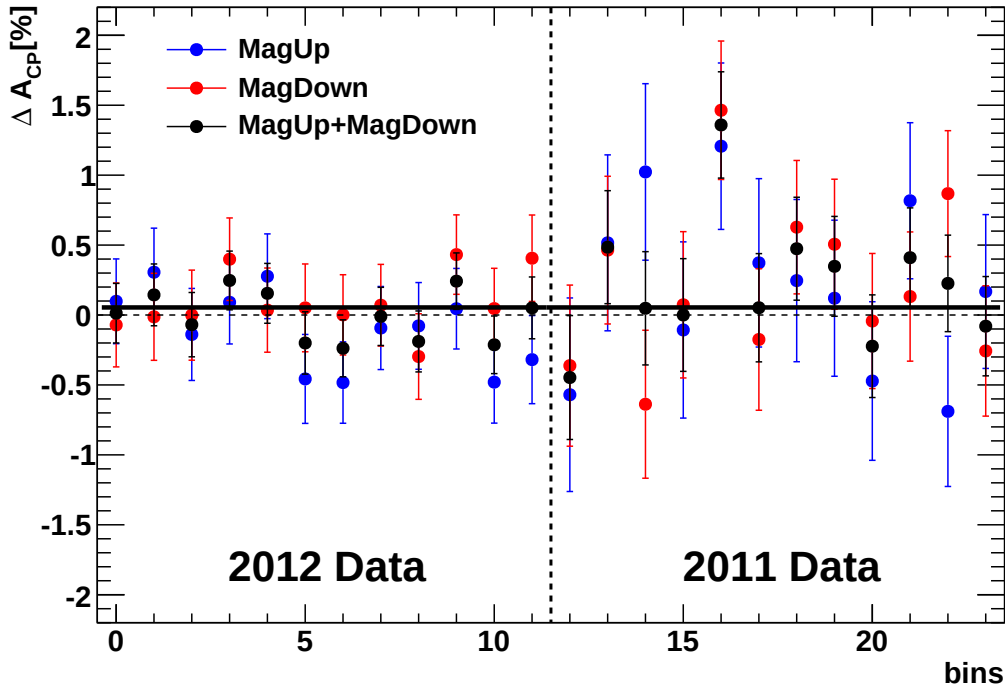


Figure 7.1: Dependence of $\Delta A_{CP}(D_s^+)$ with the π^+ kinematic bins for 2012 and 2011 data using the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning. The solid black line shows the value of a constant fit to the combined MagUp+MagDown data at $(0.054 \pm 0.054)\%$ with a p-value of 26%.

Table 7.1: ΔA_{CP} values for the control channels obtained with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (nominal), with the global fits (no binning) and with the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning.

$\Delta A_{CP}(\%)$ - MagUp+MagDown			
	2011 Data	2012 Data	2011+2012
$D^+ \rightarrow \pi^- \pi^+ \pi^+$ binning	0.236 ± 0.109	-0.003 ± 0.062	0.055 ± 0.054
Unbinned	0.241 ± 0.111	-0.013 ± 0.063	0.049 ± 0.055
$D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ binning	0.236 ± 0.109	-0.004 ± 0.062	0.055 ± 0.054

Equivalent results are shown for the signal modes in Table 7.2 and in Figure 7.2. In Appendix B, it is possible to see the global fits in Figures B.9 and B.10, the individual asymmetries as a function of kinematic bins in Figures B.11 and B.16. The mass fits per bin are shown in Figures B.12, B.13, B.14 and B.15.

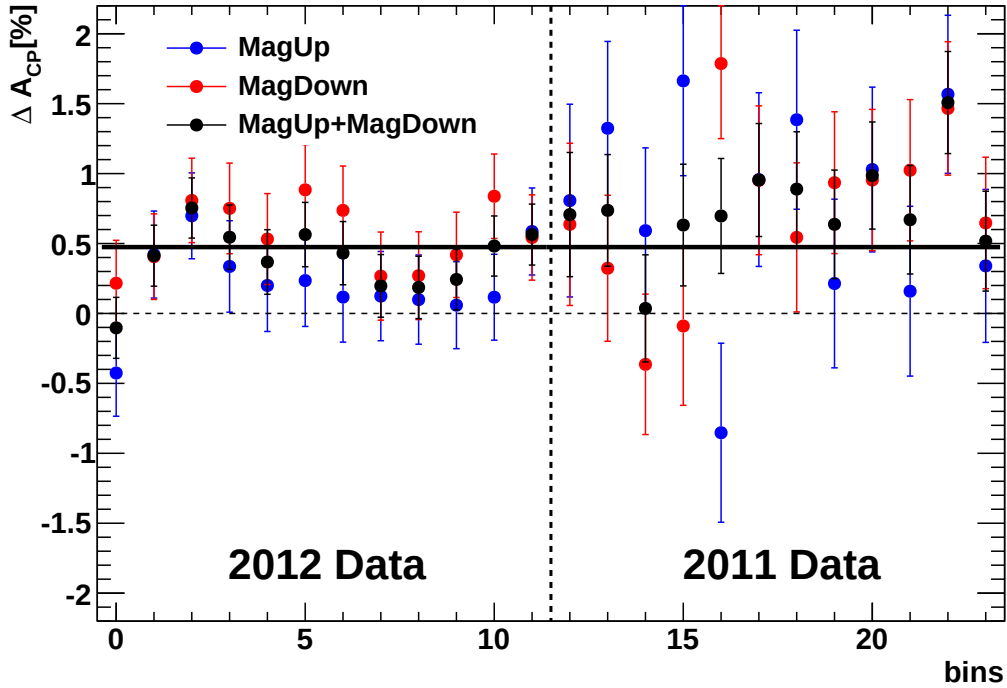


Figure 7.2: Dependence of $\Delta A_{CP}(D^+)$ with the π^+ kinematic bins for 2012 and 2011 data using the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning. The solid black line shows the value of a constant fit to the combined MagUp+MagDown data at $(0.474 \pm 0.056)\%$ with a p-value of 18%.

Table 7.2: ΔA_{CP} values for the signal channels obtained with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (nominal), with the global fits (no binning) and with the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning.

$\Delta A_{CP}(\%)$ - MagUp+MagDown			
	2011 Data	2012 Data	2011+2012
$D^+ \rightarrow \pi^- \pi^+ \pi^+$ binning	0.749 ± 0.114	0.385 ± 0.064	0.472 ± 0.056
Unbinned	0.743 ± 0.115	0.409 ± 0.065	0.490 ± 0.057
$D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ binning	0.752 ± 0.114	0.387 ± 0.064	0.474 ± 0.056

To access the impact of the binning, we look at the deviations of the unbinned result from the baseline result which is 0.006% and 0.018% for the control and signal modes, respectively, for the combined 2011+2012.

As systematic uncertainty associated to the binning, we take the deviation of the alternative binning with respect to the nominal one, obtaining 0.00% and 0.002% for the control and signal channels, respectively.

7.2 Dependence on trigger TCK

The Trigger Configuration Key (TCK) is a hexadecimal number which identifies a specific trigger configuration. This configuration consists of the set of algorithms (lines) included in the trigger selection and all the cut values they use. Changes in any line lead to a new configuration, therefore a new TCK.

In order to check if there is a dependence of the asymmetries and ΔA_{CP} with the trigger requirements, the 2012 data sample was divided in six TCK groups and the 2011 data sample was divided in four TCK groups, with uniform cuts applied in the L0Hadron, Hlt1TrackAllL0 and Hlt2CharmHadD2HHH lines, according to the information given in Tables 7.3 and 7.4.

For this study, the global unbinned asymmetries are obtained. The individual asymmetries and corresponding ΔA_{CP} values as a function of TCK index for all the groups defined are available in Appendix C. For the groups with data taken in both polarities, the ΔA_{CP} values as a function of TCK index for 2012 and 2011 data are

Table 7.3: TCKs used in the 2012 run and the relevant trigger requirements. The index given in the first column represents the trigger configuration label used in the horizontal axis of Figures C.1 and C.2. The TCK indicated with a dagger ($\dagger$) contributes with a small number of events to the total sample and is not included in these plots. Order of cuts in Hlt1TrackAllL0: $p_T >$, $p > [\text{GeV}/c]$, Track $\chi^2/ndof <$, ValidateWithTT: ON/OFF.

Group	TCK	Fraction		L0 Hadron E_T GeV	Hlt1TrackAllL0
		MagDown	MagUp		
0	0x0094003D	22.3% ($KK\pi$)	24.4% ($KK\pi$)	3.62	1.7, 10., 1.5, OFF
	0x0097003D	21.4% (3π)	23.6% (3π)		
1	0x00990042	19.9% ($KK\pi$)	39.1% ($KK\pi$)	3.62	1.6, 3., 2.0, ON
	0x00990043	20.3% (3π)	39.6% (3π)		
2	0x00990044	26.0% ($KK\pi$)	20.9% ($KK\pi$)	3.68	1.6, 3., 2.0, ON
	0x00A30044	26.9% (3π)	20.9% (3π)		
3	0x009F0045	23.7% ($KK\pi$)	14.6% ($KK\pi$)	3.74	1.6, 3., 2.0, ON
	0x00A10044	23.9% (3π)	14.9% (3π)		
	0x00A10045				
	0x00A30044				
	0x00A30046				
	0x00A90046				
	0x00AB0046				
	0x00AC0046				
	0x00AD0046				
	0x007E003A	8.0% ($KK\pi$)			
4	0x007F0040	7.4% (3π)		3.5	1.7, 10., 2.0
	0x008C0040				
	0x008E0040				
5	0x0095003D †	0.1% ($KK\pi$ and 3π)	-	3.62	1.7, 10., 2.0, ON

shown in Figures 7.3 and 7.4 for control and signal modes, respectively. The ΔA_{CP} plots are fitted with a constant value with p-values of 13% and 19% for the control and signal modes, respectively, hence no systematic uncertainty is assigned due to trigger requirements.

Table 7.4: TCKs used in the 2011 run and the relevant trigger requirements. The first column indicates the label used in the horizontal axis of Figures C.3 and C.4. Order of cuts in Hlt1TrackAllL0: $p_T > [\text{GeV}/c]$, $r_{PV} > [\text{mm}]$.

Group	TCK	Fraction		L0 Hadron E_T GeV	Hlt1TrackAllL0
		MagDown	MagUp		
0	0x00360032	33.1% ($KK\pi$)	38.1% ($KK\pi$)	3.5	1.7, 0.5
	0x00480032	34.3% (3π)	39.0% (3π)	3.5	1.7, 0.5
	0x006D0032			3.5	1.7, 0.5
	0x00700034			3.5	1.7, 0.5
	0x00710035			3.5	1.7, 0.5
	0x005A0032			3.5	1.7, 0.5
	0x005B0032			3.5	1.7, 0.5
	0x00730035			3.5	1.7, 0.5
1	0x004A0033	1.1% ($KK\pi$)	1.0% ($KK\pi$)	2.4	1.7, 0.5
	0x005D0033	1.2% (3π)	1.0% (3π)	2.4	1.7, 0.5
2	0x00760037	65.7% ($KK\pi$)	60.2% ($KK\pi$)	3.5	1.7, 0.3
	0x00790037	64.5% (3π)	59.4% (3π)	3.5	1.7, 0.3
	0x00790038			3.5	1.7, 0.3
3	0x00740036	-	0.6% ($KK\pi$ and 3π)	4	1.7, 0.5

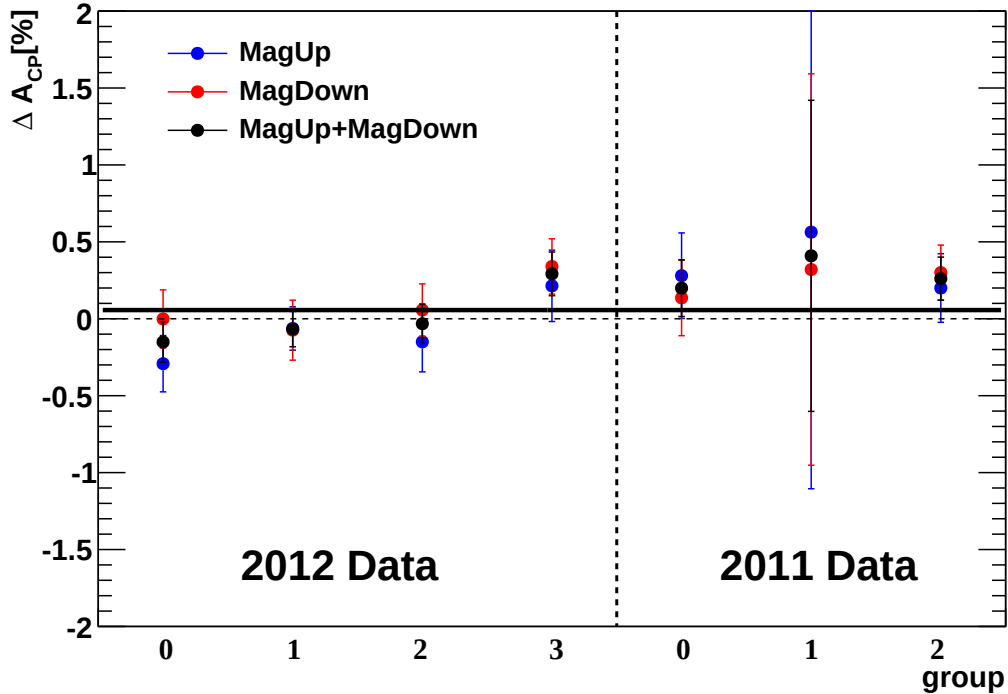


Figure 7.3: $\Delta A_{CP}(D_s^+)$ as a function of trigger configuration (2012 and 2011 data). The solid black line shows the value of a constant fit to the combined MagUp+MagDown data at $(0.057 \pm 0.055)\%$ with a p-value of 13%.

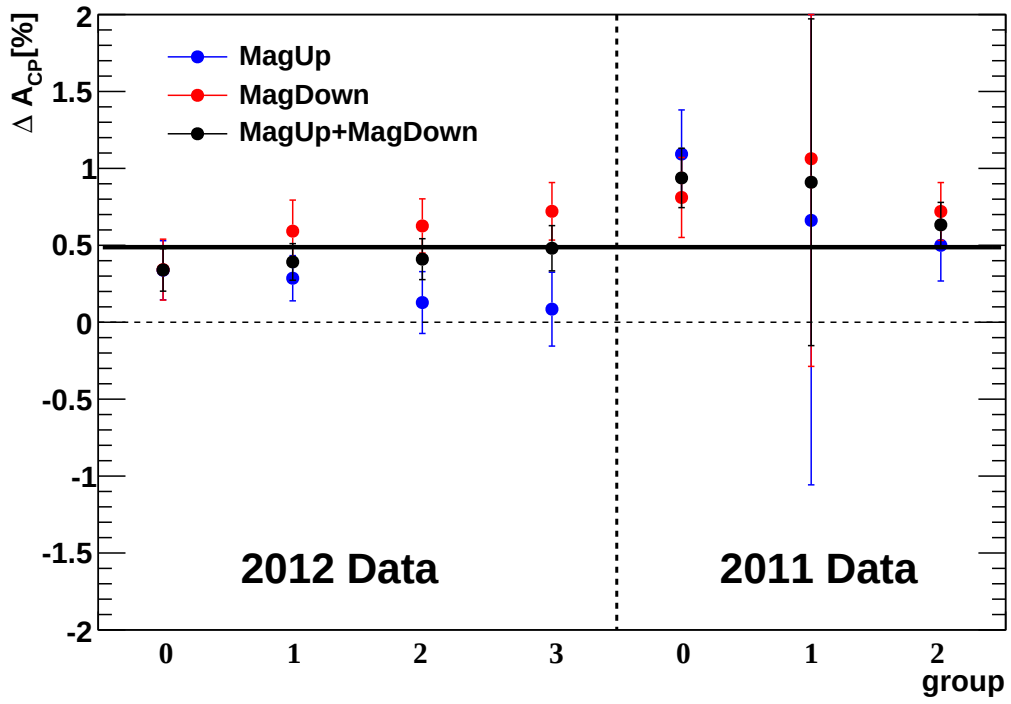


Figure 7.4: $\Delta A_{CP}(D^+)$ with 2011 and 2012 data as a function of trigger configuration. The solid black line shows the value of a constant fit to the combined MagUp+MagDown data at $(0.488 \pm 0.058)\%$ with a p-value of 19%.

7.3 Dependence on fit model

To study the uncertainty due to imperfect knowledge of the actual shape of the full PDF, several changes are made to the fit model. The individual asymmetries and ΔA_{CP} are reobtained with the nominal shape for the signal (Gaussian+CB) and background (exponential) PDF, as described in Section 5.4, with all the parameters fit to the data and with different sets of parameters fixed to the values obtained with a MC fit. The four different fit configurations studied are the following:

- with the nominal shape for the signal and background PDF:
 1. shape parameters allowed to float;
 2. R_σ , f_G , α and n fixed from MC;
 3. f_G , α and n fixed from MC;
 4. α and n fixed from MC.

It can be seen that fixing the shape parameters to the MC values has no significant impact on the measurement of ΔA_{CP} , both for the control modes, in Table 7.5, and for signal decays, in Table 7.6. At this point, no systematic uncertainty is assigned to the measurement.

Table 7.5: Results of $\Delta A_{CP}(D_s^+)$ for different fit configurations (2012 and 2011 data). Results obtained with fit configuration 1 correspond to the baseline results of the analysis.

$\Delta A_{CP}(\%)$ - MagUp+MagDown			
	2011 Data	2012 Data	2011+2012
1	0.236 ± 0.109	-0.003 ± 0.062	0.055 ± 0.054
2	0.234 ± 0.109	-0.006 ± 0.062	0.053 ± 0.054
3	0.233 ± 0.109	-0.006 ± 0.062	0.052 ± 0.054
4	0.234 ± 0.109	-0.007 ± 0.062	0.052 ± 0.054

The four fit configurations presented above were also used to extract the ΔA_{CP} results for control and signal modes using the samples split with the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$

Table 7.6: Blind results of $\Delta A_{CP}(D^+)$ for different fit configurations (2012 and 2011 data). Results obtained with fit configuration 1 correspond to the baseline results of the analysis.

$\Delta A_{CP}(\%)$ - MagUp+MagDown			
	2011 Data	2012 Data	2011+2012
1	0.749 ± 0.114	0.385 ± 0.064	0.472 ± 0.056
2	0.744 ± 0.114	0.384 ± 0.064	0.470 ± 0.056
3	0.743 ± 0.114	0.384 ± 0.064	0.470 ± 0.056
4	0.742 ± 0.114	0.384 ± 0.064	0.470 ± 0.056

driven binning and the unbinned samples. The conclusion is the same. More details can be found in Appendix D. A more complete study of the dependence on fit model would also require to modify the fitted shape, using alternative PDF for the signal and background. This was already done for the unbinned samples and is shown in Appendix D. Similar studies are intended for the binned sample and when they are available a systematic uncertainty can be estimated.

