Study of a new kinematic weighting algorithm for the measurement of CP asymmetries in charm decays

LHCb Collaboration

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August 2023

Abstract

We investigate the asymmetries that occur in charm decays at the LHCb, specifically we study $D^{\star +} \to D^0\pi^+$ and $D^{\star -} \to \bar{D}^0\pi^-$ where $D^0 \to K^-K^+$ or $D^0 \to \pi^-\pi^+$. We study the effect of CP and detection asymmetries on MC samples generated via RapidSim and Particle Gun and implement a new kinematic weighting function which allows us to keep events that are otherwise discarded from LHCb data, since they are associated with large detection asymmetries.

*Source code available at: `https://github.com/GiorgosChr/CERN_Summer_Student_Programme_2023`

1 Introduction

We investigate charm decays and specifically the $D^\star$ meson. By studying the differences between $D^{\star+}$ and $D^{\star-}$ decays we can estimate the CP asymmetry. Specifically, we are interested in

$$\begin{gathered} D^{\star+} \to D^0\pi^+ \text{ and } D^{\star-} \to \bar{D}^0\pi^-, \\ D^0 \to K^-K^+ \text{ and } D^0 \to \pi^-\pi^+ \end{gathered} \tag{1}$$

decay modes where we refer to the $\pi^\pm$ as *soft pion*.

The total asymmetry one observes at an experiment is a combination of multiple asymmetries. Namely, the total asymmetry consists of a *production*, a *CP* and a *detection* asymmetry, however, throughout this project we are not interested in production asymmetries. The CP asymmetry is associated with the decay differences of matter and anti-matter, while the detection asymmetry is associated with the differences in detecting the positive and negative soft pions ($\pi_s^\pm$).

We can calculate the *total asymmetry* by

$$A_{\text{total}} = \frac{A_{CP} + A_D}{1 + A_{CP}A_D}, \tag{2}$$

where A_{CP} and A_D are the CP and *integrated detection* asymmetries respectively. The latter is calculated using

$$A_D = \frac{\int \mathrm{d}\vec{p} N(\vec{p}) A_D(\vec{p})}{\int \mathrm{d}\vec{p} N(\vec{p})} \tag{3}$$

where $N(\vec{p})$ and $A_D(\vec{p})$ are the momentum-dependent number of events and detection asymmetry respectively. We can however, approximate the total asymmetry up to $\mathcal{O}(10^{-6})$ if A_{CP} is up to $\mathcal{O}(10^{-3})$ and A_D up to $\mathcal{O}(10^{-2})$ as

$$A_{\text{total}} = A_{CP} + A_D \tag{4}$$

The observable we can calculate from an experiment is the *total asymmetry difference* between the two modes which approximately gives us

$$\begin{aligned} \Delta A_{\text{total}} &= A^{KK}_{\text{total}} - A^{\pi\pi}_{\text{total}} \\ &= \Delta A_{CP} - \Delta A_D, \end{aligned} \tag{5}$$

however, we are interested in ΔA_{CP}, thus, we require a method to eliminate ΔA_D.

At the LHCb one observes large pion detection asymmetries that are associated with specific kinematic regions, which so far have been discarded, thus reducing the statistics. We can, however, introduce a *weighting function* based on D^0 kinematics

$$Q(\vec{p}_{D^\star}, \vec{p}_{\pi_s}) \simeq \frac{\Gamma^{\pi\pi}_{D^0}(\vec{p}_{D^\star} - \vec{p}_{\pi_s}) + \Gamma^{\pi\pi}_{\bar{D}^0}(\vec{p}_{D^\star} - \vec{p}_{\pi_s})}{\Gamma^{KK}_{D^0}(\vec{p}_{D^\star} - \vec{p}_{\pi_s}) + \Gamma^{KK}_{\bar{D}^0}(\vec{p}_{D^\star} - \vec{p}_{\pi_s})} \tag{6}$$

