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

LHCb Collaboration

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Abstract

We investigate the asymmetries that occur in charm decays at the LHCb, specifically we study $D^{\star+} \to D^0\pi^+$ and $\bar{D}^{\star-} \to D^0\pi^-$ 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 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

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

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. 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.

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

$$\begin{aligned} \Delta A_{\text{total}} &= A_{\text{total}}^{KK} - A_{\text{total}}^{\pi\pi} \\ &= \Delta A_{CP} - \Delta A_D, \end{aligned} \tag{4}$$

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* that allows us to keep events in these kinematic regions. Such a weighting function can be expressed as the following ratio

$$Q(\vec{p}_{D^\star}, \vec{p}_{\pi_s}) \simeq \frac{\Gamma_{D^0}^{\pi\pi}(\vec{p}_{D^\star} - \vec{p}_{\pi_s}) + \Gamma_{\bar{D}^0}^{\pi\pi}(\vec{p}_{D^\star} - \vec{p}_{\pi_s})}{\Gamma_{D^0}^{KK}(\vec{p}_{D^\star} - \vec{p}_{\pi_s}) + \Gamma_{\bar{D}^0}^{KK}(\vec{p}_{D^\star} - \vec{p}_{\pi_s})} \tag{5}$$

where $\Gamma_{D^0/\bar{D}^0}^{\pi\pi/KK}$ are the normalized distributions of D^0 candidates. Here, the D^0 candidates are reconstructed using the $D^\star$ and π_s, however, the new weighting function which is much more effective comes from reconstructing D^0 candidates from K^-K^+ or $\pi^-\pi^+$. This weighting function reads

$$Q(\vec{p}_{D^0}) \simeq \frac{\Gamma_{D^0}^{\pi\pi}(\vec{p}_{D^0}) + \Gamma_{\bar{D}^0}^{\pi\pi}(\vec{p}_{D^0})}{\Gamma_{D^0}^{KK}(\vec{p}_{D^0}) + \Gamma_{\bar{D}^0}^{KK}(\vec{p}_{D^0})} \tag{6}$$

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 weighting function 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 $A_{CP}^{KK} = 0.1$ and $A_{CP}^{\pi\pi} = 0.2$ and a large detection asymmetry as shown in Fig. 1 to emulate the asymmetries that are observed at LHCb. Subsequently, we calculate the weighting function using both methods, once with D^0 candidates reconstructed using $D^\star$ and π_s and once reconstructed with K^-K^+ or $\pi^-\pi^+$.

We present the distribution of the weighting function values using the two techniques we discussed in Fig. 2. 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.

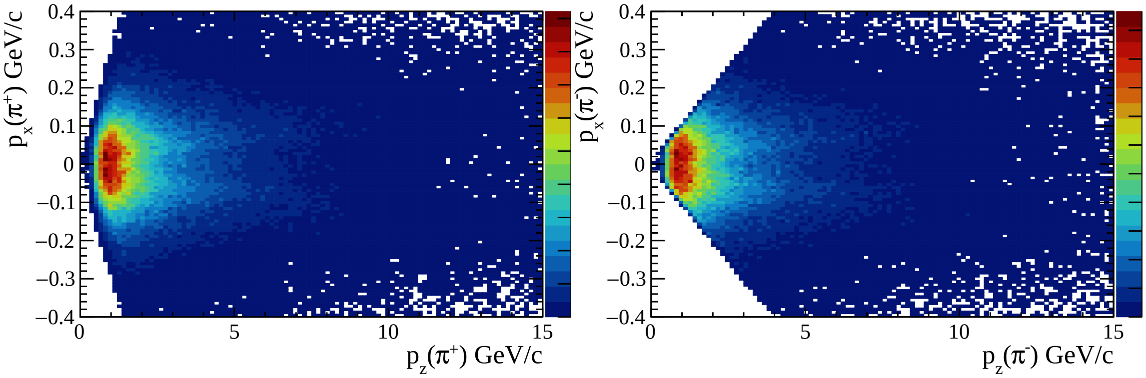

Figure 1: Positive and negative soft pion $p_x - p_z$ momentum plane for the $D^0 \to k^- K^+$ sample. We remove negative soft pions from kinematic regions associated with $A_D(\vec{p}) = 1$.