7.4 Studies on the cancellation hypothesis

An important assumption of the ΔA_{CP} measurement is that, for a decay $D_{(s)}^+ \rightarrow h^- h^+ h'^+$, the asymmetry of the pair $h^- h^+$ is null because the contribution from the first hadron is equal in modulus and opposite in sign to the asymmetry due to the second hadron, which has opposite charge. Therefore, the only remaining asymmetry due to instrumental sources is the one due to the bachelor pion. A first indication that this assumption is indeed valid is given by the measurement performed with the control channels, which provides a ΔA_{CP} consistent with zero within one standard deviation. However, one may argue that local asymmetries across the phase space could contribute with different weights to the control and signal decays, due to the different magnitudes of the intermediate states contributing to each of them. We then investigated the sensitivity of our samples to local asymmetries across the phase space, using the D_s^+ control channels.

In the first test, we look for asymmetries in regions of the phase space comparing directly the Dalitz plot distributions of D_s^+ and D_s^- . This comparison is performed bin-by-bin using the significance of the difference between the number of D_s^+ and D_s^- , $\mathcal{S}_{CP}^i$, computed as [81, 82]

$$\mathcal{S}_{CP}^i \equiv \frac{N_i^+ - \alpha_N N_i^-}{\sqrt{\alpha_N(N_i^+ - N_i^-)}}, \quad \alpha_N \equiv \frac{N^+}{N^-}, \quad (7.1)$$

where $N_i^+(N_i^-)$ is the number of D_s^+ (D_s^-) candidates in the i th bin and the $N^+(N^-)$ is the sum of $N_i^+(N_i^-)$ over all bins. The parameter α accounts for global asymmetries. In the absence of local asymmetries, the $\mathcal{S}_{CP}^i$ values follow a Gaussian distribution with zero mean and unit width. The $\mathcal{S}_{CP}^i$ distribution over the $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ Dalitz plots and the corresponding one-dimensional distributions are shown in Figure 7.5.

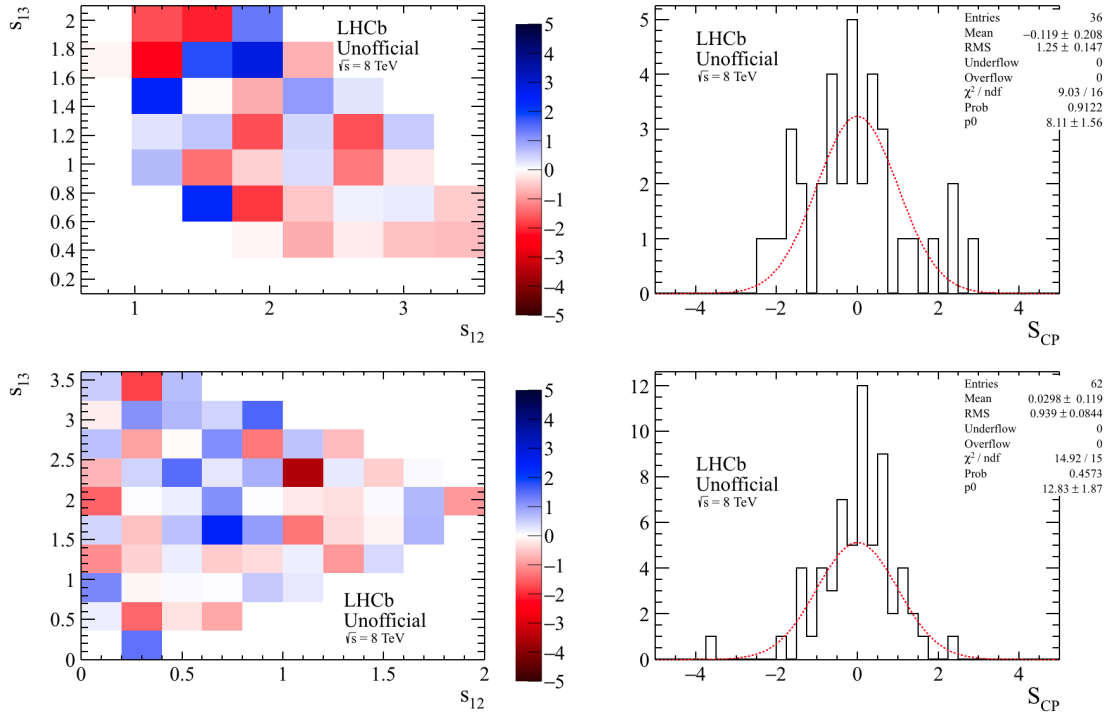


Figure 7.5: $\mathcal{S}_{CP}^i$ in each bin of the Dalitz plot (left) and distribution of all $\mathcal{S}_{CP}$ values (right) for $D_s^+ \rightarrow K^- K^+ \pi^+$ (top) and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (bottom) decays.

The p-values for the consistency with the normal distributions are 91% and 41%, respectively, for $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ decays. Testing different binning schemes, we always find p-values higher than 1% for the consistency with the hypothesis of absence of local asymmetries, for both decay channels.

As a second study, we look at the momentum asymmetry of the pair of opposite sign daughters $K^- K^+$ and $\pi^- \pi^+$ of the decays $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$, respectively. Denoting the daughter particle which has charge opposite to the mother's charge as particle 1 and the daughter of same charge as particle 2, we can define the momentum asymmetry of the pair, α , as

$$\alpha = \frac{P_1 - P_2}{P_1 + P_2}. \quad (7.2)$$

The individual asymmetries are then obtained in 10 bins of α , from -1 to 1. The first and last bins $([-1.0, -0.8], [0.8, 1.0])$ have very low statistics and are not considered here. The asymmetries for $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ as a function of α for 2012 data are shown in Figure 7.6.

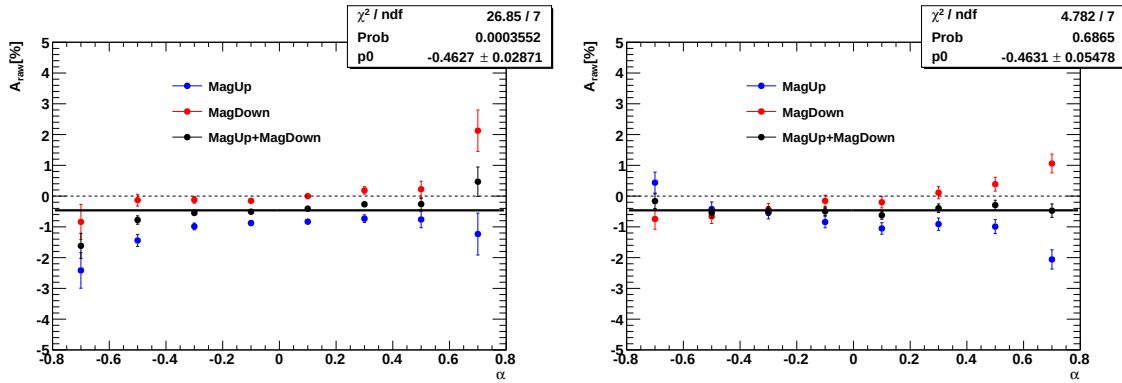


Figure 7.6: Asymmetries for $D_s^+ \rightarrow K^- K^+ \pi^+$ (left) and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (right) as a function of α .

The combined MagUp+MagDown $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ asymmetries are fitted to a constant with a p-value of 69%. However, for the $D_s^+ \rightarrow K^- K^+ \pi^+$ decay, the asymmetries get to larger values at the bins of large $|\alpha|$.

Although the asymmetries tend to cancel for opposite values of α , a cut in α is considered to exclude these regions with larger asymmetries. By tightening the cut on α for both $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$, the central value of ΔA_{CP} is always consistent with the original value, without any cut, as can be seen from Table 7.7. For $|\alpha| < 0.4$, the asymmetries can be considered constant. Therefore, we can evaluate a systematic uncertainty due to the limited validity of the cancellation of the instrumental asymmetry of the pair $h^+ h^-$ from the discrepancy of the asymmetries obtained for the independent samples corresponding to these two regions of α . The combined 2011+2012 individual raw asymmetries for $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ are shown in Table 7.8 together with the ΔA_{CP} results.

Table 7.7: ΔA_{CP} values with different cuts on the momentum asymmetry of daughters α .

$\Delta A_{CP}(\%)$	
MagUp+MagDown - 2011+2012	
$ \alpha < 1.0$	0.050 ± 0.055
$ \alpha < 0.8$	0.048 ± 0.055
$ \alpha < 0.6$	0.075 ± 0.057
$ \alpha < 0.4$	0.086 ± 0.065

The χ^2/dof for the compatibility of the values of ΔA_{CP} obtained with the two independent samples, $|\alpha| < 0.4$ and $|\alpha| > 0.4$, is 1.73. Using the recipe from [83], a systematic uncertainty of 0.049% is estimated.

Table 7.8: Asymmetry values with different cuts on momentum asymmetry of daughters α .

MagUp+MagDown - 2011+2012			
	$A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+)[\%]$	$A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+)[\%]$	$\Delta A_{CP}(D_s^+) [\%]$
$ \alpha < 0.4$	-0.435 ± 0.026	-0.523 ± 0.060	0.086 ± 0.065
$ \alpha > 0.4$	-0.547 ± 0.092	-0.453 ± 0.082	-0.098 ± 0.122

Chapter 8

Conclusion

Charm physics is a very interesting ground for CPV searches, where it is possible to test the Standard Model limits and seek for New Physics. The subject of this thesis was the asymmetry measurement in the Cabibbo-suppressed decays $D^+ \rightarrow K^- K^+ \pi^+$ and $D^+ \rightarrow \pi^- \pi^+ \pi^+$. The analysis was performed using the data collected in pp collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV by the LHCb, corresponding to an integrated luminosity of 3.0 fb^{-1} . The chosen observable was the difference between the asymmetries of the two decay modes, ΔA_{CP} , allowing the cancellation of production and detection asymmetries. A blind approach was used in order not to bias the measurement. Therefore, the analysis strategy was developed without looking at the actual values of the D^+ asymmetries. The $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ decays, where no CPV is expected, were used as control channels.

The four $D_{(s)}^+$ decays were selected among the collected data with criteria designed to reduce the contribution of specific backgrounds and to exclude candidates in phase space regions with high asymmetry induced by instrumental sources. The data sample was divided according to the year of data taking (2012/2011), magnet polarity (MagUp/MagDown) and the 12 kinematic bins defined. In each of these subsamples, the raw asymmetries for $KK\pi$ and $\pi\pi\pi$ were extracted through a simultaneous fit to the invariant mass distribution and the ΔA_{CP} was computed. The values obtained from the 48 subsamples were combined to provide the main result.

For the control channels, we measure $\Delta A_{CP}(D_s^+) = (0.055 \pm 0.054)\%$ which is consistent with zero within about one standard deviation, in agreement with the hypothesis of cancellation of production and detection asymmetries. For the signal channels, the ΔA_{CP} is still blind. However, we were able to study its behavior with respect to subsamples and know the statistical uncertainty of the measurement to be 0.056%. This analysis is currently under the Charm Working Group review and, once approved by the LHCb collaboration, the offsets will be removed and the ΔA_{CP} values will be known.

Some studies were performed to identify sources of systematic uncertainties. We considered the dependence on the binning choice, trigger configuration, fit model and estimated the uncertainty due to the limited validity of the hypothesis of cancellation of the instrumental asymmetries related to the pair K^-K^+ or $\pi^-\pi^+$ in 0.049%. The blind measurement is $\Delta A_{CP}(D^+) = (0.472 \pm 0.056 \pm 0.049)\%$. With the present estimative for the systematic uncertainty, the total absolute uncertainty is 0.074%, making this the most precise charm measurement of the LHCb to date.

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Appendix A

L0 trigger studies

In order to study how the L0 trigger affects our asymmetry measurements, we divided our data in three samples according to the L0 requirement. The criteria considered are the following:

- $L0TIS \equiv D_L0Hadron_TIS \parallel D_L0Muon_TIS \parallel D_L0Electron_TIS \parallel D_L0Photon_TIS$
- $L0TOS \equiv D_L0Hadron_TOS$
- $L0TIS \parallel L0TOS$

The third one is our total sample after trigger and stripping requirements. The first and the second are not independent samples, but we wanted to see the effect of requiring the L0-Hadron-TOS compared to a L0-TIS. For each of them, the raw asymmetries and ΔA_{CP} values are determined and the results are compared. Here the simultaneous fits to the $D_{(s)}^+$ and $D_{(s)}^-$ samples are performed for the global samples, without any kinematic binning. The results for the control modes are shown in Figure A.1 and in Table A.1. The blind values obtained for the signal channels are shown in Figure A.2 and in Table A.2. Although they are blind, they can be used to compare the difference among the samples and magnet polarities.

As expected, there are differences among the different L0 trigger configurations. More concerning, though, are the differences between the control and signal channels when considering the behavior with respect to the trigger configuration and the

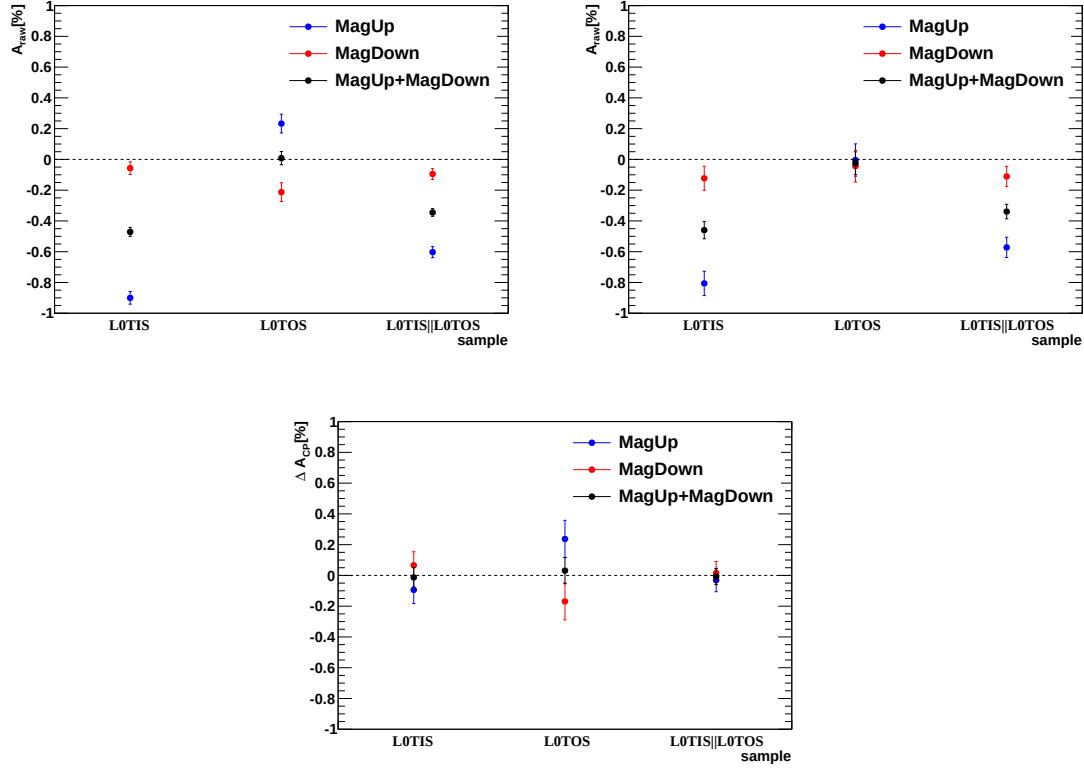


Figure A.1: Asymmetries of control channels with respect to L0 trigger requirement using 2012 data. Top-left plot is $A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+)$, top-right plot is $A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+)$ and bottom plot is $\Delta A_{CP}(D_s^+)$.

differences between MagUp and MagDown. For example, the $\pi^- \pi^+ \pi^+$ raw asymmetry of the L0TOS sample shows for the D^+ a higher difference MagUp/MagDown in comparison with the D_s^+ , while the opposite (a smaller MagUp/MagDown difference) is seen for the $K^- K^+ \pi^+$ signal in comparison with the control mode. These differences result in a difference on the behaviour of the ΔA_{CP} measurement. The difference between the ΔA_{CP} results obtained with the MagUp and MagDown samples for the signal modes are opposite in sign for the L0TOS sample, compared to the control modes. For these reasons, we decided to use only the L0TIS sample for the baseline result.

Table A.1: Asymmetry values of control channels for different trigger choices using 2012 data.

Trigger	MagUp	MagDown	Up+Down
$A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+)$			
L0TIS	$(-0.900 \pm 0.041)\%$	$(-0.057 \pm 0.041)\%$	$(-0.471 \pm 0.029)\%$
L0TOS	$(0.233 \pm 0.061)\%$	$(-0.213 \pm 0.061)\%$	$(0.008 \pm 0.043)\%$
L0TIS L0TOS	$(-0.603 \pm 0.036)\%$	$(-0.095 \pm 0.035)\%$	$(-0.345 \pm 0.025)\%$
$A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+)$			
L0TIS	$(-0.806 \pm 0.079)\%$	$(-0.123 \pm 0.078)\%$	$(-0.460 \pm 0.056)\%$
L0TOS	$(-0.004 \pm 0.105)\%$	$(-0.044 \pm 0.103)\%$	$(-0.025 \pm 0.074)\%$
L0TIS L0TOS	$(-0.572 \pm 0.066)\%$	$(-0.111 \pm 0.066)\%$	$(-0.339 \pm 0.047)\%$
$\Delta A_{CP}(D_s^+)$			
L0TIS	$(-0.094 \pm 0.089)\%$	$(0.066 \pm 0.088)\%$	$(-0.013 \pm 0.063)\%$
L0TOS	$(0.237 \pm 0.121)\%$	$(-0.169 \pm 0.120)\%$	$(0.031 \pm 0.085)\%$
L0TIS L0TOS	$(-0.031 \pm 0.075)\%$	$(0.016 \pm 0.075)\%$	$(-0.007 \pm 0.053)\%$

Table A.2: Blinded asymmetry values of signal channels for different trigger choices using 2012 data.