where $\Gamma^{\pi\pi/KK}_{D^0/\bar{D}^0}$ are the normalized distributions of D^0 candidates. Here, the D^0 candidates are reconstructed using the $D^\star$ and π_s, however, this weighting function does not allow for events associated with large detection asymmetries to be included to the analysis since it is biased. A new weighting function which is much more effective comes from reconstructing D^0 candidates without associating them with π_s, thus, the weighting is not affected by the detection asymmetry that occurs from the soft pions. This weighting function reads

$$Q(\vec{p}_{D^0}) \simeq \frac{\Gamma^{\pi\pi}_{D^0}(\vec{p}_{D^0}) + \Gamma^{\pi\pi}_{\bar{D}^0}(\vec{p}_{D^0})}{\Gamma^{KK}_{D^0}(\vec{p}_{D^0}) + \Gamma^{KK}_{\bar{D}^0}(\vec{p}_{D^0})} \tag{7}$$

Unfortunately in Run-2 such candidates were discarded, thus, we do not have a large enough sample to accurately calculate the weighting function and we resort to Monte Carlo simulations.

Both of these weighting functions equalize the kinematic distributions of $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ samples such that ΔA_D reduces to zero. As a result the physical observable ΔA_{total} should give us ΔA_{CP}.

The goal of this project is to introduce CP and large detection asymmetries to MC data generated with RapidSim and test the weighting procedures we previously discussed. Subsequently, we test the weighting functions using Particle Gun data which is a more realistic scenario.

2 Analysis

2.1 RapidSim

For the analysis we make use of the RapidSim simulation [1] to generate $D^{\star\pm} \to D^0\pi^\pm$ events where D^0 subsequently decays into K^-K^+ or $\pi^-\pi^+$. We present the RapidSim parameters in Tab. 1

	Parameter	Value
Center of mass energy	`energy`	`13`
Detector geometry	`geometry`	`LHCb`
Acceptance region	`acceptance`	`AllIn`
Smearing on produced particles	`smear`	`LHCbGeneric`

Table 1: RapidSim parameters used to generate our data.

2.2 Calculation of the Q function

As previously discussed, the new weighting technique allows us to keep events from LHCb with large detection asymmetries in order to have more accurate results. Thus, the calculation of the weighting function needs to be done correctly and with enough precision.

We generate separate samples for calculating the weighting function Q and analyzing our data. Both samples start with 10 million events, to have high enough statistics and then events are discarded due to the selections we applied in Tab. 1, thus we are left with 4.8 and 4.2 million events for the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ samples respectively. We then introduce $A^{KK}_{CP} = 0.1$ and $A^{\pi\pi}_{CP} = 0.2$ and a large detection asymmetry as shown in Fig. 1. Subsequently, we calculate the weighting function using both techniques.

We present in Fig. 2 the distribution of the weighting function values using the two techniques we discussed. As we can see the two weighting methods have subtle differences. Lastly, we present the D^0 kinematic distributions with and without weighting in Fig. 3.

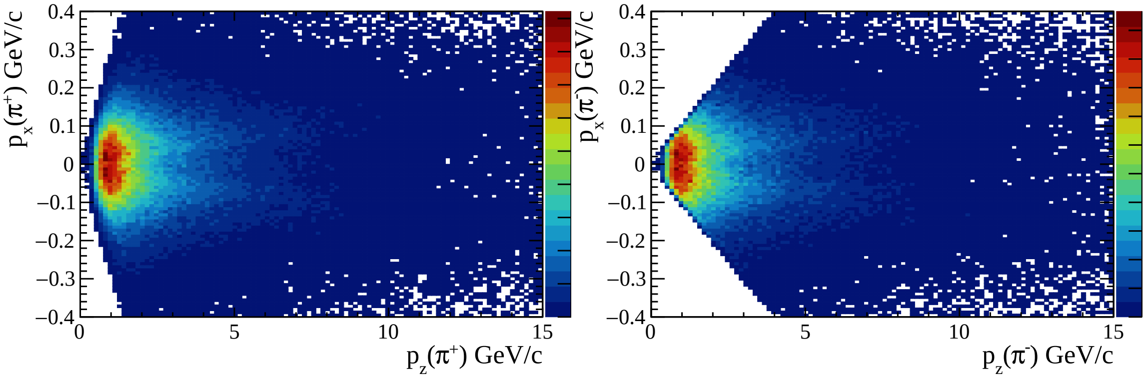

Figure 1: Positive and negative soft pion $p_x - p_z$ momentum plane for the $D^0 \to K^- K^+$ sample. We remove negative soft pions from kinematic regions associated with $A_D(\vec{p}) = 1$.