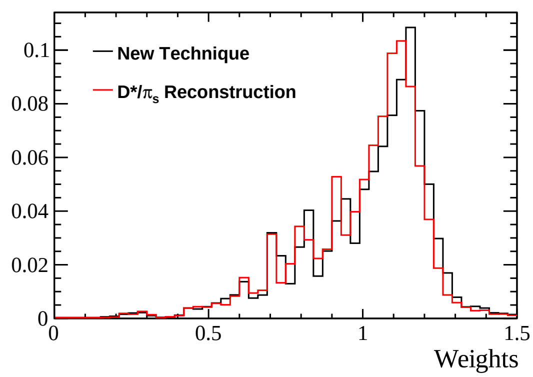

Figure 2: Distribution of weighting function values. The black histogram represents the new technique where we reconstruct D^0 candidates from either $K^- K^+$ or $\pi^- \pi^+$ while the red histogram represents the old weighting function where D^0 candidates were reconstructed using the $D^\star$ and the 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

$$A_{\text{total}} = \frac{N_+ - N_-}{N_+ + N_-} \tag{7}$$

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

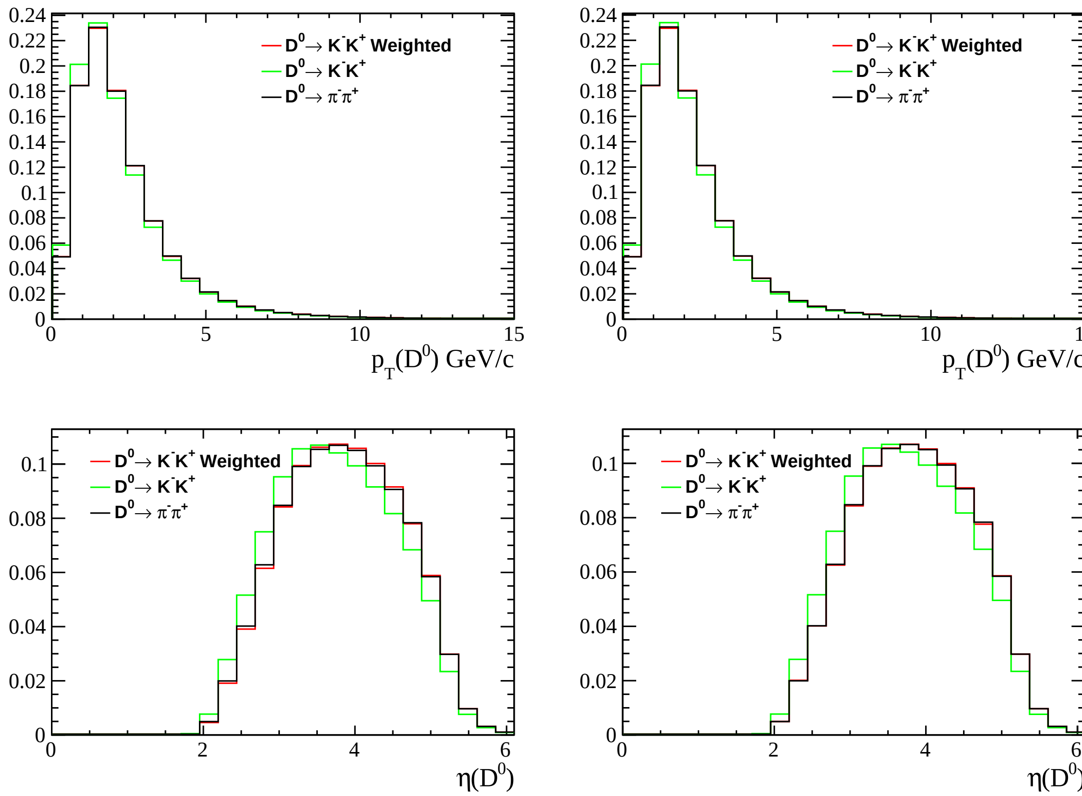

Figure 3: Comparison of D^0 kinematics with and without weighting. On the left column we present we new weighting technique with D^0 candidates reconstructed from K^-K^+ and on the right the baseline technique.