Trigger	MagUp	MagDown	Up+Down
$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+)$			
L0TIS	$(-0.186 \pm 0.045)\%$	$(0.643 \pm 0.044)\%$	$(0.235 \pm 0.032)\%$
L0TOS	$(0.810 \pm 0.070)\%$	$(0.646 \pm 0.069)\%$	$(0.727 \pm 0.049)\%$
L0TIS L0TOS	$(0.050 \pm 0.040)\%$	$(0.660 \pm 0.039)\%$	$(0.360 \pm 0.028)\%$
$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+)$			
L0TIS	$(-0.418 \pm 0.081)\%$	$(0.062 \pm 0.080)\%$	$(-0.175 \pm 0.057)\%$
L0TOS	$(0.356 \pm 0.113)\%$	$(-0.252 \pm 0.112)\%$	$(0.048 \pm 0.080)\%$
L0TIS L0TOS	$(-0.233 \pm 0.069)\%$	$(-0.058 \pm 0.068)\%$	$(-0.145 \pm 0.048)\%$
$\Delta A_{CP}(D^+)$			
L0TIS	$(0.232 \pm 0.093)\%$	$(0.581 \pm 0.091)\%$	$(0.409 \pm 0.065)\%$
L0TOS	$(0.454 \pm 0.133)\%$	$(0.898 \pm 0.132)\%$	$(0.678 \pm 0.094)\%$
L0TIS L0TOS	$(0.283 \pm 0.080)\%$	$(0.718 \pm 0.078)\%$	$(0.504 \pm 0.056)\%$

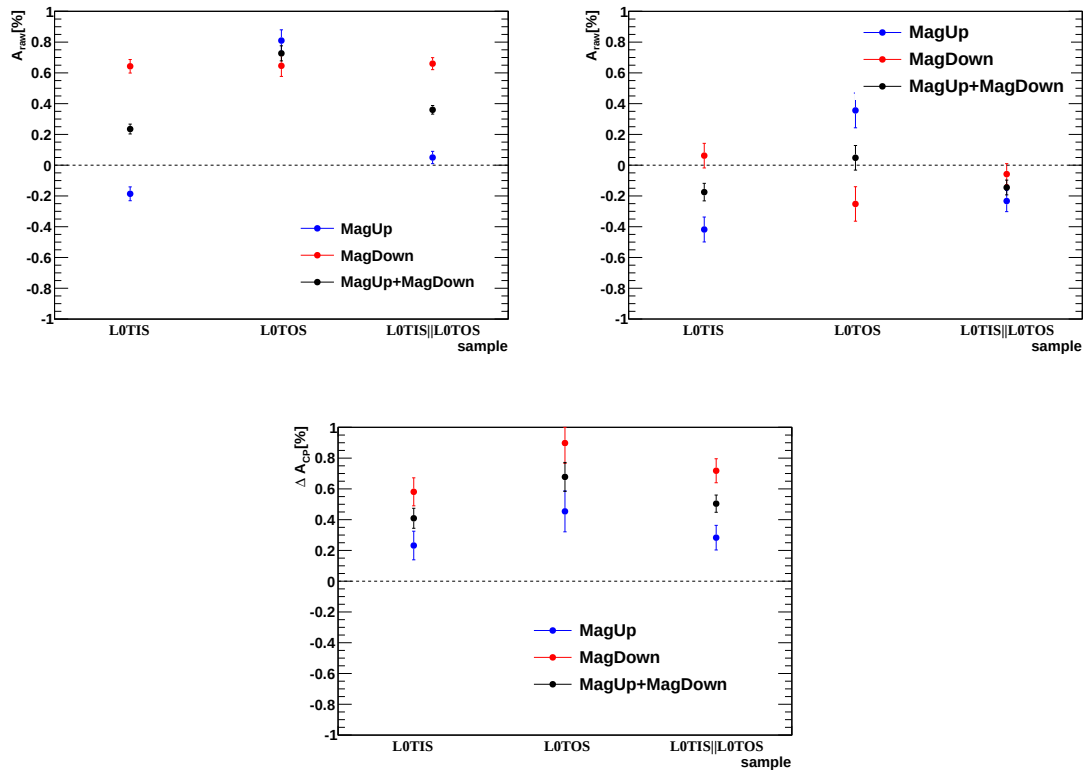


Figure A.2: Blind asymmetries of signal channels with respect to L0 trigger requirement using 2012 data. Top-left plot is $A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+)$, top-right plot is $A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+)$ and bottom plot is $\Delta A_{CP}(D^+)$.

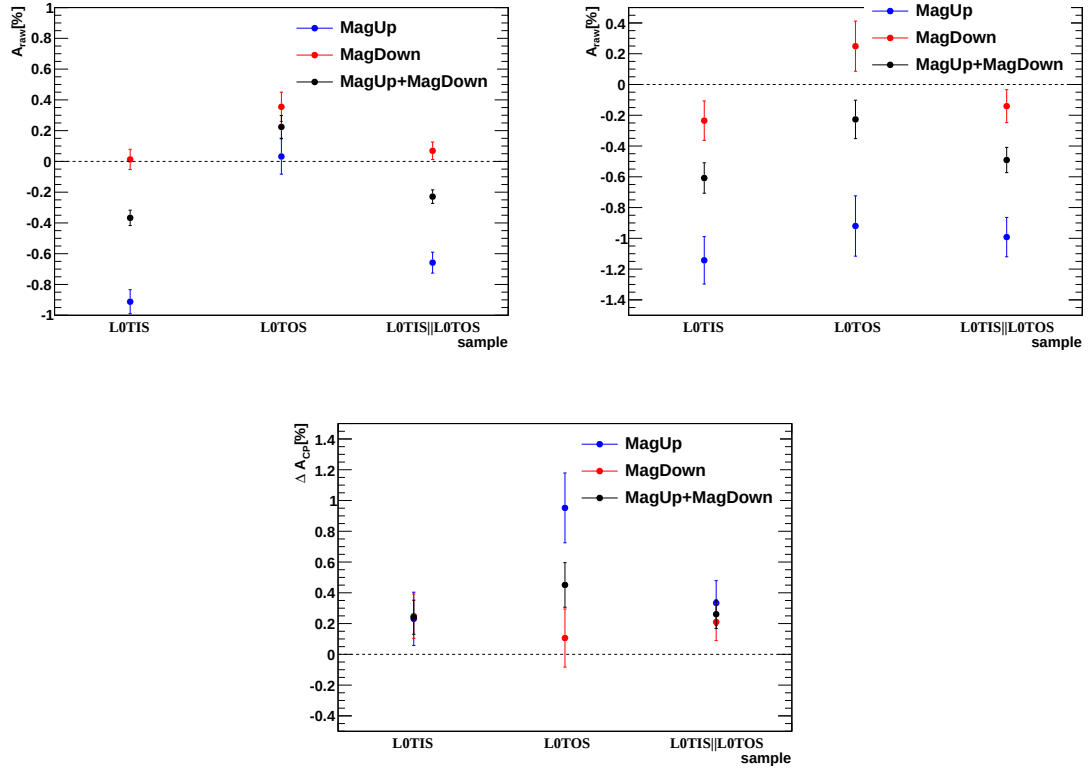


Figure A.3: Asymmetries of control channels with respect to L0 trigger requirement using 2011 data. Top-left plot is $A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+)$, top-right plot is $A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+)$ and bottom plot is $\Delta A_{CP}(D_s^+)$.

Table A.3: Asymmetry values of control channels for different trigger choices using 2011 data.

Trigger	MagUp	MagDown	Up+Down
$A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+)$			
L0TIS	$(-0.912 \pm 0.078)\%$	$(0.013 \pm 0.066)\%$	$(-0.367 \pm 0.050)\%$
L0TOS	$(0.032 \pm 0.115)\%$	$(0.355 \pm 0.095)\%$	$(0.224 \pm 0.074)\%$
L0TIS L0TOS	$(-0.658 \pm 0.068)\%$	$(0.069 \pm 0.057)\%$	$(-0.229 \pm 0.044)\%$
$A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+)$			
L0TIS	$(-1.143 \pm 0.154)\%$	$(-0.235 \pm 0.128)\%$	$(-0.608 \pm 0.099)\%$
L0TOS	$(-0.920 \pm 0.196)\%$	$(0.249 \pm 0.163)\%$	$(-0.227 \pm 0.125)\%$
L0TIS L0TOS	$(-0.992 \pm 0.128)\%$	$(-0.141 \pm 0.107)\%$	$(-0.491 \pm 0.082)\%$
$\Delta A_{CP}(D_s^+)$			
L0TIS	$(0.231 \pm 0.173)\%$	$(0.248 \pm 0.144)\%$	$(0.241 \pm 0.111)\%$
L0TOS	$(0.952 \pm 0.227)\%$	$(0.106 \pm 0.189)\%$	$(0.451 \pm 0.145)\%$
L0TIS L0TOS	$(0.334 \pm 0.145)\%$	$(0.210 \pm 0.121)\%$	$(0.261 \pm 0.093)\%$

Table A.4: Blinded asymmetry values of signal channels for different trigger choices using 2011 data.

Trigger	MagUp	MagDown	Up+Down
$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+)$			
L0TIS	$(-0.247 \pm 0.087)\%$	$(0.787 \pm 0.073)\%$	$(0.358 \pm 0.056)\%$
L0TOS	$(0.416 \pm 0.131)\%$	$(1.077 \pm 0.110)\%$	$(0.806 \pm 0.084)\%$
L0TIS L0TOS	$(-0.063 \pm 0.076)\%$	$(0.806 \pm 0.064)\%$	$(0.447 \pm 0.049)\%$
$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+)$			
L0TIS	$(-0.986 \pm 0.157)\%$	$(0.042 \pm 0.132)\%$	$(-0.386 \pm 0.101)\%$
L0TOS	$(-0.005 \pm 0.211)\%$	$(0.280 \pm 0.177)\%$	$(0.162 \pm 0.136)\%$
L0TIS L0TOS	$(-0.656 \pm 0.132)\%$	$(0.075 \pm 0.112)\%$	$(-0.230 \pm 0.085)\%$
$\Delta A_{CP}(D^+)$			
L0TIS	$(0.739 \pm 0.179)\%$	$(0.745 \pm 0.151)\%$	$(0.743 \pm 0.115)\%$
L0TOS	$(0.421 \pm 0.248)\%$	$(0.797 \pm 0.208)\%$	$(0.642 \pm 0.160)\%$
L0TIS L0TOS	$(0.593 \pm 0.152)\%$	$(0.731 \pm 0.129)\%$	$(0.673 \pm 0.098)\%$

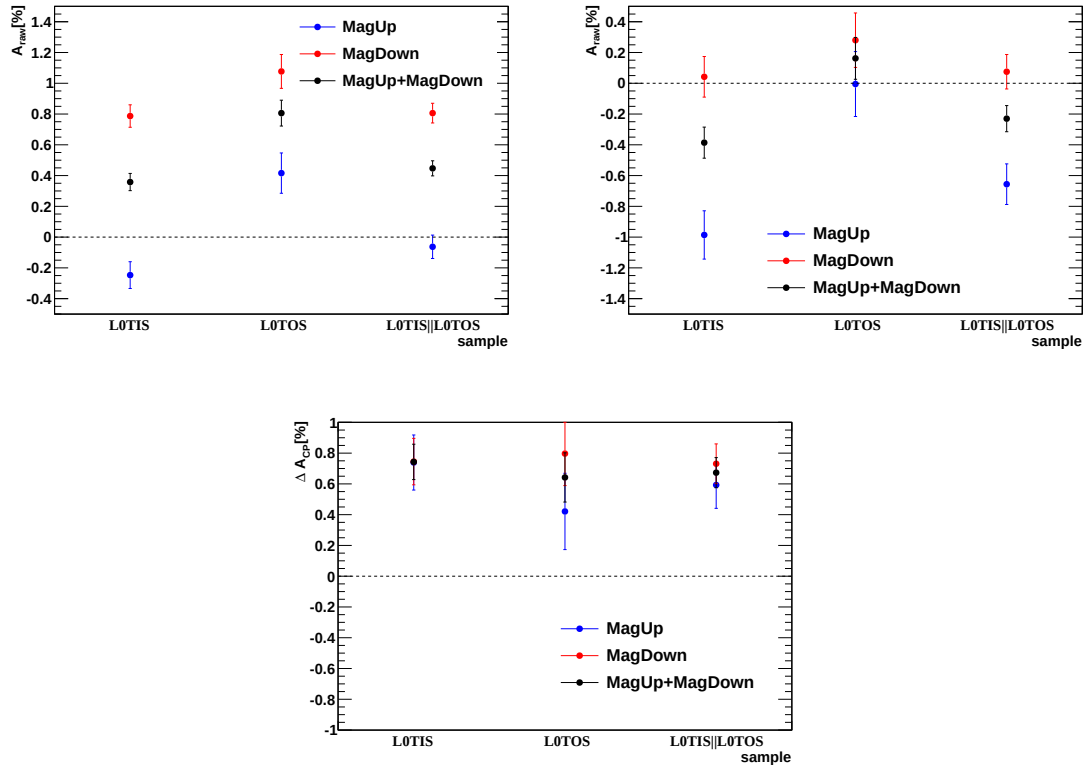


Figure A.4: Blind asymmetries of signal channels with respect to L0 trigger requirement using 2011 data. Top-left plot is $A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+)$, top-right plot is $A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+)$ and bottom plot is $\Delta A_{CP}(D^+)$.

Appendix B

Additional tables, mass fits and asymmetry plots for different binning configurations

B.1 Control Channels

Table B.1: ΔA_{CP} of control channels for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2012 data.

Bin	$\Delta A_{CP}(D_s^+) (\%)$		
	MagUp	MagDown	Up+Down
0	0.09 ± 0.31	-0.10 ± 0.31	-0.00 ± 0.22
1	0.33 ± 0.33	-0.20 ± 0.33	0.06 ± 0.23
2	-0.22 ± 0.36	-0.08 ± 0.35	-0.15 ± 0.25
3	0.13 ± 0.28	0.52 ± 0.28	0.33 ± 0.20
4	0.37 ± 0.29	0.02 ± 0.29	0.20 ± 0.21
5	-0.63 ± 0.32	0.07 ± 0.31	-0.28 ± 0.22
6	-0.45 ± 0.28	0.02 ± 0.28	-0.21 ± 0.20
7	-0.35 ± 0.29	0.26 ± 0.29	-0.04 ± 0.20
8	-0.28 ± 0.32	-0.26 ± 0.31	-0.27 ± 0.22
9	0.22 ± 0.28	0.26 ± 0.27	0.24 ± 0.20
10	-0.23 ± 0.30	0.00 ± 0.30	-0.11 ± 0.21
11	-0.26 ± 0.34	0.39 ± 0.33	0.07 ± 0.24

Table B.2: ΔA_{CP} values for the control channels obtained with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2012 data).

Magnet Polarity	ΔA_{CP} (%)
Up	-0.099 ± 0.088
Down	0.089 ± 0.087
Up+Down	-0.003 ± 0.062

Table B.3: Asymmetries of control channels for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2011 data.

Bin	$\Delta A_{CP}(D_s^+) \text{ (%)}$		
	MagUp	MagDown	Up+Down
0	-0.38 ± 0.71	-0.70 ± 0.59	-0.57 ± 0.45
1	0.14 ± 0.66	0.46 ± 0.55	0.33 ± 0.42
2	1.37 ± 0.68	-0.58 ± 0.57	0.23 ± 0.44
3	-0.02 ± 0.59	0.22 ± 0.49	0.12 ± 0.38
4	1.06 ± 0.57	1.44 ± 0.48	1.28 ± 0.36
5	0.22 ± 0.60	-0.16 ± 0.50	-0.00 ± 0.38
6	0.41 ± 0.55	0.78 ± 0.46	0.63 ± 0.35
7	-0.10 ± 0.54	0.33 ± 0.46	0.15 ± 0.35
8	-0.59 ± 0.57	-0.20 ± 0.49	-0.36 ± 0.37
9	0.75 ± 0.54	-0.07 ± 0.44	0.26 ± 0.34
10	-0.38 ± 0.55	1.03 ± 0.46	0.44 ± 0.36
11	0.12 ± 0.58	-0.18 ± 0.49	-0.05 ± 0.38

Table B.4: ΔA_{CP} values for the control channels obtained with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2011 data).

Magnet Polarity	ΔA_{CP} (%)
Up	0.21 ± 0.17
Down	0.25 ± 0.14
Up+Down	0.24 ± 0.11

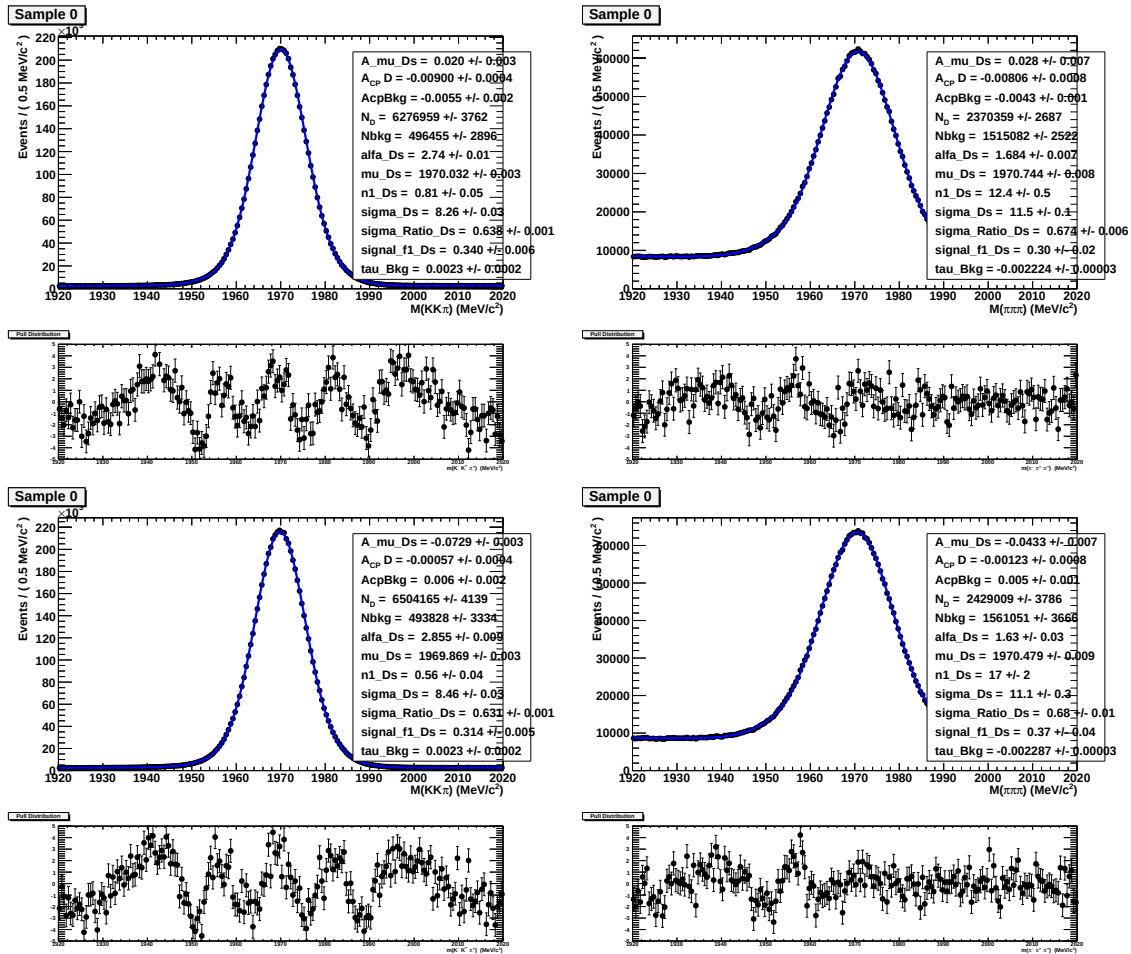


Figure B.1: Global fits to the invariant mass distributions for $D_s^+ \rightarrow K^- K^+ \pi^+$ (left) and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (right), MagUp (top) and MagDown (bottom) (2012 data).