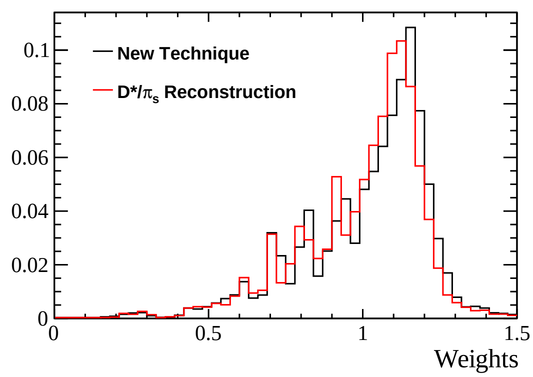

Figure 2: Distribution of weighting function values. The black histogram represents the new technique while the red histogram represents the old weighting function where D^0 candidates were associated with soft pion.

2.3 Asymmetry calculation

Using the weighting function we can calculate the total asymmetry for $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ samples and compare to the unweighted result. The total asymmetry can be calculated through

$$A_{\text{total}} = \frac{N_+ - N_-}{N_+ + N_-} \tag{8}$$

where for the case of unweighted samples, the number of positive and negative soft pion events are N_+ and N_- respectively, and the uncertainties are given by $\sigma(N_\pm) = \sqrt{N_\pm}$. On the contrary, for

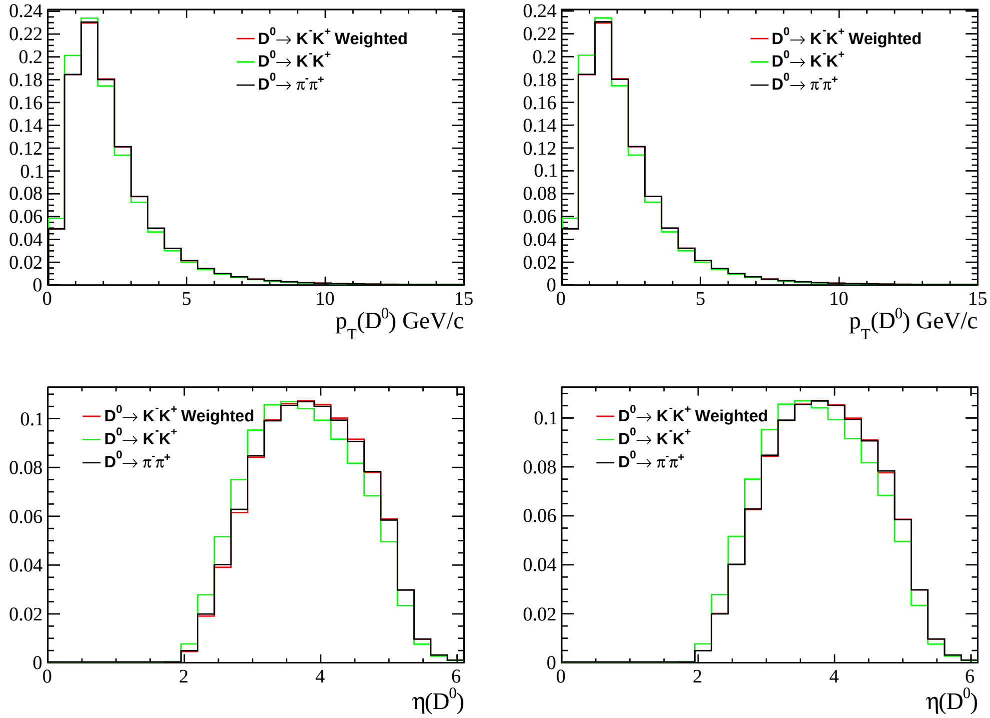

Figure 3: Comparison of D^0 kinematics with and without weighting. On the left column we present the new weighting technique and on the right the baseline technique.