weighted samples, we have

$$N_{\pm} = \sum_i w_i^{\pm}, \text{ and } \sigma\left(N_{\pm}\right) = \sqrt{\sum_i (w_i^{\pm})^2} \tag{8}$$

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

$$\sigma\left(A_{\text{total}}^2\right) = \left(\frac{\partial A_{\text{total}}}{\partial N^+}\sigma\left(N^+\right)\right)^2 + \left(\frac{\partial A_{\text{total}}}{\partial N^-}\sigma\left(N^-\right)\right)^2 \tag{9}$$

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

Reconstruction	Weighted	Unweighted
K^-K^+	$A_{\text{total}} = 0.14726 \pm 0.00066$	$A_{\text{total}} = 0.16268 \pm 0.00064$
$D^\star\pi_s$	$A_{\text{total}} = 0.14994 \pm 0.00066$	

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

$$A_{\text{total}} = 0.24571 \pm 0.00067 \tag{10}$$

The estimated total asymmetry difference is $\Delta A_{\text{total}} = -0.1$, 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.

Reconstruction		Weighted	Unweighted
$K^- K^+$	ΔA_{total}	-0.09845 ± 0.00094	-0.08303 ± 0.00093
	Deviation (σ)	1.65	18.2
$D^\star \pi_s$	ΔA_{total}	-0.09578 ± 0.00094	-0.08303 ± 0.00093
	Deviation (σ)	4.49	18.2

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 Eq. 6 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.

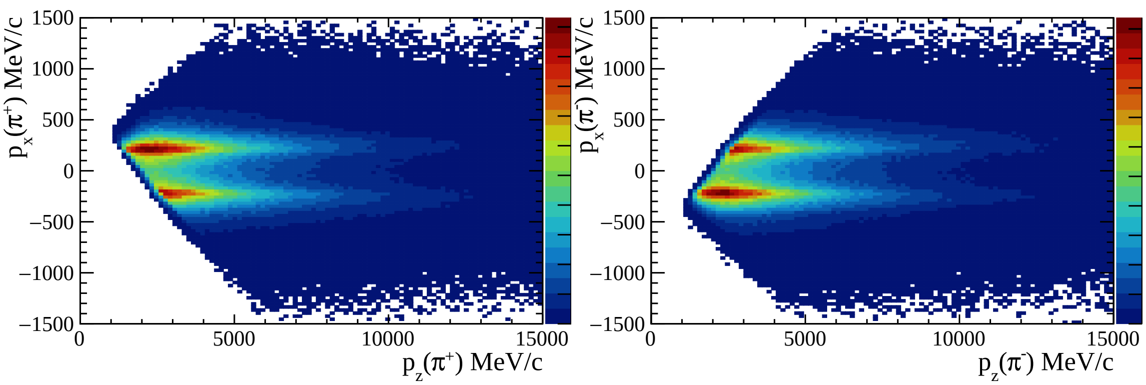

Figure 4: We present the positive (left) and negative (right) soft pion $p_x - p_z$ momentum planes for the $D^0 \to K^- K^+$ sample generated using Particle Gun.

We present the distribution of the weighting function values in Fig. 5. With the implementation of the weighting function, the detection asymmetries should cancel out when calculating ΔA_{total}, thus the calculated value should be consistent with zero.

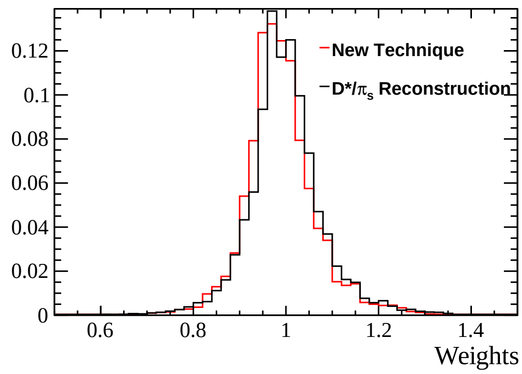

Figure 5: Normalized distribution of weighting function values obtained using the two techniques.