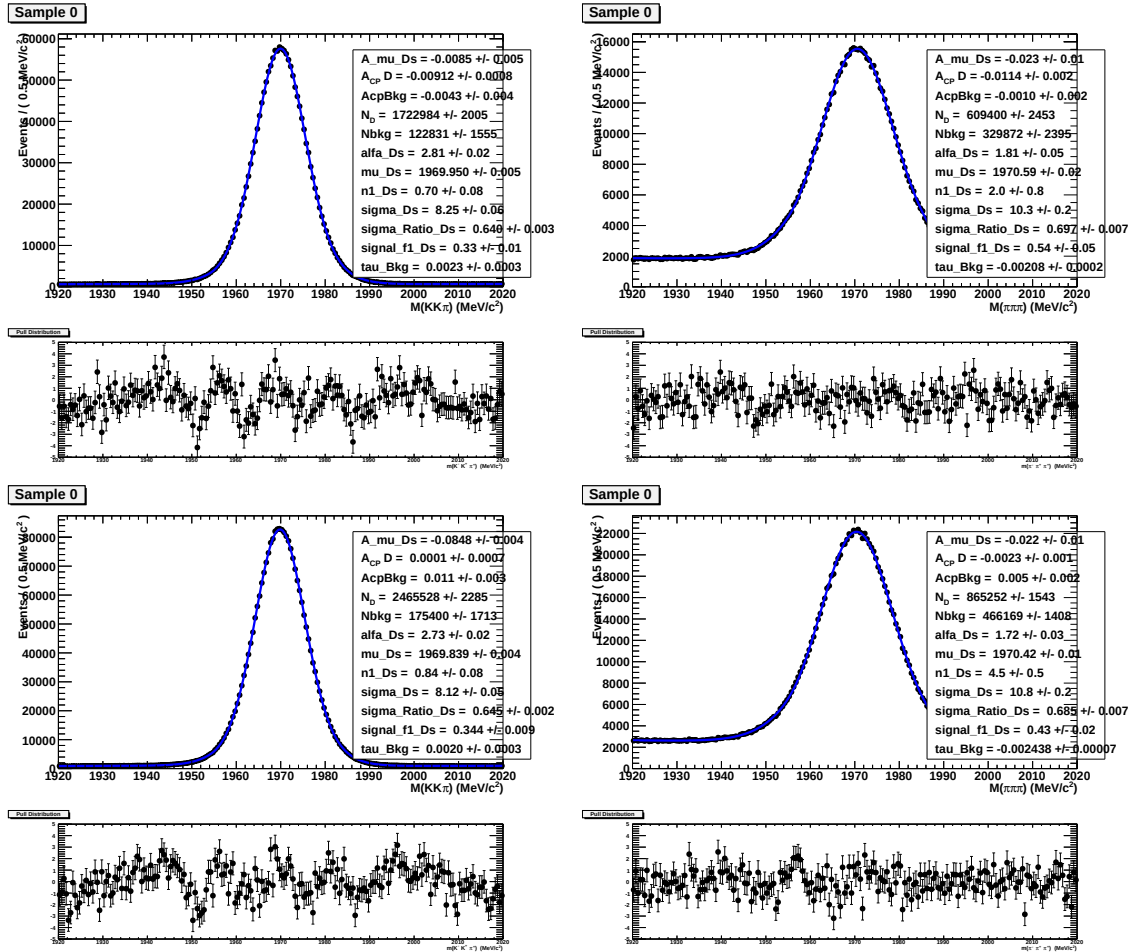


Figure B.2: Global fits to the invariant mass distributions for $D_s^+ \rightarrow K^- K^+ \pi^+$ (left) and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (right), MagUp (top) and MagDown (bottom) (2011 data).

Figure B.3: Invariant mass distributions for $D_s^+ \rightarrow K^- K^+ \pi^+$ with fitted PDF superimposed for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2012 Data.

Figure B.4: Invariant mass distributions for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ with fitted PDF superimposed for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2012 Data.

Figure B.5: Invariant mass distributions for $D_s^+ \rightarrow K^- K^+ \pi^+$ with fitted PDF superimposed for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2011 Data.

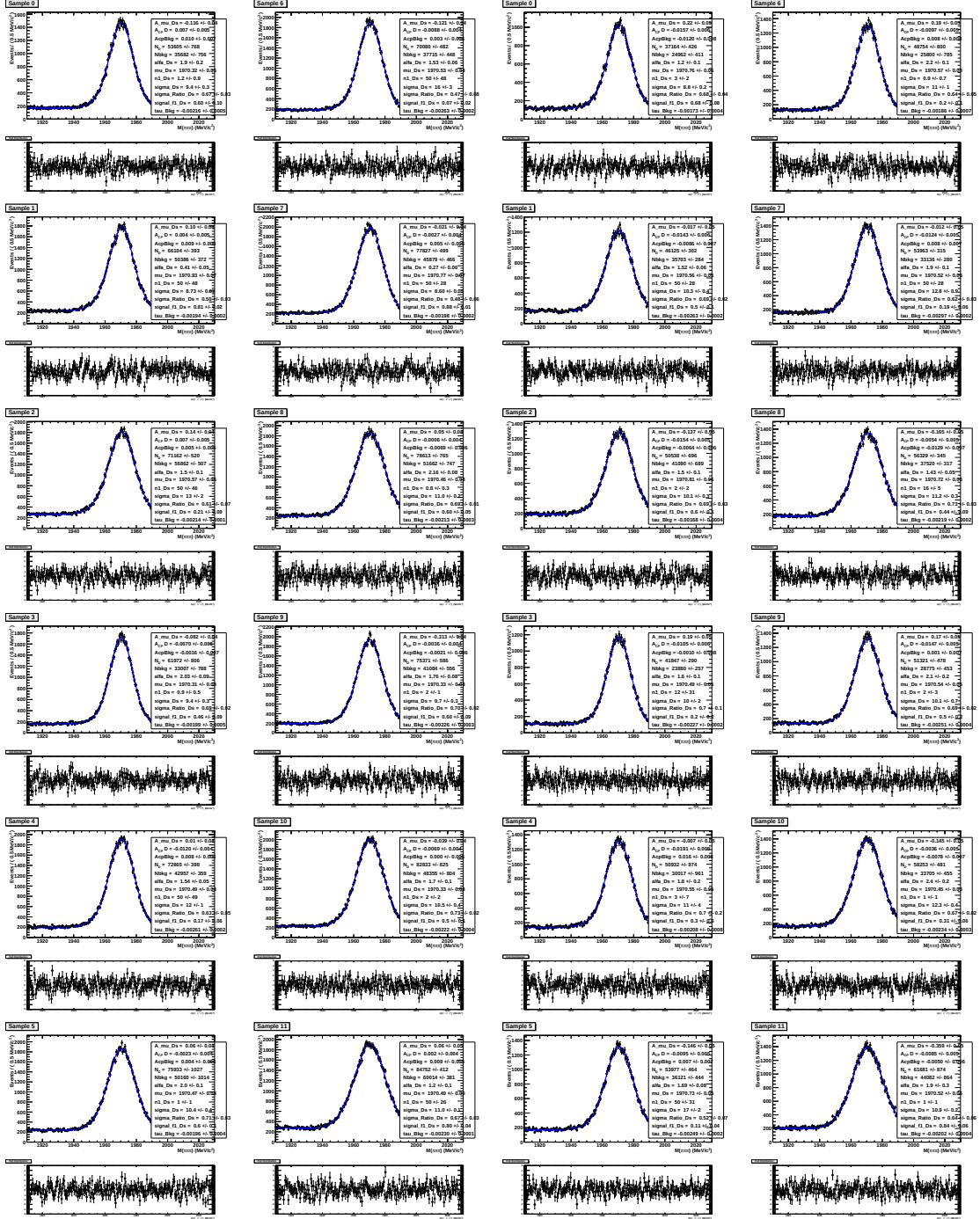


Figure B.6: Invariant mass distributions for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ with fitted PDF superimposed for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2011 Data.

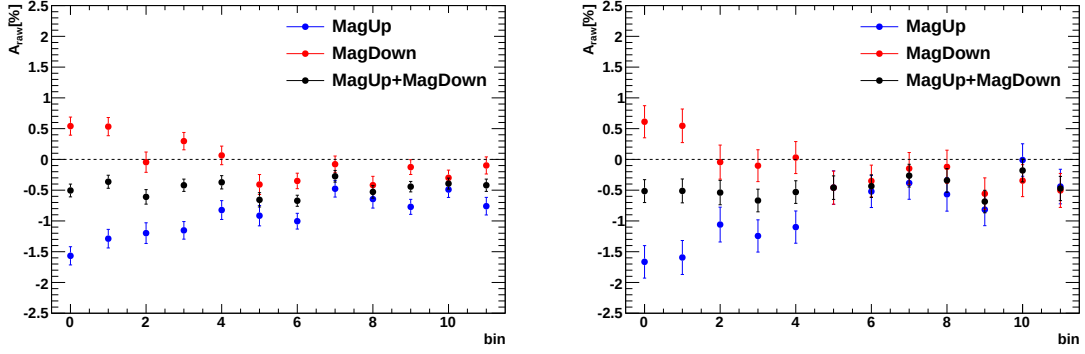


Figure B.7: Raw asymmetries for $D_s^+ \rightarrow K^- K^+ \pi^+$ (left) and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (right) obtained with the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2012 data).

Table B.5: Asymmetries of control channels for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2012 data.

Bin	$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+) (\%)$			$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$		
	MagUp	MagDown	Up+Down	MagUp	MagDown	Up+Down
0	-1.57 ± 0.15	0.54 ± 0.15	-0.50 ± 0.10	-1.66 ± 0.26	0.61 ± 0.26	-0.52 ± 0.19
1	-1.29 ± 0.15	0.53 ± 0.15	-0.36 ± 0.11	-1.59 ± 0.28	0.55 ± 0.27	-0.51 ± 0.19
2	-1.20 ± 0.17	-0.04 ± 0.16	-0.61 ± 0.12	-1.06 ± 0.28	-0.04 ± 0.28	-0.54 ± 0.20
3	-1.15 ± 0.14	0.30 ± 0.14	-0.42 ± 0.10	-1.24 ± 0.26	-0.10 ± 0.26	-0.67 ± 0.18
4	-0.82 ± 0.15	0.06 ± 0.15	-0.37 ± 0.11	-1.10 ± 0.26	0.03 ± 0.26	-0.53 ± 0.18
5	-0.92 ± 0.16	-0.41 ± 0.16	-0.66 ± 0.12	-0.46 ± 0.27	-0.46 ± 0.27	-0.46 ± 0.19
6	-1.00 ± 0.13	-0.35 ± 0.13	-0.67 ± 0.09	-0.52 ± 0.26	-0.35 ± 0.26	-0.43 ± 0.18
7	-0.48 ± 0.14	-0.08 ± 0.13	-0.27 ± 0.10	-0.38 ± 0.26	-0.15 ± 0.26	-0.26 ± 0.18
8	-0.64 ± 0.15	-0.42 ± 0.14	-0.53 ± 0.10	-0.57 ± 0.27	-0.12 ± 0.27	-0.34 ± 0.19
9	-0.77 ± 0.12	-0.12 ± 0.12	-0.44 ± 0.08	-0.82 ± 0.26	-0.56 ± 0.25	-0.68 ± 0.18
10	-0.49 ± 0.13	-0.30 ± 0.12	-0.39 ± 0.09	-0.01 ± 0.26	-0.34 ± 0.26	-0.18 ± 0.18
11	-0.76 ± 0.14	-0.10 ± 0.14	-0.42 ± 0.10	-0.44 ± 0.28	-0.50 ± 0.28	-0.47 ± 0.20

Table B.6: ΔA_{CP} of control channels for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2012 data.

Bin	$\Delta A_{CP}(D_s^+) (\%)$		
	MagUp	MagDown	Up+Down
0	0.10 ± 0.30	-0.07 ± 0.30	0.01 ± 0.21
1	0.31 ± 0.32	-0.01 ± 0.31	0.14 ± 0.22
2	-0.14 ± 0.33	-0.00 ± 0.32	-0.07 ± 0.23
3	0.09 ± 0.30	0.40 ± 0.30	0.25 ± 0.21
4	0.28 ± 0.30	0.04 ± 0.30	0.16 ± 0.21
5	-0.46 ± 0.32	0.05 ± 0.31	-0.20 ± 0.22
6	-0.48 ± 0.29	0.00 ± 0.29	-0.24 ± 0.20
7	-0.09 ± 0.30	0.07 ± 0.29	-0.01 ± 0.21
8	-0.08 ± 0.31	-0.30 ± 0.31	-0.19 ± 0.22
9	0.04 ± 0.29	0.43 ± 0.28	0.24 ± 0.20
10	-0.48 ± 0.29	0.05 ± 0.29	-0.21 ± 0.21
11	-0.32 ± 0.32	0.41 ± 0.31	0.05 ± 0.22

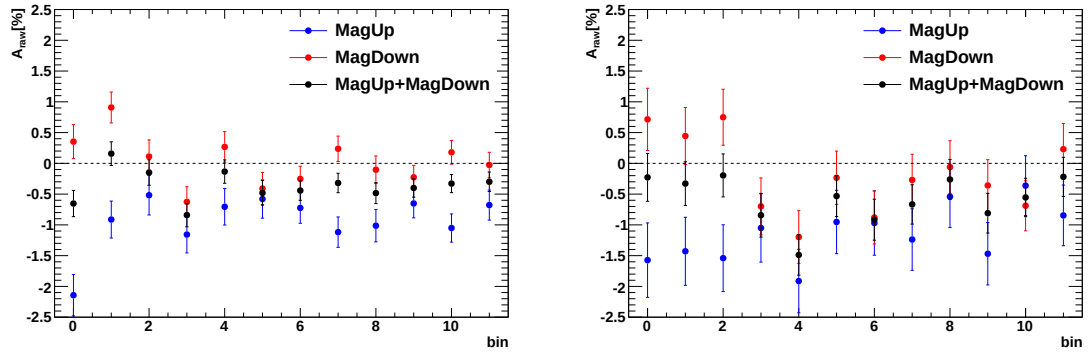


Figure B.8: Raw asymmetries for $D_s^+ \rightarrow K^- K^+ \pi^+$ (left) and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ (right) obtained with the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2011 data).

Table B.7: Asymmetries of control channels for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2011 data.

Bin	$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+) (\%)$			$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$		
	MagUp	MagDown	Up+Down	MagUp	MagDown	Up+Down
0	-2.14 ± 0.34	0.35 ± 0.28	-0.65 ± 0.21	-1.57 ± 0.60	0.72 ± 0.51	-0.23 ± 0.39
1	-0.91 ± 0.30	0.91 ± 0.25	0.16 ± 0.19	-1.43 ± 0.55	0.44 ± 0.46	-0.33 ± 0.36
2	-0.52 ± 0.32	0.11 ± 0.27	-0.15 ± 0.21	-1.54 ± 0.54	0.75 ± 0.46	-0.20 ± 0.35
3	-1.16 ± 0.30	-0.63 ± 0.25	-0.84 ± 0.19	-1.05 ± 0.56	-0.70 ± 0.46	-0.84 ± 0.36
4	-0.71 ± 0.30	0.27 ± 0.25	-0.13 ± 0.19	-1.91 ± 0.52	-1.18 ± 0.43	-1.49 ± 0.33
5	-0.58 ± 0.31	-0.41 ± 0.26	-0.48 ± 0.20	-0.95 ± 0.52	-0.23 ± 0.43	-0.53 ± 0.33
6	-0.72 ± 0.25	-0.25 ± 0.20	-0.44 ± 0.16	-0.97 ± 0.52	-0.88 ± 0.43	-0.92 ± 0.33
7	-1.12 ± 0.25	0.24 ± 0.21	-0.32 ± 0.16	-1.24 ± 0.50	-0.27 ± 0.42	-0.67 ± 0.32
8	-1.01 ± 0.26	-0.10 ± 0.22	-0.48 ± 0.17	-0.54 ± 0.50	-0.06 ± 0.43	-0.26 ± 0.33
9	-0.65 ± 0.23	-0.23 ± 0.19	-0.40 ± 0.15	-1.47 ± 0.51	-0.36 ± 0.42	-0.81 ± 0.32
10	-1.05 ± 0.23	0.18 ± 0.19	-0.33 ± 0.15	-0.36 ± 0.49	-0.69 ± 0.41	-0.55 ± 0.31
11	-0.68 ± 0.24	-0.03 ± 0.21	-0.30 ± 0.16	-0.85 ± 0.49	0.23 ± 0.42	-0.22 ± 0.32

Table B.8: ΔA_{CP} of control channels for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2011 data.

Bin	$\Delta A_{CP}(D_s^+) (\%)$		
	MagUp	MagDown	Up+Down
0	-0.57 ± 0.69	-0.36 ± 0.58	-0.45 ± 0.44
1	0.52 ± 0.63	0.46 ± 0.53	0.48 ± 0.40
2	1.02 ± 0.63	-0.64 ± 0.53	0.05 ± 0.40
3	-0.11 ± 0.63	0.07 ± 0.52	-0.00 ± 0.40
4	1.21 ± 0.60	1.46 ± 0.50	1.36 ± 0.38
5	0.37 ± 0.60	-0.18 ± 0.51	0.05 ± 0.39
6	0.25 ± 0.58	0.63 ± 0.48	0.47 ± 0.37
7	0.12 ± 0.56	0.51 ± 0.46	0.35 ± 0.36
8	-0.47 ± 0.57	-0.04 ± 0.48	-0.22 ± 0.37
9	0.82 ± 0.56	0.13 ± 0.46	0.41 ± 0.36
10	-0.69 ± 0.54	0.87 ± 0.45	0.23 ± 0.34
11	0.17 ± 0.55	-0.26 ± 0.47	-0.08 ± 0.36

Table B.9: ΔA_{CP} values for the control channels obtained with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (nominal), with the global fits (no binning) and with the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2012 data).

Magnet Polarity	ΔA_{CP} (%)	ΔA_{CP} (%)	ΔA_{CP} (%)
	$D^+ \rightarrow \pi^- \pi^+ \pi^+$ binning	Unbinned	$D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ binning
Up	-0.099 ± 0.088	-0.094 ± 0.089	-0.104 ± 0.088
Down	0.089 ± 0.087	0.066 ± 0.088	0.093 ± 0.087
Up+Down	-0.003 ± 0.062	-0.013 ± 0.063	-0.004 ± 0.062

Table B.10: ΔA_{CP} values for the control channels obtained with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (nominal), with the global fits (no binning) and with the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2011 data).

Magnet Polarity	ΔA_{CP} (%)	ΔA_{CP} (%)	ΔA_{CP} (%)
	$D^+ \rightarrow \pi^- \pi^+ \pi^+$ binning	Unbinned	$D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ binning
Up	0.21 ± 0.17	0.23 ± 0.17	0.21 ± 0.17
Down	0.25 ± 0.14	0.25 ± 0.14	0.25 ± 0.14
Up+Down	0.24 ± 0.11	0.24 ± 0.11	0.23 ± 0.11

B.2 Signal Channels

Table B.11: Blind ΔA_{CP} of the signal channels for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2012 data.