weighted samples, we have

$$N_{\pm} = \sum_i w_i^{\pm}, \text{ and } \sigma\left(N_{\pm}\right) = \sqrt{\sum_i (w_i^{\pm})^2} \tag{9}$$

and using propagation of uncertainties we can calculate the total asymmetry error

$$\sigma\left(A_{\text{total}}\right)^2 = \left(\frac{\partial A_{\text{total}}}{\partial N^+}\sigma\left(N^+\right)\right)^2 + \left(\frac{\partial A_{\text{total}}}{\partial N^-}\sigma\left(N^-\right)\right)^2 \tag{10}$$

We present the calculated asymmetries for the $D^0 \to K^-K^+$ sample in Tab. 2

Technique	Weighted	Unweighted
Not associated	$A_{\text{total}} = 0.14726 \pm 0.00050$	$A_{\text{total}} = 0.16268 \pm 0.00049$
Associated with π_s	$A_{\text{total}} = 0.14994 \pm 0.00050$	

Table 2: A_{total} for the $D^0 \to K^-K^+$ sample with and without weighting.

and for the $D^0 \to \pi^-\pi^+$ sample we get

$$A_{\text{total}} = 0.24571 \pm 0.00053 \tag{11}$$

If the effect of the detection asymmetry is properly canceled, then the estimated total asymmetry difference should be $\Delta A_{\text{total}} = \Delta A_{CP} = -0.1$, according to the CP asymmetries we introduced. We present the results of the total asymmetry difference in Tab. 3 as well as the deviation from the expected value. Both weighting techniques appear to correct the measurement of ΔA_{total}, however, there is much improvement between the previous weighting function and the new one.

Technique		Weighted	Unweighted
Not associated	ΔA_{total}	-0.09845 ± 0.00073	-0.08303 ± 0.00072
	Deviation (σ)	2.12	23.6
Associated with π_s	ΔA_{total}	-0.09578 ± 0.00073	
	Deviation (σ)	5.78	

Table 3: Total asymmetry difference with and without weights. We present both weighting procedures, before and after the detection asymmetry.

2.4 Particle Gun analysis

The final test of the weighting function in Eq. 7 is the implementation on samples generated with Particle Gun. In these samples there is no CP asymmetry, however the simulation includes a detection asymmetry for soft pions as shown in Fig. 4.

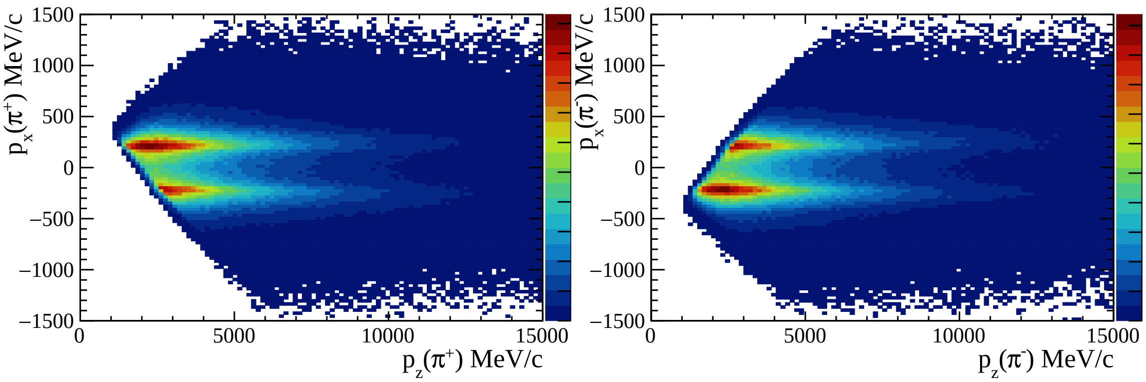

Figure 4: We present the positive (left) and negative (right) soft pion $p_x - p_z$ momentum planes for the 2018 $D^0 \to K^-K^+$ with up magnet polarity sample generated using Particle Gun.