Bin	$\Delta A_{CP}(D^+) (\%)$		
	MagUp	MagDown	Up+Down
0	-0.26 ± 0.32	0.27 ± 0.31	0.01 ± 0.22
1	0.24 ± 0.32	0.53 ± 0.32	0.39 ± 0.23
2	0.69 ± 0.33	0.82 ± 0.32	0.76 ± 0.23
3	0.23 ± 0.31	0.67 ± 0.30	0.45 ± 0.22
4	0.46 ± 0.32	0.36 ± 0.31	0.41 ± 0.22
5	0.16 ± 0.32	0.76 ± 0.32	0.47 ± 0.23
6	0.01 ± 0.31	0.80 ± 0.30	0.41 ± 0.22
7	0.34 ± 0.31	0.36 ± 0.31	0.35 ± 0.22
8	0.01 ± 0.32	0.43 ± 0.32	0.22 ± 0.22
9	0.03 ± 0.30	0.36 ± 0.29	0.20 ± 0.21
10	-0.02 ± 0.32	0.76 ± 0.31	0.38 ± 0.22
11	0.76 ± 0.33	0.52 ± 0.32	0.64 ± 0.23

Table B.12: ΔA_{CP} values for the signal channels obtained with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2012 data).

Magnet Polarity	$\Delta A_{CP} (\%)$
Up	0.212 ± 0.091
Down	0.552 ± 0.090
Up+Down	0.385 ± 0.064

Table B.13: Blind ΔA_{CP} of signal channels for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2011 data.

Bin	$\Delta A_{CP}(D^+) (\%)$		
	MagUp	MagDown	Up+Down
0	0.63 ± 0.70	0.25 ± 0.59	0.41 ± 0.45
1	1.56 ± 0.65	0.40 ± 0.55	0.88 ± 0.42
2	0.74 ± 0.63	-0.27 ± 0.54	0.15 ± 0.41
3	1.51 ± 0.63	0.20 ± 0.53	0.74 ± 0.41
4	-0.97 ± 0.61	1.72 ± 0.51	0.61 ± 0.39
5	0.97 ± 0.62	0.66 ± 0.52	0.79 ± 0.40
6	1.35 ± 0.61	0.79 ± 0.51	1.02 ± 0.39
7	-0.04 ± 0.59	1.09 ± 0.50	0.62 ± 0.38
8	1.03 ± 0.59	1.34 ± 0.51	1.21 ± 0.39
9	0.37 ± 0.58	0.79 ± 0.49	0.62 ± 0.37
10	1.60 ± 0.58	1.23 ± 0.49	1.38 ± 0.38
11	0.48 ± 0.58	0.37 ± 0.50	0.42 ± 0.38

Table B.14: ΔA_{CP} values for the signal channels obtained with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2011 data).

Magnet Polarity	$\Delta A_{CP} (\%)$
Up	0.76 ± 0.18
Down	0.74 ± 0.15
Up+Down	0.75 ± 0.11

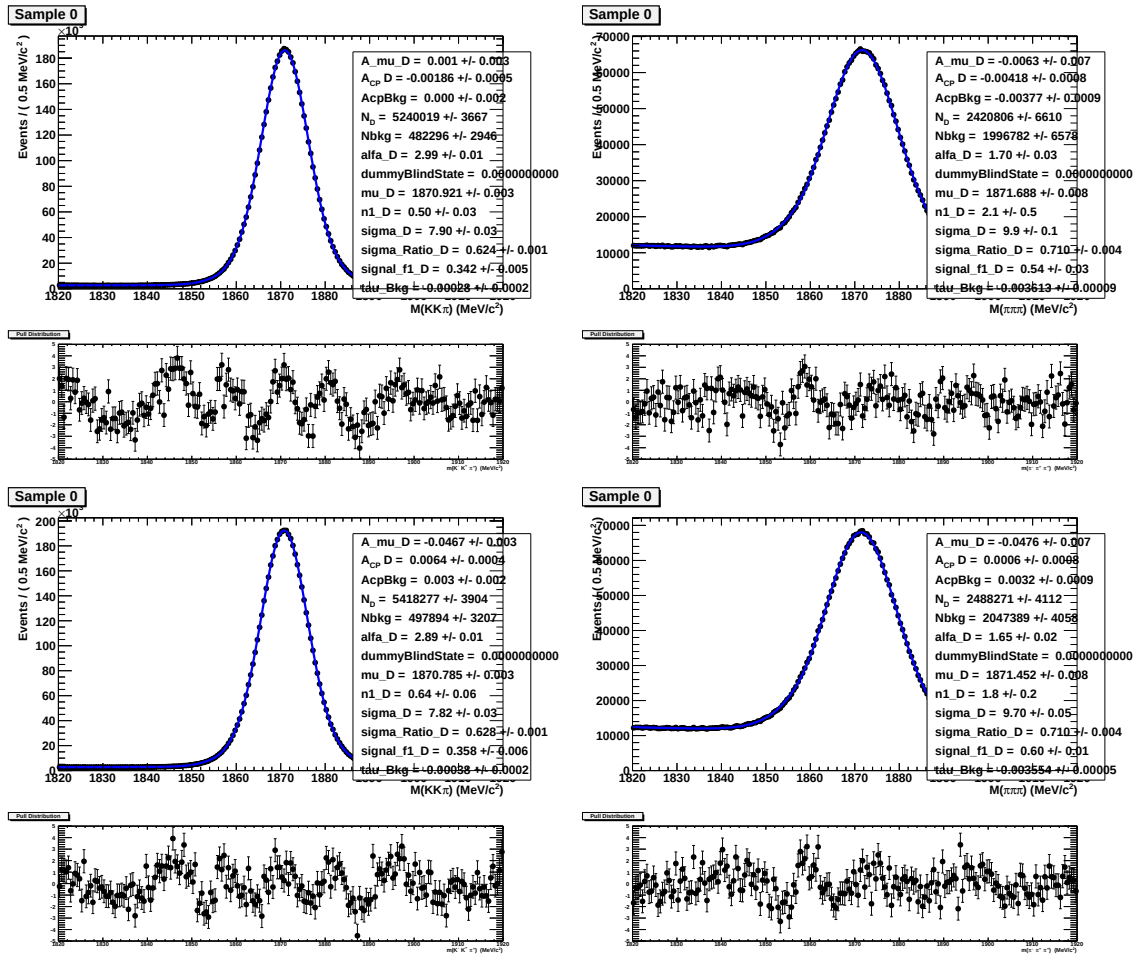


Figure B.9: Fit to invariant mass for $D^+ \rightarrow K^- K^+ \pi^+$ (left) and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (right), MagUp (top) and MagDown (bottom) and using 2012 data.

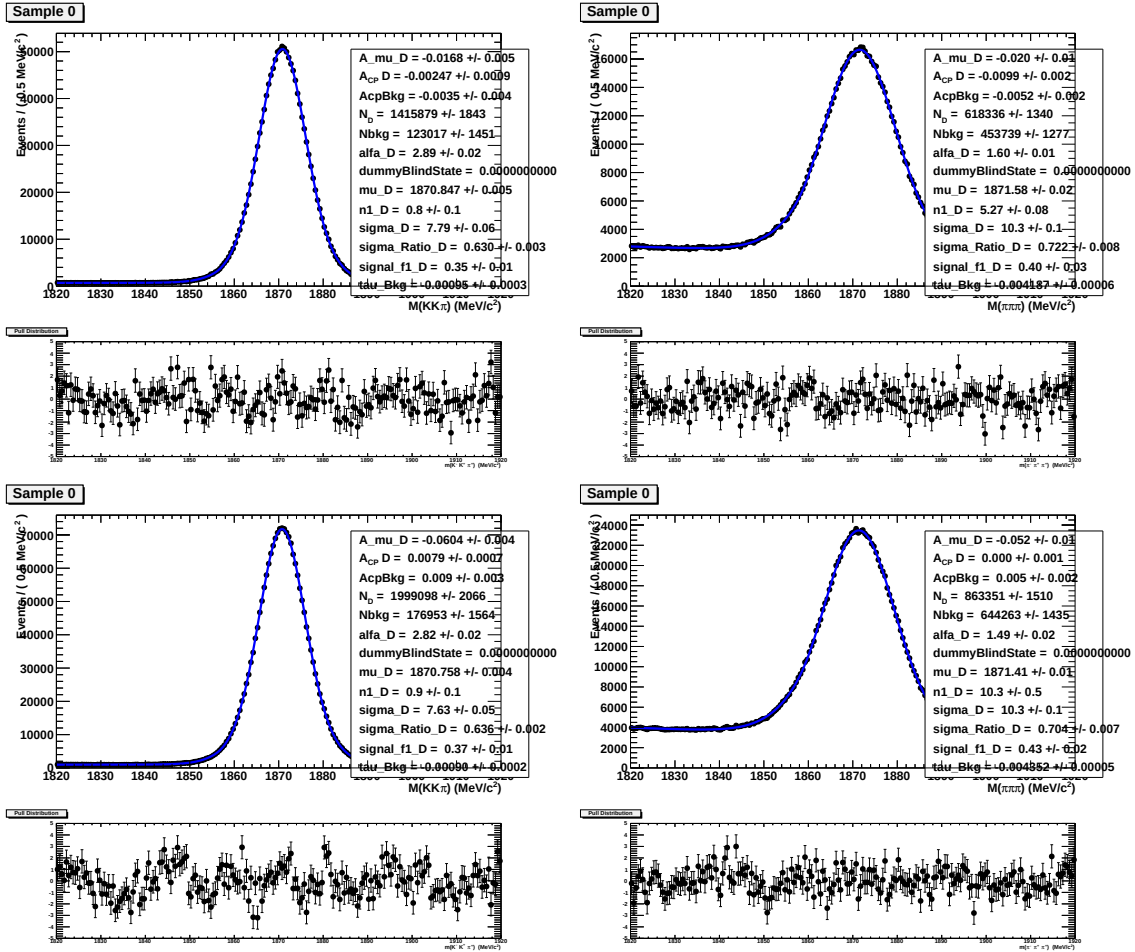


Figure B.10: Fit to invariant mass for $D^+ \rightarrow K^- K^+ \pi^+$ (left) and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (right), MagUp (top) and MagDown (bottom) and using 2011 data.

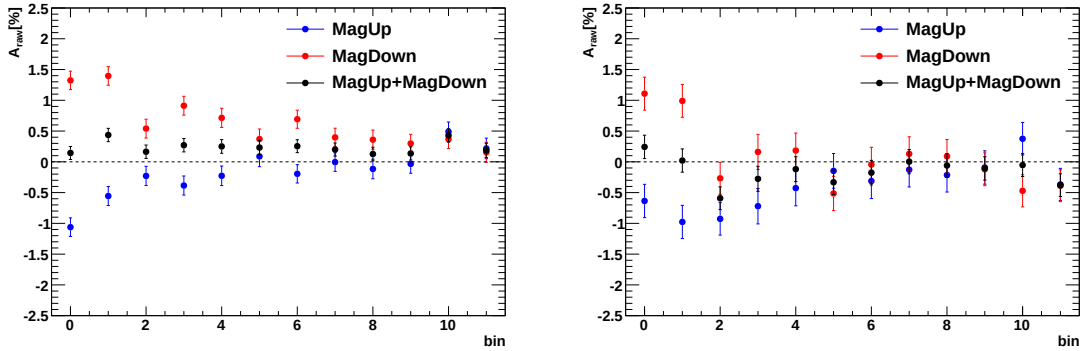


Figure B.11: Raw asymmetries for $D^+ \rightarrow K^- K^+ \pi^+$ (left) and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (right) obtained with the $D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2012 data).

Table B.15: Blind asymmetries of signal channels for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2012 data.

Bin	$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+) (\%)$			$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$		
	MagUp	MagDown	Up+Down	MagUp	MagDown	Up+Down
0	-1.06 ± 0.15	1.32 ± 0.15	0.14 ± 0.11	-0.64 ± 0.27	1.11 ± 0.27	0.24 ± 0.19
1	-0.56 ± 0.15	1.40 ± 0.15	0.44 ± 0.11	-0.98 ± 0.27	0.99 ± 0.27	0.02 ± 0.19
2	-0.23 ± 0.16	0.54 ± 0.15	0.16 ± 0.11	-0.93 ± 0.26	-0.27 ± 0.26	-0.59 ± 0.18
3	-0.38 ± 0.16	0.91 ± 0.15	0.27 ± 0.11	-0.72 ± 0.29	0.16 ± 0.29	-0.28 ± 0.20
4	-0.23 ± 0.16	0.72 ± 0.16	0.25 ± 0.11	-0.43 ± 0.29	0.18 ± 0.28	-0.12 ± 0.20
5	0.09 ± 0.17	0.37 ± 0.16	0.23 ± 0.12	-0.15 ± 0.28	-0.51 ± 0.28	-0.33 ± 0.20
6	-0.20 ± 0.15	0.69 ± 0.15	0.25 ± 0.10	-0.31 ± 0.28	-0.04 ± 0.28	-0.18 ± 0.20
7	-0.00 ± 0.15	0.40 ± 0.15	0.20 ± 0.11	-0.13 ± 0.28	0.13 ± 0.28	0.00 ± 0.20
8	-0.12 ± 0.16	0.36 ± 0.16	0.13 ± 0.11	-0.22 ± 0.28	0.09 ± 0.27	-0.06 ± 0.19
9	-0.03 ± 0.15	0.30 ± 0.15	0.14 ± 0.11	-0.09 ± 0.27	-0.12 ± 0.27	-0.11 ± 0.19
10	0.49 ± 0.16	0.37 ± 0.15	0.43 ± 0.11	0.38 ± 0.26	-0.47 ± 0.26	-0.05 ± 0.19
11	0.22 ± 0.17	0.15 ± 0.16	0.18 ± 0.12	-0.37 ± 0.26	-0.39 ± 0.26	-0.38 ± 0.18

Table B.16: Blind ΔA_{CP} of signal channels for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2012 data.

Bin	$\Delta A_{CP}(D^+) (\%)$		
	MagUp	MagDown	Up+Down
0	-0.43 ± 0.31	0.22 ± 0.31	-0.10 ± 0.22
1	0.42 ± 0.31	0.41 ± 0.31	0.41 ± 0.22
2	0.70 ± 0.31	0.81 ± 0.30	0.75 ± 0.22
3	0.34 ± 0.33	0.75 ± 0.32	0.54 ± 0.23
4	0.20 ± 0.33	0.53 ± 0.32	0.37 ± 0.23
5	0.24 ± 0.33	0.88 ± 0.32	0.56 ± 0.23
6	0.12 ± 0.32	0.74 ± 0.32	0.43 ± 0.23
7	0.12 ± 0.32	0.27 ± 0.32	0.20 ± 0.22
8	0.10 ± 0.32	0.27 ± 0.31	0.19 ± 0.22
9	0.06 ± 0.31	0.42 ± 0.30	0.24 ± 0.22
10	0.12 ± 0.31	0.84 ± 0.30	0.48 ± 0.22
11	0.59 ± 0.31	0.54 ± 0.30	0.56 ± 0.22

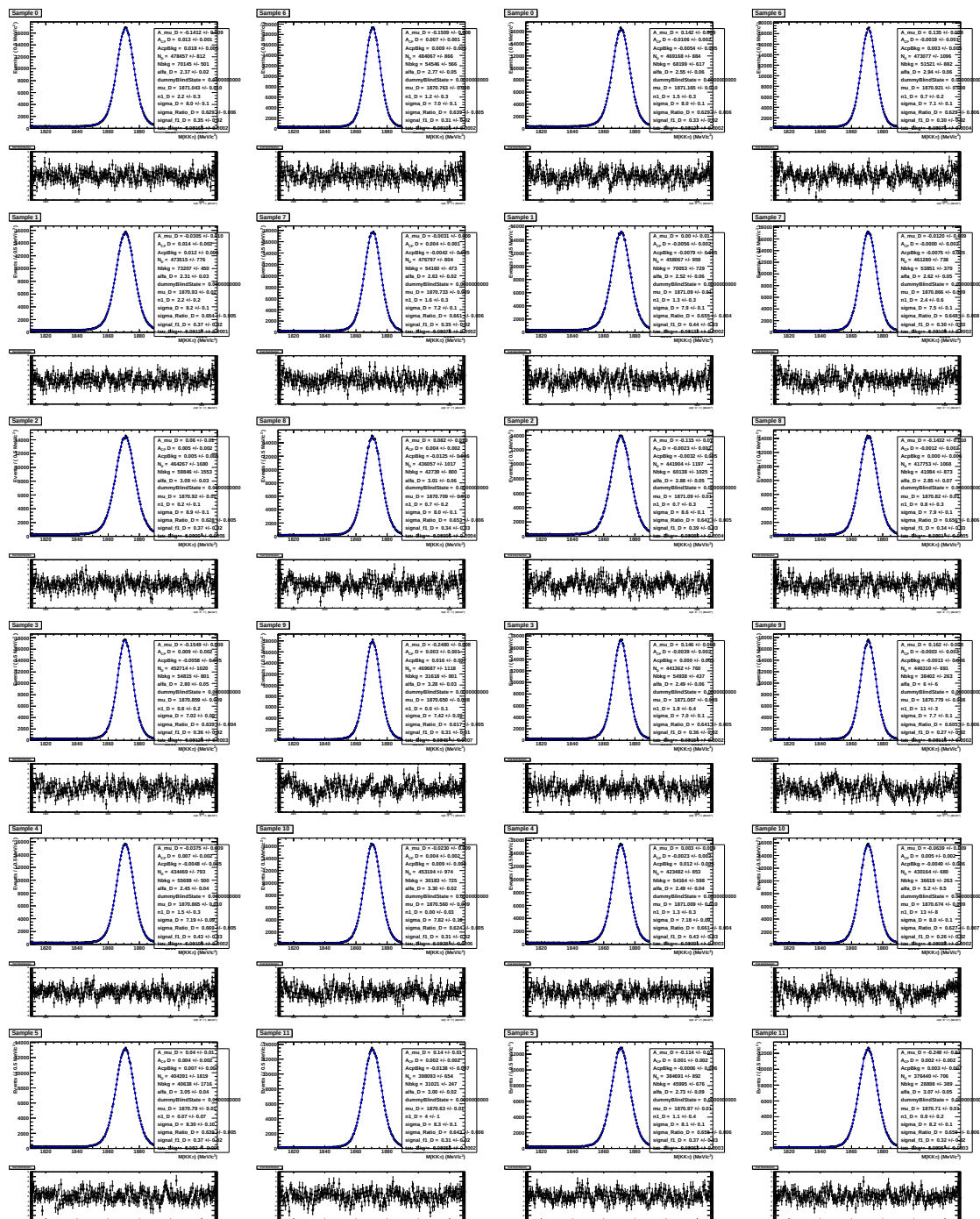


Figure B.12: Invariant mass distributions for $D^+ \rightarrow K^- K^+ \pi^+$ with fitted PDF superimposed for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2012 Data.

Figure B.13: Invariant mass distributions for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ with fitted PDF superimposed for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2012 Data.

Figure B.14: Invariant mass distributions for $D^+ \rightarrow K^- K^+ \pi^+$ with fitted PDF superimposed for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2011 Data.

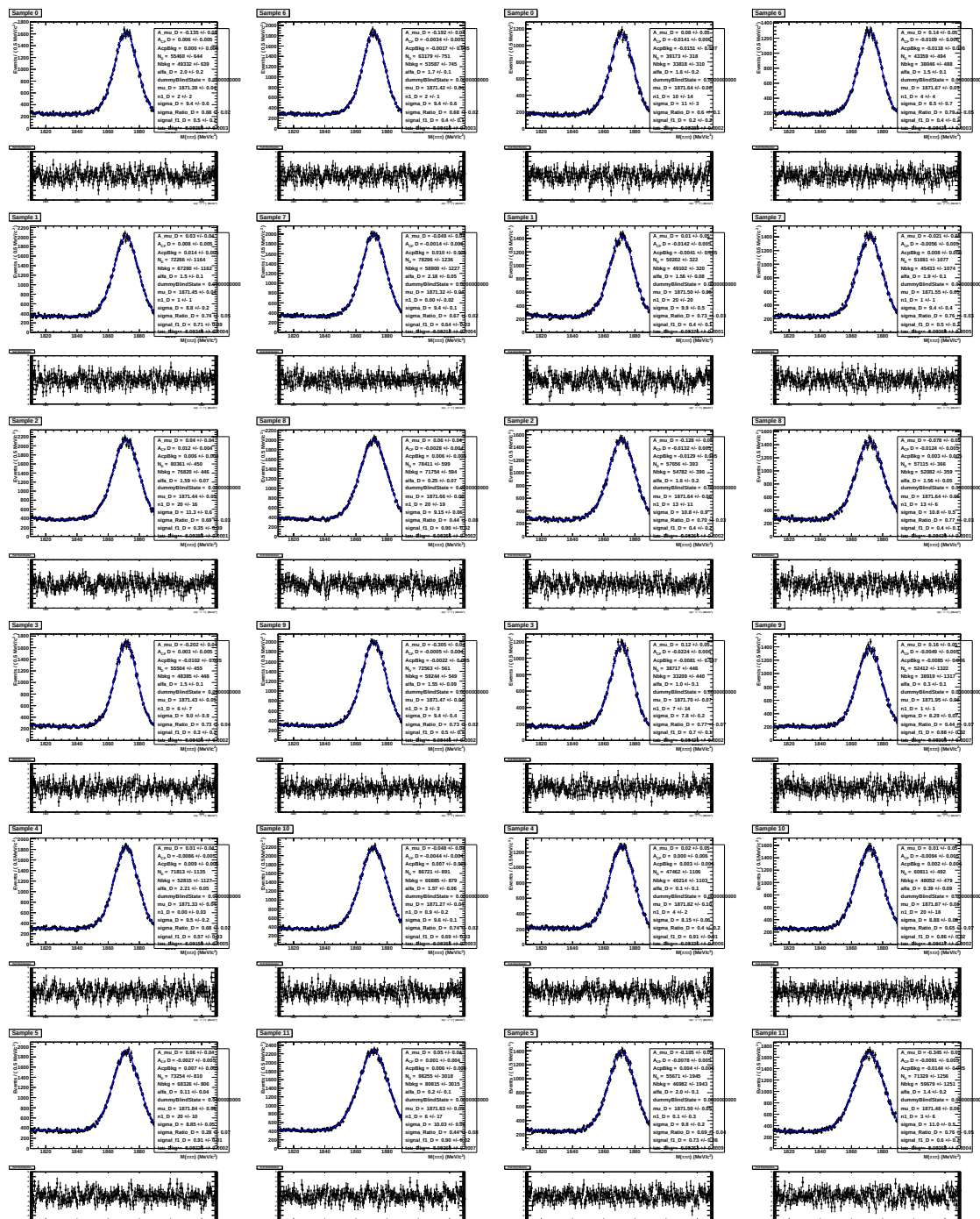


Figure B.15: Invariant mass distributions for $D^+ \rightarrow \pi^- \pi^+ \pi^+$ with fitted PDF superimposed for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning using 2011 Data.

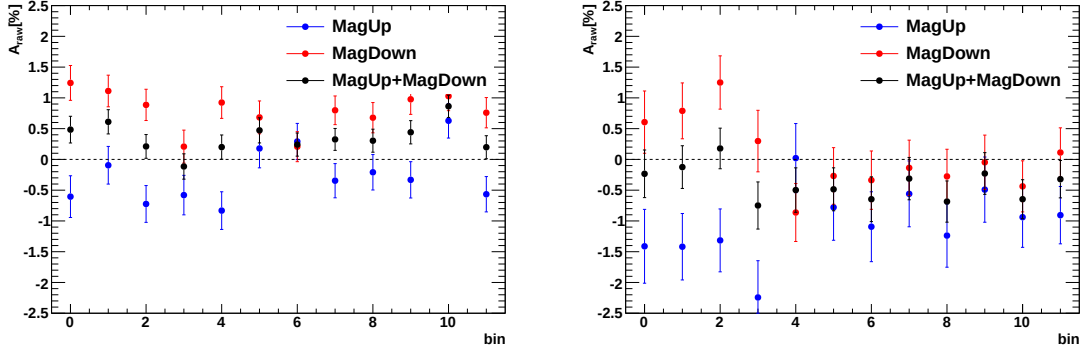


Figure B.16: Raw asymmetries for $D^+ \rightarrow K^- K^+ \pi^+$ (left) and $D^+ \rightarrow \pi^- \pi^+ \pi^+$ (right) obtained with the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2011 data).

Table B.17: Blind asymmetries of signal channels for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2011 data.

Bin	$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+) (\%)$			$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$		
	MagUp	MagDown	Up+Down	MagUp	MagDown	Up+Down
0	-0.60 ± 0.34	1.24 ± 0.28	0.48 ± 0.22	-1.41 ± 0.60	0.61 ± 0.51	-0.23 ± 0.39
1	-0.10 ± 0.31	1.11 ± 0.26	0.61 ± 0.20	-1.42 ± 0.54	0.79 ± 0.45	-0.12 ± 0.35
2	-0.72 ± 0.30	0.89 ± 0.25	0.21 ± 0.19	-1.32 ± 0.51	1.25 ± 0.43	0.18 ± 0.33
3	-0.58 ± 0.32	0.21 ± 0.27	-0.12 ± 0.21	-2.24 ± 0.60	0.30 ± 0.50	-0.75 ± 0.38
4	-0.83 ± 0.31	0.92 ± 0.26	0.20 ± 0.20	0.02 ± 0.56	-0.86 ± 0.47	-0.50 ± 0.36
5	0.18 ± 0.32	0.68 ± 0.27	0.47 ± 0.20	-0.78 ± 0.53	-0.27 ± 0.46	-0.49 ± 0.35
6	0.29 ± 0.29	0.21 ± 0.24	0.24 ± 0.19	-1.09 ± 0.57	-0.34 ± 0.47	-0.65 ± 0.36
7	-0.35 ± 0.28	0.80 ± 0.23	0.32 ± 0.18	-0.56 ± 0.54	-0.14 ± 0.45	-0.31 ± 0.34
8	-0.21 ± 0.29	0.68 ± 0.25	0.30 ± 0.19	-1.24 ± 0.51	-0.28 ± 0.44	-0.68 ± 0.34
9	-0.33 ± 0.30	0.98 ± 0.24	0.44 ± 0.19	-0.49 ± 0.53	-0.05 ± 0.44	-0.23 ± 0.34
10	0.63 ± 0.28	1.03 ± 0.24	0.86 ± 0.18	-0.94 ± 0.49	-0.44 ± 0.42	-0.65 ± 0.32
11	-0.57 ± 0.29	0.76 ± 0.25	0.20 ± 0.19	-0.91 ± 0.47	0.11 ± 0.40	-0.32 ± 0.30

Table B.18: Blind ΔA_{CP} of signal channels for $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning with 2011 data.

Bin	$\Delta A_{CP}(D^+) (\%)$		
	MagUp	MagDown	Up+Down
0	0.81 ± 0.69	0.64 ± 0.58	0.71 ± 0.44
1	1.32 ± 0.62	0.32 ± 0.52	0.74 ± 0.40
2	0.59 ± 0.59	-0.36 ± 0.50	0.04 ± 0.38
3	1.66 ± 0.68	-0.09 ± 0.57	0.63 ± 0.44
4	-0.85 ± 0.64	1.79 ± 0.54	0.70 ± 0.41
5	0.96 ± 0.62	0.95 ± 0.53	0.95 ± 0.40
6	1.38 ± 0.64	0.54 ± 0.53	0.89 ± 0.41
7	0.21 ± 0.60	0.93 ± 0.51	0.64 ± 0.39
8	1.03 ± 0.59	0.95 ± 0.50	0.99 ± 0.38
9	0.16 ± 0.61	1.02 ± 0.50	0.67 ± 0.39
10	1.57 ± 0.56	1.47 ± 0.48	1.51 ± 0.36
11	0.34 ± 0.55	0.65 ± 0.47	0.52 ± 0.36

Table B.19: ΔA_{CP} values for the signal channels obtained with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (nominal), with the global fits (no binning) and with the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2012 data).

Magnet Polarity	$\Delta A_{CP} (\%)$	$\Delta A_{CP} (\%)$	$\Delta A_{CP} (\%)$
	$D^+ \rightarrow \pi^- \pi^+ \pi^+$ binning	Unbinned	$D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ binning
Up	0.212 ± 0.091	0.232 ± 0.093	0.214 ± 0.091
Down	0.552 ± 0.090	0.581 ± 0.091	0.554 ± 0.090
Up+Down	0.385 ± 0.064	0.409 ± 0.065	0.387 ± 0.064

Table B.20: ΔA_{CP} values for the signal channels obtained with the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (nominal), with the global fits (no binning) and with the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning (2011 data).

Magnet Polarity	$\Delta A_{CP} (\%)$	$\Delta A_{CP} (\%)$	$\Delta A_{CP} (\%)$
	$D^+ \rightarrow \pi^- \pi^+ \pi^+$ binning	Unbinned	$D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ binning
Up	0.76 ± 0.18	0.74 ± 0.18	0.76 ± 0.18
Down	0.74 ± 0.15	0.74 ± 0.15	0.75 ± 0.15
Up+Down	0.75 ± 0.11	0.74 ± 0.11	0.75 ± 0.11

Appendix C

Tables and plots of asymmetries as a function of trigger configuration

Table C.1: Asymmetries of control channels grouped by TCK with 2012 MagUp data.

Group	$A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+) (\%)$	$A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$	$\Delta A_{CP}(D_s^+) (\%)$
0	-0.939 ± 0.084	-0.65 ± 0.16	-0.29 ± 0.18
1	-0.844 ± 0.066	-0.78 ± 0.12	-0.06 ± 0.14
2	-1.023 ± 0.090	-0.87 ± 0.17	-0.15 ± 0.20
3	-0.81 ± 0.11	-1.02 ± 0.20	0.21 ± 0.23

Table C.2: Blind asymmetries of signal channels grouped by TCK with 2012 MagUp data.

Group	$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+) (\%)$	$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$	$\Delta A_{CP}(D^+) (\%)$
0	-0.057 ± 0.093	-0.40 ± 0.17	0.34 ± 0.19
1	-0.137 ± 0.072	-0.42 ± 0.13	0.29 ± 0.15
2	-0.340 ± 0.098	-0.47 ± 0.18	0.13 ± 0.20
3	-0.31 ± 0.12	-0.39 ± 0.21	0.08 ± 0.24

Table C.3: Asymmetries of control channels grouped by TCK with 2012 MagDown data.

Group	$A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+) (\%)$	$A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$	$\Delta A_{CP}(D_s^+) (\%)$
0	-0.162 ± 0.086	-0.16 ± 0.17	-0.00 ± 0.19
1	0.035 ± 0.091	0.11 ± 0.17	-0.07 ± 0.20
2	-0.109 ± 0.079	-0.17 ± 0.15	0.06 ± 0.17
3	0.003 ± 0.083	-0.34 ± 0.16	0.34 ± 0.18
4	0.02 ± 0.14	0.18 ± 0.29	-0.17 ± 0.32

Table C.4: Blind asymmetries of signal channels grouped by TCK with 2012 MagDown data.

Group	$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+) (\%)$	$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$	$\Delta A_{CP}(D^+) (\%)$
0	0.631 ± 0.095	0.29 ± 0.17	0.34 ± 0.20
1	0.685 ± 0.099	0.09 ± 0.18	0.59 ± 0.20
2	0.504 ± 0.087	-0.12 ± 0.15	0.63 ± 0.18
3	0.725 ± 0.091	0.00 ± 0.16	0.72 ± 0.19
4	0.81 ± 0.16	0.16 ± 0.30	0.64 ± 0.34

Table C.5: Asymmetries of control channels grouped by TCK with 2011 MagUp data.

Group	$A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+) (\%)$	$A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$	$\Delta A_{CP}(D_s^+) (\%)$
0	-0.81 ± 0.13	-1.09 ± 0.25	0.28 ± 0.28
1	-1.16 ± 0.76	-1.7 ± 1.5	0.56 ± 1.7
2	-0.96 ± 0.10	-1.16 ± 0.20	0.20 ± 0.22
3	-1.5 ± 1.0	-1.1 ± 1.8	-0.4 ± 2.1

Table C.6: Blind asymmetries of signal channels grouped by TCK with 2011 MagUp data.

Group	$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+) (\%)$	$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$	$\Delta A_{CP}(D^+) (\%)$
0	-0.06 ± 0.14	-1.16 ± 0.25	1.09 ± 0.29
1	-0.70 ± 0.85	-1.4 ± 1.5	0.7 ± 1.7
2	-0.34 ± 0.11	-0.84 ± 0.20	0.50 ± 0.23
3	-2.0 ± 1.1	-3.5 ± 2.0	1.5 ± 2.3

Table C.7: Asymmetries of control channels grouped by TCK with 2011 MagDown data.

Group	$A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+) (\%)$	$A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$	$\Delta A_{CP}(D_s^+) (\%)$
0	0.07 ± 0.11	-0.07 ± 0.22	0.14 ± 0.25
1	0.08 ± 0.60	-0.2 ± 1.1	0.3 ± 1.3
2	-0.016 ± 0.081	-0.32 ± 0.16	0.30 ± 0.18

Table C.8: Blind asymmetries of signal channels grouped by TCK with 2011 MagDown data.

Group	$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+) (\%)$	$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+) (\%)$	$\Delta A_{CP}(D^+) (\%)$
0	1.06 ± 0.13	0.24 ± 0.23	0.81 ± 0.26
1	0.54 ± 0.68	-0.5 ± 1.2	1.1 ± 1.4
2	0.654 ± 0.090	-0.07 ± 0.16	0.72 ± 0.19

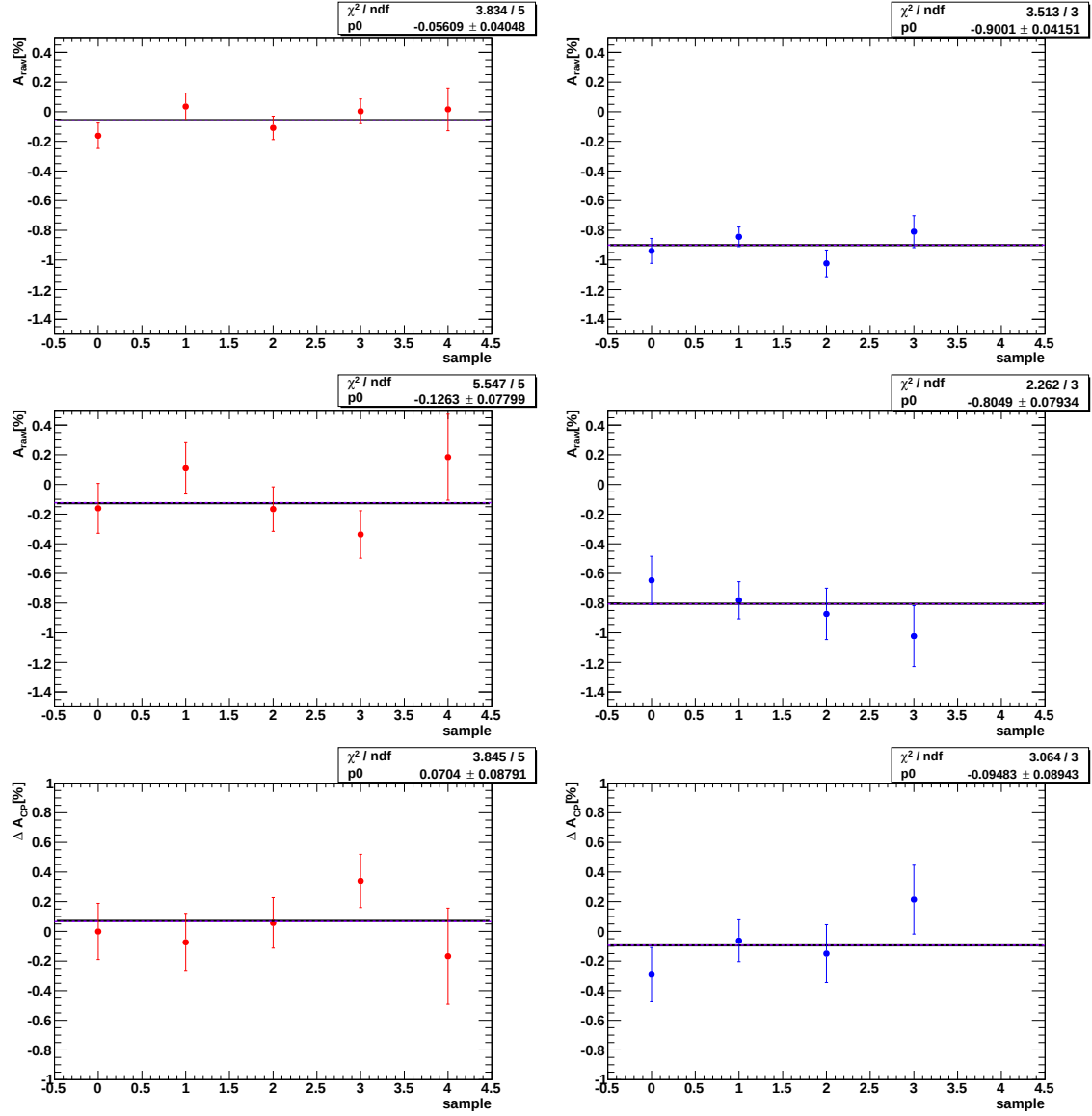


Figure C.1: Asymmetries of D_s^+ control channels using 2012 Data, MagDown (left) and MagUp (right), for different TCKs grouped by cuts according to table 7.3. Top plots are $A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+)$, middle plots are $A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+)$ and bottom plots are $\Delta A_{CP}(D_s^+)$. The black solid line corresponds to a fit of a constant. For $\Delta A_{CP}(D_s^+)$ plots, it has a p-value of 57%, for MagDown, and 38%, for MagUp. The purple dashed line indicates the asymmetry value obtained from the full sample.