We test the new weighting technique on Particle Gun data with different magnet polarities. We present the A_{total} results for the $D^0 \to \pi^-\pi^+$ samples in Tab. 4 and for $D^0 \to K^-K^+$ in Tab. 5, 6, 7 and 8.

Year	Polarity	A_{total}
2015	Down	0.00284 ± 0.00048
	Up	-0.00033 ± 0.00048
2016	Down	0.00296 ± 0.00049
	Up	-0.00130 ± 0.00048
2017	Down	0.00349 ± 0.00053
	Up	-0.00091 ± 0.00052
2018	Down	0.00260 ± 0.00053
	Up	-0.00024 ± 0.00052

Table 4: Total asymmetry of 2015-2018 $D^0 \to \pi^-\pi^+$ samples with both magnet polarities.

Polarity	Technique	Weighted	Unweighted
Down	Not associated	$A_{\text{total}} = 0.00300 \pm 0.00053$	$A_{\text{total}} = 0.00272 \pm 0.00053$
	Associated with π_s	$A_{\text{total}} = 0.00306 \pm 0.00053$	
Up	Not associated	$A_{\text{total}} = -0.00063 \pm 0.00053$	$A_{\text{total}} = -0.00018 \pm 0.00052$
	Associated with π_s	$A_{\text{total}} = -0.00031 \pm 0.00053$	

Table 5: We present the A_{total} for the $D^0 \to K^-K^+$ Particle Gun 2015 sample weighted using the two techniques and unweighted for both polarities.

Polarity	Technique	Weighted	Unweighted
Down	Not associated	$A_{\text{total}} = 0.00359 \pm 0.00052$	$A_{\text{total}} = 0.00331 \pm 0.00052$
	Associated with π_s	$A_{\text{total}} = 0.00339 \pm 0.00052$	
Up	Not associated	$A_{\text{total}} = -0.00122 \pm 0.00053$	$A_{\text{total}} = -0.00082 \pm 0.00053$
	Associated with π_s	$A_{\text{total}} = -0.00105 \pm 0.00053$	

Table 6: We present the A_{total} for the $D^0 \to K^-K^+$ Particle Gun 2016 sample weighted using the two techniques and unweighted for both polarities.

Polarity	Technique	Weighted	Unweighted
Down	Not associated	$A_{\text{total}} = 0.00208 \pm 0.00056$	$A_{\text{total}} = 0.00191 \pm 0.00056$
	Associated with π_s	$A_{\text{total}} = 0.00186 \pm 0.00056$	
Up	Not associated	$A_{\text{total}} = -0.00095 \pm 0.00056$	$A_{\text{total}} = -0.00059 \pm 0.00056$
	Associated with π_s	$A_{\text{total}} = -0.00109 \pm 0.00056$	

Table 7: We present the A_{total} for the $D^0 \to K^-K^+$ Particle Gun 2017 sample weighted using the two techniques and unweighted for both polarities.

Polarity	Technique	Weighted	Unweighted
Down	Not associated	$A_{\text{total}} = 0.00265 \pm 0.00056$	$A_{\text{total}} = 0.00246 \pm 0.00056$
	Associated with π_s	$A_{\text{total}} = 0.00281 \pm 0.00056$	
Up	Not associated	$A_{\text{total}} = -0.00023 \pm 0.00056$	$A_{\text{total}} = 0.00002 \pm 0.00056$
	Associated with π_s	$A_{\text{total}} = -0.00002 \pm 0.00056$	

Table 8: We present the A_{total} for the $D^0 \to K^-K^+$ Particle Gun 2018 sample weighted using the two techniques and unweighted for both polarities.