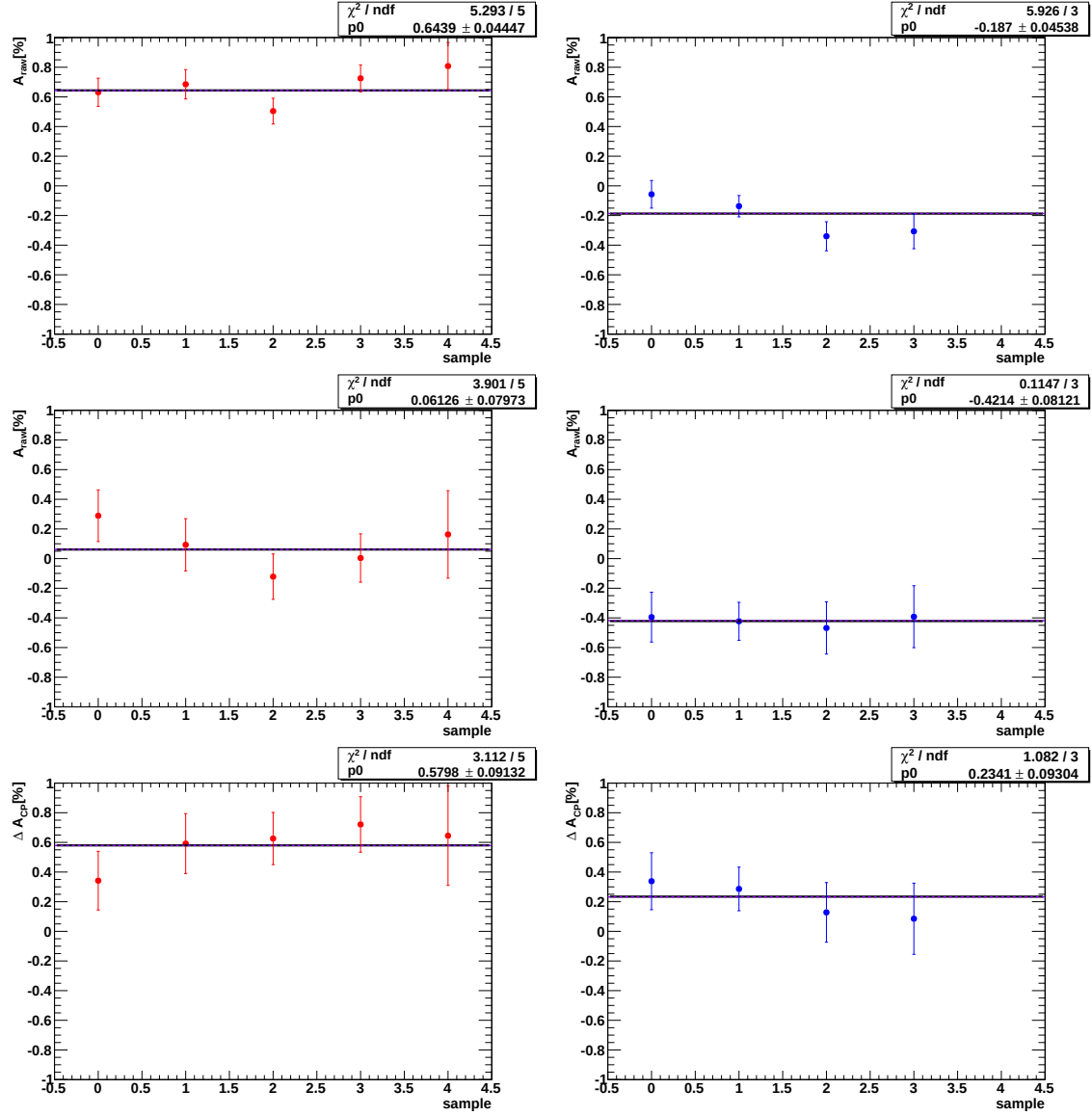


Figure C.2: Asymmetries of signal channels (D) using 2012 Data, MagDown (left) and MagUp (right), for different TCKs grouped by cuts according to table 7.3. Top plots are $A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+)$, middle plots are $A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+)$ and bottom plots are $\Delta A_{CP}(D)$. The black solid line corresponds to a fit of a constant. For $\Delta A_{CP}(D^+)$ plots, it has a p-value of 68%, for MagDown, and 78%, for MagUp. The purple dashed line indicates the asymmetry value obtained from the full sample.

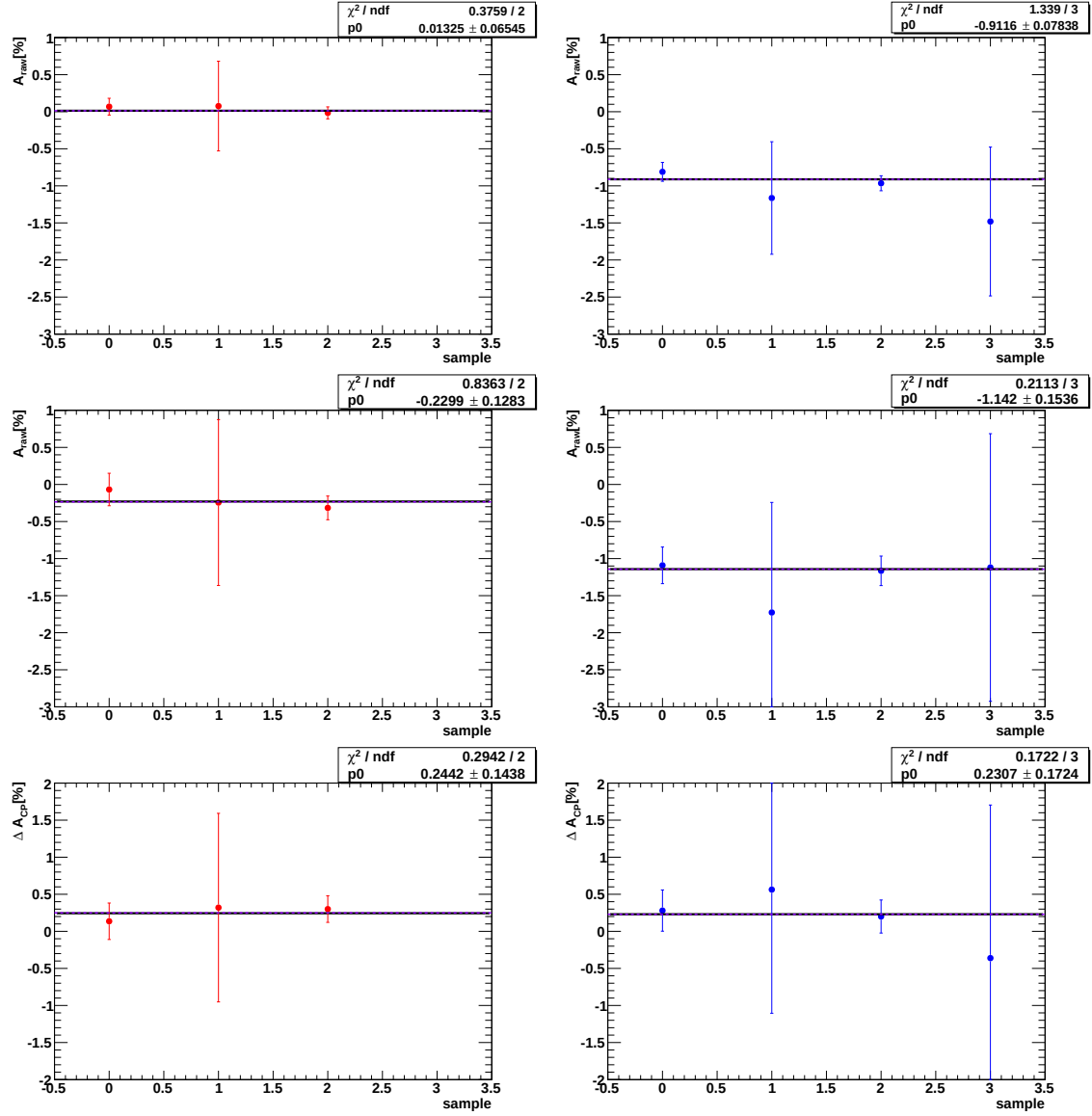


Figure C.3: Asymmetries of control channels (D_s^+) using 2011 Data, MagDown (left) and MagUp (right), for different TCKs grouped by cuts according to table 7.4. Top plots are $A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+)$, middle plots are $A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+)$ and bottom plots are $\Delta A_{CP}(D_s)$. The black solid line corresponds to a fit of a constant. For $\Delta A_{CP}(D_s^+)$ plots, it has a p-value of 86%, for MagDown, and 98%, for MagUp. The purple dashed line indicates the asymmetry value obtained from the full sample.

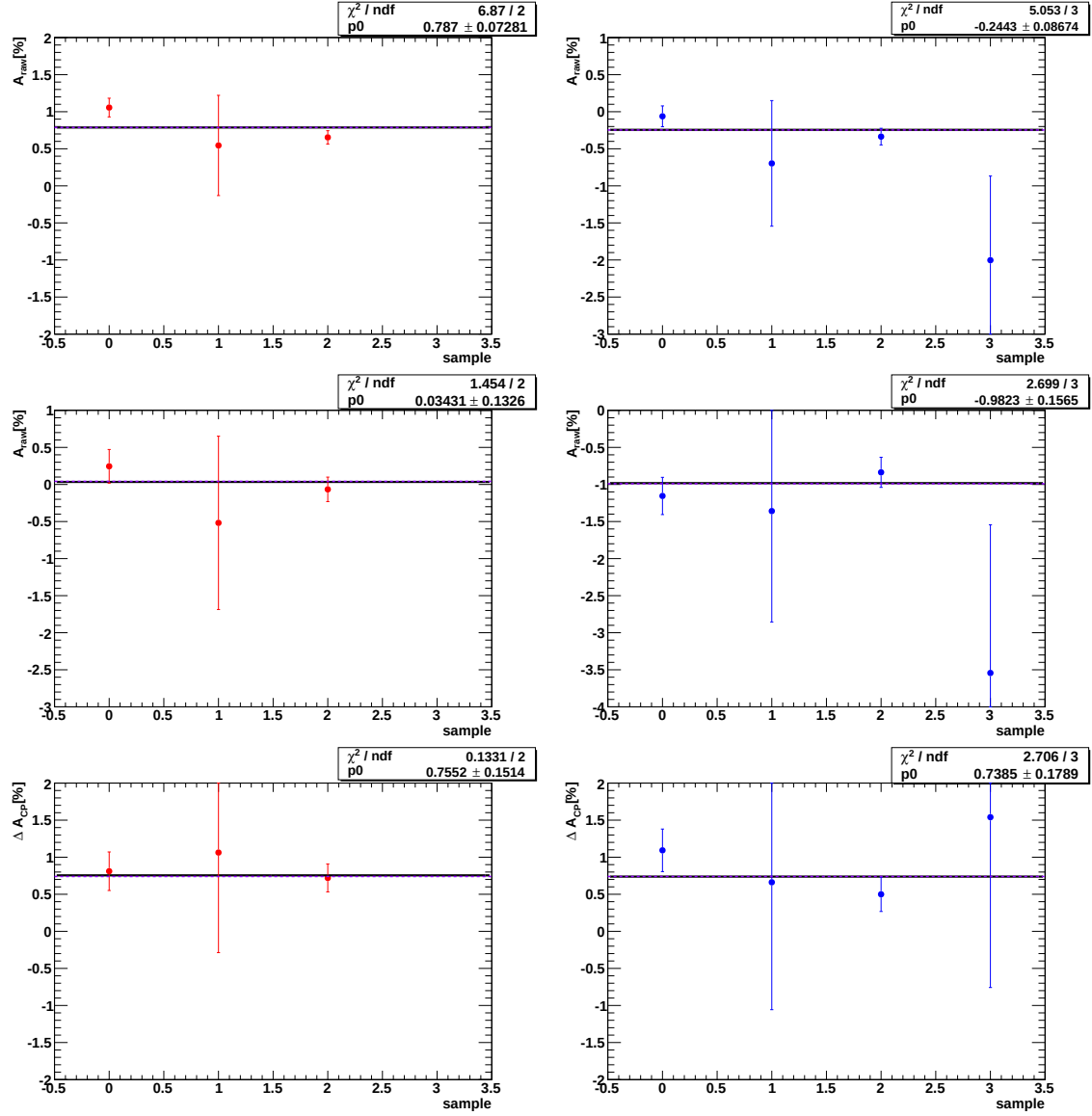


Figure C.4: Asymmetries of signal channels (D^+) using 2011 Data, MagDown (left) and MagUp (right), for different TCKs grouped by cuts according to table 7.4. Top plots are $A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+)$, middle plots are $A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+)$ and bottom plots are $\Delta A_{CP}(D)$. The black solid line corresponds to a fit of a constant. For $\Delta A_{CP}(D^+)$ plots, it has a p-value of 94%, for MagDown, and 44%, for MagUp. The purple dashed line indicates the asymmetry value obtained from the full sample.

Appendix D

Studies of the impact of the fit model on the asymmetries

The impact of fixing parameters of the PDF according to the values obtained from MC fits is shown also for the unbinned data fits and the per bin data fits, where now the bins are defined according to the kinematics of the π^+ in the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ decay. The ΔA_{CP} results are shown both for the control modes, in Tables D.1 and D.2, and for the signal samples, in Tables D.3 and D.4.

For the unbinned samples, we also show results obtained with alternative PDF for the signal and background. These numbers provide a preliminary idea of the impact of different shapes for the mass distribution description.

The different fit configurations used in the tables of this section are then:

1. CB+G for the signal shape and exponential for the background with shape parameters allowed to float;
2. CB+G for the signal shape and exponential for the background with R_σ , f_G , α and n fixed from MC;
3. CB+G for the signal shape and exponential for the background with f_G , α and n fixed from MC;
4. CB+G for the signal shape and exponential for the background with α and n fixed from MC.

5. CB+G for the signal shape and a first order polynomial for the background (all shape parameters floating)
6. Apollonios for the signal and exponential for the background (all shape parameters floating)
7. Apollonios for the signal and a first order polynomial for the background (all shape parameters floating)

Table D.1: Results of $\Delta A_{CP}(D_s^+)$ for different fit configurations (2012 and 2011 data) using the unbinned fits.

Model	MagUp	MagDown	Up+Down
2012 data			
1	$(-0.094 \pm 0.089)\%$	$(0.066 \pm 0.088)\%$	$(-0.013 \pm 0.063)\%$
2	$(-0.097 \pm 0.089)\%$	$(0.066 \pm 0.088)\%$	$(-0.015 \pm 0.063)\%$
3	$(-0.097 \pm 0.089)\%$	$(0.065 \pm 0.088)\%$	$(-0.015 \pm 0.063)\%$
4	$(-0.097 \pm 0.089)\%$	$(0.065 \pm 0.088)\%$	$(-0.015 \pm 0.063)\%$
5	$(-0.093 \pm 0.089)\%$	$(0.069 \pm 0.088)\%$	$(-0.011 \pm 0.063)\%$
6	$(-0.093 \pm 0.089)\%$	$(0.067 \pm 0.088)\%$	$(-0.012 \pm 0.063)\%$
7	$(-0.093 \pm 0.089)\%$	$(0.067 \pm 0.088)\%$	$(-0.012 \pm 0.063)\%$
2011 data			
1	$(0.23 \pm 0.17)\%$	$(0.25 \pm 0.14)\%$	$(0.24 \pm 0.11)\%$
2	$(0.23 \pm 0.17)\%$	$(0.25 \pm 0.14)\%$	$(0.24 \pm 0.11)\%$
3	$(0.23 \pm 0.17)\%$	$(0.25 \pm 0.14)\%$	$(0.24 \pm 0.11)\%$
4	$(0.23 \pm 0.17)\%$	$(0.25 \pm 0.14)\%$	$(0.24 \pm 0.11)\%$
5	$(0.21 \pm 0.17)\%$	$(0.24 \pm 0.14)\%$	$(0.23 \pm 0.11)\%$
6	$(0.23 \pm 0.17)\%$	$(0.25 \pm 0.14)\%$	$(0.24 \pm 0.11)\%$
7	$(0.23 \pm 0.17)\%$	$(0.25 \pm 0.14)\%$	$(0.24 \pm 0.11)\%$

For the unbinned fits, the shape parameters are also shown, for comparison, in Tables D.5 to D.8 (2012 data samples). Although in some cases these parameters are significantly different from the MC values, the impact on the ΔA_{CP} measurement is irrelevant.

Table D.2: Results of $\Delta A_{CP}(D_s^+)$ for different fit configurations (2012 and 2011 data) using the $D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning.

Model	MagUp	MagDown	Up+Down
2012 data			
1	$(-0.104 \pm 0.088)\%$	$(0.093 \pm 0.087)\%$	$(-0.004 \pm 0.062)\%$
2	$(-0.106 \pm 0.088)\%$	$(0.091 \pm 0.087)\%$	$(-0.006 \pm 0.062)\%$
3	$(-0.107 \pm 0.088)\%$	$(0.089 \pm 0.087)\%$	$(-0.008 \pm 0.062)\%$
4	$(-0.108 \pm 0.088)\%$	$(0.089 \pm 0.087)\%$	$(-0.008 \pm 0.062)\%$
2011 data			
1	$(0.21 \pm 0.17)\%$	$(0.25 \pm 0.14)\%$	$(0.23 \pm 0.11)\%$
2	$(0.21 \pm 0.17)\%$	$(0.25 \pm 0.14)\%$	$(0.23 \pm 0.11)\%$
3	$(0.21 \pm 0.17)\%$	$(0.25 \pm 0.14)\%$	$(0.23 \pm 0.11)\%$
4	$(0.21 \pm 0.17)\%$	$(0.25 \pm 0.14)\%$	$(0.23 \pm 0.11)\%$

Table D.3: Blind results of $\Delta A_{CP}(D^+)$ for different fit configurations (2012 and 2011 data) using the unbinned fits.

Model	MagUp	MagDown	Up+Down
2012 data			
1	$(0.232 \pm 0.093)\%$	$(0.581 \pm 0.091)\%$	$(0.409 \pm 0.065)\%$
2	$(0.237 \pm 0.093)\%$	$(0.579 \pm 0.091)\%$	$(0.411 \pm 0.065)\%$
3	$(0.235 \pm 0.093)\%$	$(0.579 \pm 0.091)\%$	$(0.410 \pm 0.065)\%$
4	$(0.235 \pm 0.093)\%$	$(0.579 \pm 0.091)\%$	$(0.410 \pm 0.065)\%$
5	$(0.233 \pm 0.093)\%$	$(0.582 \pm 0.091)\%$	$(0.410 \pm 0.065)\%$
6	$(0.232 \pm 0.093)\%$	$(0.582 \pm 0.091)\%$	$(0.410 \pm 0.065)\%$
7	$(0.240 \pm 0.093)\%$	$(0.583 \pm 0.091)\%$	$(0.414 \pm 0.065)\%$
2011 data			
1	$(0.74 \pm 0.18)\%$	$(0.74 \pm 0.15)\%$	$(0.74 \pm 0.11)\%$
2	$(0.75 \pm 0.18)\%$	$(0.74 \pm 0.15)\%$	$(0.74 \pm 0.11)\%$
3	$(0.75 \pm 0.18)\%$	$(0.74 \pm 0.15)\%$	$(0.74 \pm 0.11)\%$
4	$(0.75 \pm 0.18)\%$	$(0.74 \pm 0.15)\%$	$(0.74 \pm 0.11)\%$
5	$(0.75 \pm 0.18)\%$	$(0.75 \pm 0.15)\%$	$(0.75 \pm 0.12)\%$
6	$(0.73 \pm 0.18)\%$	$(0.75 \pm 0.15)\%$	$(0.74 \pm 0.12)\%$
7	$(0.74 \pm 0.18)\%$	$(0.75 \pm 0.15)\%$	$(0.74 \pm 0.12)\%$

Table D.4: Blind results of $\Delta A_{CP}(D^+)$ for different fit configurations (2012 and 2011 data) using the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ driven binning.