We calculate ΔA_{total} for all samples and subsequently perform a weighted average to obtain our final results. We present the average of all samples in Tab. 10. As we can see, the weighting function where D^0 is associated with π_s introduced bias to our final results. Moreover, we observe that in this instance, the new weighting technique does not improve the ΔA_{total} average value.

Year	Polarity	Technique		Weighted	Unweighted
2015	Down	Not associated	ΔA_{total}	0.00016 ± 0.00072	-0.00012 ± 0.00072
			Deviation (σ)	0.22	-0.17
		Associated with π_s	ΔA_{total}	0.00022 ± 0.00072	
			Deviation (σ)	0.31	
	Up	Not associated	ΔA_{total}	-0.00030 ± 0.00072	0.00015 ± 0.00072
			Deviation (σ)	-0.30	0.15
		Associated with π_s	ΔA_{total}	0.00002 ± 0.00072	
			Deviation (σ)	0.02	
2016	Down	Not associated	ΔA_{total}	0.00063 ± 0.00071	0.00035 ± 0.00071
			Deviation (σ)	0.89	0.49
		Associated with π_s	ΔA_{total}	0.00043 ± 0.00071	
			Deviation (σ)	0.61	
	Up	Not associated	ΔA_{total}	0.00008 ± 0.00072	0.00048 ± 0.00072
			Deviation (σ)	0.11	0.67
		Associated with π_s	ΔA_{total}	0.00025 ± 0.00072	
			Deviation (σ)	0.35	
2017	Down	Not associated	ΔA_{total}	-0.00141 ± 0.00077	-0.00158 ± 0.00077
			Deviation (σ)	1.83	-2.05
		Associated with π_s	ΔA_{total}	-0.00163 ± 0.00077	
			Deviation (σ)	-2.12	
	Up	Not associated	ΔA_{total}	-0.00004 ± 0.00076	0.00032 ± 0.00076
			Deviation (σ)	0.05	0.42
		Associated with π_s	ΔA_{total}	-0.00018 ± 0.00076	
			Deviation (σ)	0.24	
2018	Down	Not associated	ΔA_{total}	0.00004 ± 0.00077	-0.00014 ± 0.00077
			Deviation (σ)	0.05	0.18
		Associated with π_s	ΔA_{total}	0.00021 ± 0.00077	
			Deviation (σ)	0.27	
	Up	Not associated	ΔA_{total}	0.00001 ± 0.00076	0.00026 ± 0.00076
			Deviation (σ)	0.01	0.34
		Associated with π_s	ΔA_{total}	0.00022 ± 0.00076	
			Deviation (σ)	0.29	

Table 9: We present the values of ΔA_{total} for all samples.

3 Conclusions

As demonstrated the weighting function allows us to keep events with kinematics associated with large detection asymmetries without affecting our results.

Year	Polarity	Technique		Weighted	Unweighted
Average	Both	Not associated	ΔA_{total}	-0.000084 ± 0.000262	-0.000015 ± 0.000262
			Deviation (σ)	0.32	0.057
		Associated with π_s	ΔA_{total}	-0.000036 ± 0.000262	
			Deviation (σ)	0.14	

Table 10: We present the weighted average value of ΔA_{CP} for all samples.

From the analysis of the RapidSim data we observe a reduction in the deviation of ΔA_{total} when applying the old weighting function (association with π_s), however, by employing the new weighting technique the deviation reduces by more than a factor of 10. Thus, from this data sample we conclude that the new weighting technique (not associated with π_s) is much more effective.

Furthermore, we employed the weighting functions to Particle Gun data in order to study a more realistic scenario. For these specific datasets we noticed that both weighting functions do not improve the ΔA_{total} result after averaging all samples and all magnet polarities.

In conclusion, the weighting function we examined needs to be studied further before being employed on real Run-3 data. For the RapidSim case we noticed an improvement of the ΔA_{total} result, but not for the Particle Gun case with the current statistics.

References

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