Model	MagUp	MagDown	Up+Down
2012 data			
1	$(0.214 \pm 0.091)\%$	$(0.554 \pm 0.090)\%$	$(0.387 \pm 0.064)\%$
2	$(0.216 \pm 0.091)\%$	$(0.553 \pm 0.090)\%$	$(0.387 \pm 0.064)\%$
3	$(0.215 \pm 0.091)\%$	$(0.552 \pm 0.090)\%$	$(0.386 \pm 0.064)\%$
4	$(0.214 \pm 0.091)\%$	$(0.554 \pm 0.090)\%$	$(0.386 \pm 0.064)\%$
2011 data			
1	$(0.76 \pm 0.18)\%$	$(0.75 \pm 0.15)\%$	$(0.75 \pm 0.11)\%$
2	$(0.76 \pm 0.18)\%$	$(0.74 \pm 0.15)\%$	$(0.75 \pm 0.11)\%$
3	$(0.76 \pm 0.18)\%$	$(0.74 \pm 0.15)\%$	$(0.75 \pm 0.11)\%$
4	$(0.75 \pm 0.18)\%$	$(0.74 \pm 0.15)\%$	$(0.74 \pm 0.11)\%$

Table D.5: Shape parameters for the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ fit (2012).

Mag Up Data				
Parameter	Model 1	Model 2	Model 3	Model 4
R_σ	0.6378 ± 0.0014	0.49 ± 0 (fixed)	0.5105 ± 0.0012	0.6031 ± 0.0019
f_G	0.3401 ± 0.0055	0.12 ± 0 (fixed)	0.12 ± 0 (fixed)	0.2653 ± 0.0046
α	2.741 ± 0.011	3.89 ± 0 (fixed)	3.89 ± 0 (fixed)	3.89 ± 0 (fixed)
n	0.806 ± 0.048	0 ± 0 (fixed)	0 ± 0 (fixed)	0 ± 0 (fixed)
Mag Down Data				
R_σ	0.6306 ± 0.0014	0.49 ± 0 (fixed)	0.5115 ± 0.0012	0.6011 ± 0.0019
f_G	0.3138 ± 0.0049	0.12 ± 0 (fixed)	0.12 ± 0 (fixed)	0.2549 ± 0.0043
α	2.8547 ± 0.0095	3.89 ± 0 (fixed)	3.89 ± 0 (fixed)	3.89 ± 0 (fixed)
n	0.564 ± 0.036	0 ± 0 (fixed)	0 ± 0 (fixed)	0 ± 0 (fixed)

Table D.6: Shape parameters for the $D_{(s)}^+ \rightarrow \pi^- \pi^+ \pi^+$ fit (2012).

Mag Up Data				
Parameter	Model 1	Model 2	Model 3	Model 4
R_σ	0.6743 ± 0.0057	0.535 ± 0 (fixed)	0.5486 ± 0.0043	0.6253 ± 0.0047
f_G	0.3026 ± 0.016	0.2 ± 0 (fixed)	0.2 ± 0 (fixed)	0.345 ± 0.010
α	1.6839 ± 0.0068	3.52 ± 0 (fixed)	3.52 ± 0 (fixed)	3.52 ± 0 (fixed)
n	12.36 ± 0.52	0 ± 0 (fixed)	0 ± 0 (fixed)	0 ± 0 (fixed)
Mag Down Data				
R_σ	0.683 ± 0.010	0.535 ± 0 (fixed)	0.54662 ± 0.00072	0.6369 ± 0.0037
f_G	0.370 ± 0.042	0.2 ± 0 (fixed)	0.2 ± 0 (fixed)	0.410 ± 0.010
α	1.631 ± 0.026	3.52 ± 0 (fixed)	3.52 ± 0 (fixed)	3.52 ± 0 (fixed)
n	17.2 ± 2.4	0 ± 0 (fixed)	0 ± 0 (fixed)	0 ± 0 (fixed)

Table D.7: Shape parameters for the $D^+ \rightarrow K^- K^+ \pi^+$ fit (2012).

Mag Up Data				
Parameter	Model 1	Model 2	Model 3	Model 4
R_σ	0.6239 ± 0.0013	0.484 ± 0 (fixed)	0.5093 ± 0.00044	0.6083 ± 0.0016
f_G	0.3422 ± 0.0047	0.119 ± 0 (fixed)	0.119 ± 0 (fixed)	0.3049 ± 0.0049
α	2.991 ± 0.011	3.9 ± 0 (fixed)	3.9 ± 0 (fixed)	3.9 ± 0 (fixed)
n	0.496 ± 0.030	0 ± 0 (fixed)	0 ± 0 (fixed)	0 ± 0 (fixed)
Mag Down Data				
R_σ	0.6275 ± 0.0013	0.484 ± 0 (fixed)	0.5088 ± 0.0013	0.6083 ± 0.0015
f_G	0.3580 ± 0.0056	0.119 ± 0 (fixed)	0.119 ± 0 (fixed)	0.3106 ± 0.0048
α	2.887 ± 0.012	3.9 ± 0 (fixed)	3.9 ± 0 (fixed)	3.9 ± 0 (fixed)
n	0.641 ± 0.060	0 ± 0 (fixed)	0 ± 0 (fixed)	0 ± 0 (fixed)

Table D.8: Shape parameters for the $D^+ \rightarrow \pi^- \pi^+ \pi^+$ fit (2012).

Mag Up Data				
Parameter	Model 1	Model 2	Model 3	Model 4
R_σ	0.7105 ± 0.0045	0.542 ± 0 (fixed)	0.5387 ± 0.0054	0.6451 ± 0.0037
f_G	0.537 ± 0.034	0.18 ± 0 (fixed)	0.18 ± 0 (fixed)	0.436 ± 0.013
α	1.705 ± 0.026	3.27 ± 0 (fixed)	3.27 ± 0 (fixed)	3.27 ± 0 (fixed)
n	2.12 ± 0.54	0.22 ± 0 (fixed)	0.22 ± 0 (fixed)	0.22 ± 0 (fixed)
Mag Down Data				
R_σ	0.7101 ± 0.0044	0.542 ± 0 (fixed)	0.5444 ± 0.0047	0.6521 ± 0.0034
f_G	0.605 ± 0.014	0.18 ± 0 (fixed)	0.18 ± 0 (fixed)	0.465 ± 0.015
α	1.652 ± 0.016	3.27 ± 0 (fixed)	3.27 ± 0 (fixed)	3.27 ± 0 (fixed)
n	1.84 ± 0.17	0.22 ± 0 (fixed)	0.22 ± 0 (fixed)	0.22 ± 0 (fixed)

Appendix E

Further studies related to fiducial cut

A fiducial cut was defined according to the distribution of the raw asymmetry in the $p_z \times p_x$ plane for $D_s^+ \rightarrow K^- K^+ \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$, as described in Section 4.2.3, to eliminate the regions with high asymmetry. The cut is given by $(p_z > 3.3 * |p_x| + 2500)$ and is applied to all daughters. We want to study how the ΔA_{CP} changes when these fiducial cuts are applied, also considering what happens when the cut is applied only to the bachelor pion (π^+) or to the opposite charged daughters ($K^- K^+$, $\pi^- \pi^+$).

Using the 2012 data split by magnet polarity, we extract the raw asymmetries and ΔA_{CP} for control and signal modes considering four configurations:

- fiducial cut $(p_z > 3.3 * |p_x| + 2500)$ applied to the bachelor pion π^+ (p3);
- fiducial cut $(p_z > 3.3 * |p_x| + 2500)$ applied to the opposite charged daughters $K^- K^+$, $\pi^- \pi^+$ (p1 & p2);
- fiducial cut $(p_z > 3.3 * |p_x| + 2500)$ applied to all daughters (p1 & p2 & p3);
- fiducial cut $(p_z > 3.3 * |p_x| + 2500)$ not applied (no fiducial).

The asymmetries with respect to the fiducial cuts are shown in Figures E.1 and E.2, for control and signal modes, respectively. The values are listed in Tables E.1 and E.2. The results of the four configurations are compatible.

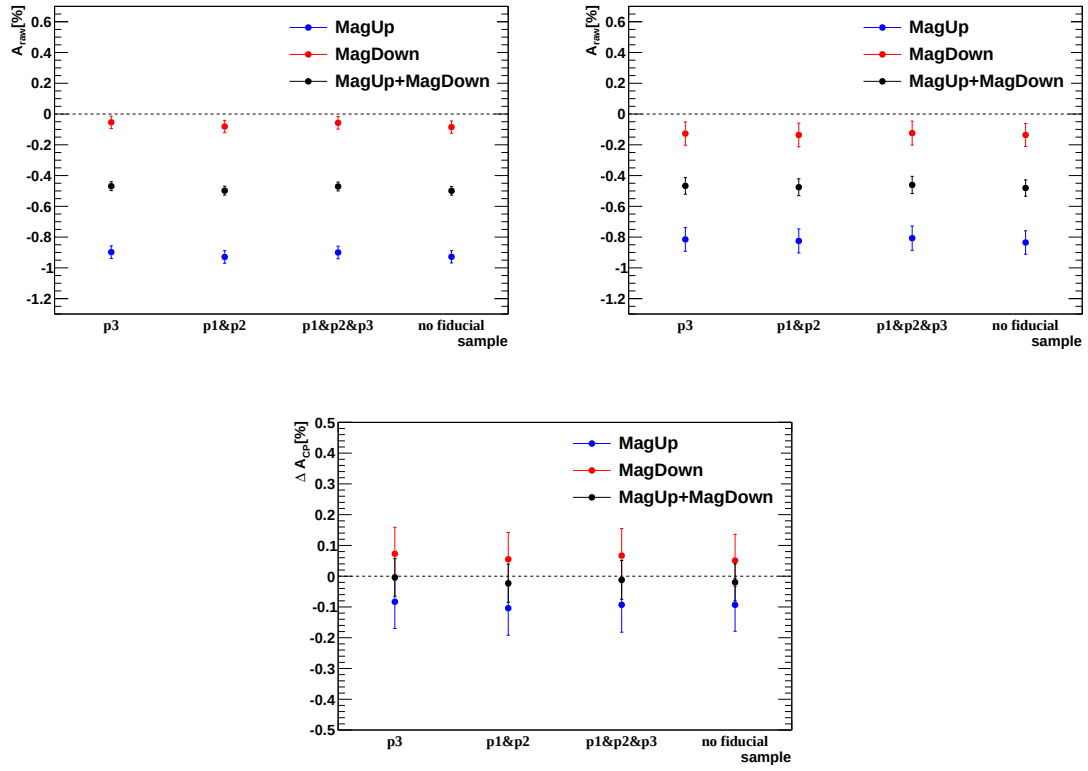


Figure E.1: Asymmetries of control channels with respect to the fiducial cut using 2012 data. Top-left plot is $A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+)$, top-right plot is $A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+)$ and bottom plot is $\Delta A_{CP}(D_s^+)$.

Table E.1: Asymmetry values of control channels with respect to the fiducial cut using 2012 data.

Sample	MagUp	MagDown	Up+Down
$A_{\text{raw}}(D_s^+ \rightarrow K^- K^+ \pi^+)$			
fiducial in p3	$(-0.898 \pm 0.041)\%$	$(-0.054 \pm 0.040)\%$	$(-0.469 \pm 0.029)\%$
fiducial in p1 & p2	$(-0.929 \pm 0.041)\%$	$(-0.081 \pm 0.040)\%$	$(-0.498 \pm 0.029)\%$
fiducial in all daughters	$(-0.900 \pm 0.041)\%$	$(-0.057 \pm 0.041)\%$	$(-0.471 \pm 0.029)\%$
no fiducial	$(-0.928 \pm 0.040)\%$	$(-0.085 \pm 0.040)\%$	$(-0.499 \pm 0.028)\%$
$A_{\text{raw}}(D_s^+ \rightarrow \pi^- \pi^+ \pi^+)$			
fiducial in p3	$(-0.815 \pm 0.077)\%$	$(-0.127 \pm 0.076)\%$	$(-0.467 \pm 0.054)\%$
fiducial in p1 & p2	$(-0.825 \pm 0.078)\%$	$(-0.136 \pm 0.077)\%$	$(-0.476 \pm 0.055)\%$
fiducial in all daughters	$(-0.807 \pm 0.079)\%$	$(-0.124 \pm 0.078)\%$	$(-0.461 \pm 0.056)\%$
no fiducial	$(-0.835 \pm 0.076)\%$	$(-0.136 \pm 0.075)\%$	$(-0.481 \pm 0.053)\%$
$\Delta A_{CP}(D_s^+)$			
fiducial in p3	$(-0.083 \pm 0.087)\%$	$(0.073 \pm 0.086)\%$	$(-0.004 \pm 0.061)\%$
fiducial in p1 & p2	$(-0.104 \pm 0.088)\%$	$(0.055 \pm 0.087)\%$	$(-0.023 \pm 0.062)\%$
fiducial in all daughters	$(-0.093 \pm 0.089)\%$	$(0.067 \pm 0.088)\%$	$(-0.012 \pm 0.063)\%$
no fiducial	$(-0.093 \pm 0.086)\%$	$(0.051 \pm 0.085)\%$	$(-0.020 \pm 0.060)\%$

Table E.2: Blind asymmetry values of signal channels with respect to the fiducial cut using 2012 data.

Sample	MagUp	MagDown	Up+Down
$A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+)$			
fiducial in p3	$(-0.176 \pm 0.045)\%$	$(0.647 \pm 0.044)\%$	$(0.242 \pm 0.031)\%$
fiducial in p1 & p2	$(-0.224 \pm 0.045)\%$	$(0.631 \pm 0.044)\%$	$(0.211 \pm 0.031)\%$
fiducial in all daughters	$(-0.186 \pm 0.045)\%$	$(0.643 \pm 0.044)\%$	$(0.235 \pm 0.032)\%$
no fiducial	$(-0.213 \pm 0.044)\%$	$(0.627 \pm 0.043)\%$	$(0.214 \pm 0.031)\%$
$A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+)$			
fiducial in p3	$(-0.423 \pm 0.078)\%$	$(0.068 \pm 0.077)\%$	$(-0.174 \pm 0.055)\%$
fiducial in p1 & p2	$(-0.443 \pm 0.080)\%$	$(0.057 \pm 0.079)\%$	$(-0.190 \pm 0.056)\%$
fiducial in all daughters	$(-0.418 \pm 0.081)\%$	$(0.062 \pm 0.080)\%$	$(-0.175 \pm 0.057)\%$
no fiducial	$(-0.450 \pm 0.077)\%$	$(0.064 \pm 0.076)\%$	$(-0.190 \pm 0.054)\%$
$\Delta A_{CP}(D^+)$			
fiducial in p3	$(0.247 \pm 0.090)\%$	$(0.579 \pm 0.089)\%$	$(0.416 \pm 0.063)\%$
fiducial in p1 & p2	$(0.219 \pm 0.092)\%$	$(0.574 \pm 0.090)\%$	$(0.399 \pm 0.064)\%$
fiducial in all daughters	$(0.232 \pm 0.093)\%$	$(0.581 \pm 0.091)\%$	$(0.409 \pm 0.065)\%$
no fiducial	$(0.237 \pm 0.089)\%$	$(0.563 \pm 0.087)\%$	$(0.403 \pm 0.062)\%$

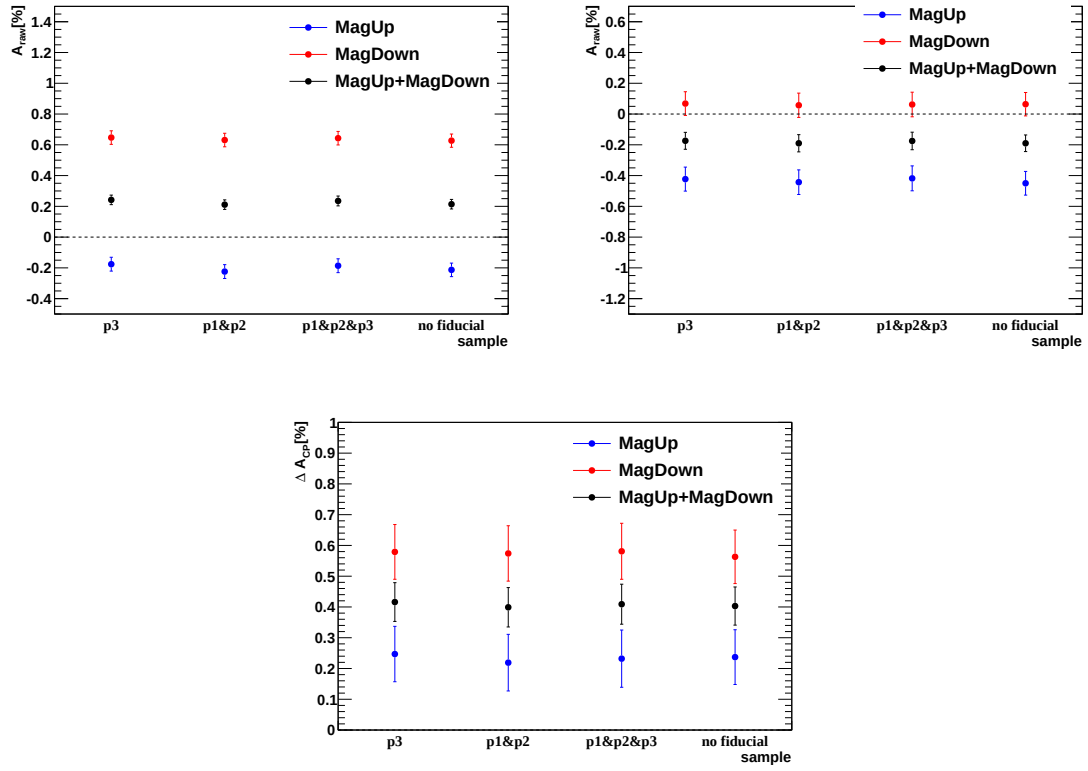


Figure E.2: Blind asymmetries of signal channels with respect to the fiducial cut using 2012 data. Top-left plot is $A_{\text{raw}}(D^+ \rightarrow K^- K^+ \pi^+)$, top-right plot is $A_{\text{raw}}(D^+ \rightarrow \pi^- \pi^+ \pi^+)$ and bottom plot is $\Delta A_{CP}(D^+)$.