Using the same procedure as before, we calculate the total asymmetries of the two samples and the total asymmetry difference. Our results are shown in Tab. 4 for the $D^0 \to K^-K^+$ sample, while for the $D^0 \to \pi^-\pi^+$ sample we get

$$A_{\text{total}} = -0.00024 \pm 0.00074 \tag{11}$$

Reconstruction	Weighted	Unweighted
K^-K^+	$A_{\text{total}} = -0.00023 \pm 0.00079$	$A_{\text{total}} = 0.00002 \pm 0.00079$
$D^\star\pi_s$	$A_{\text{total}} = -0.00002 \pm 0.00079$	

Table 4: We present the A_{total} for the $D^0 \to K^-K^+$ Particle Gun sample with weighted using the two techniques and unweighted.

Using the these values we calculate the total asymmetry difference between the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ modes. The results are shown in Tab. 5, and the kinematics of D^0 with and without weights are shown in Fig. 6.

Reconstruction		Weighted	Unweighted
K^-K^+	ΔA_{total}	0.00001 ± 0.00108	0.00026 ± 0.00108
	Deviation (σ)	0.009	0.24
$D^\star\pi_s$	ΔA_{total}	0.00022 ± 0.00108	0.00026 ± 0.00108
	Deviation (σ)	0.20	0.24

Table 5: Total asymmetry difference and deviation from the expected value. We present both weighting procedures and the unweighted result.

3 Conclusions

As demonstrated the weighting function allows us to keep events with kinematics associated with large detection asymmetries and still perform calculations that are in agreement with the expected values.

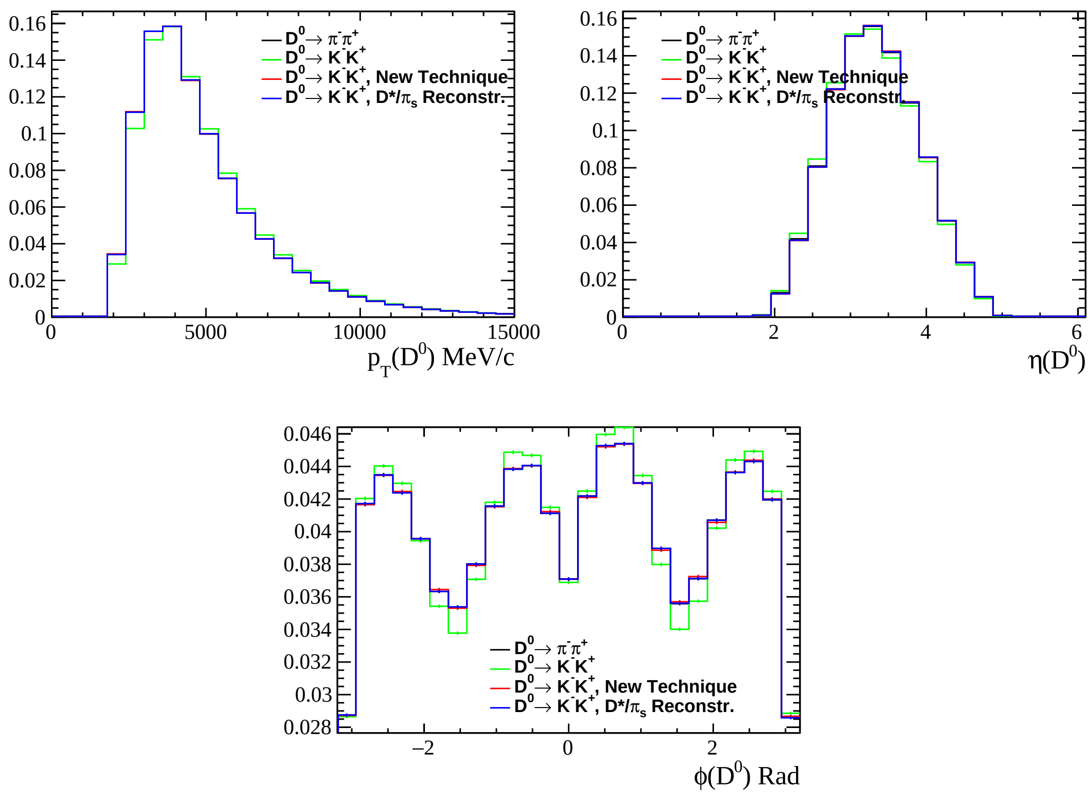

Figure 6: We present the D^0 normalized kinematic distributions with and without weighting for the two Particle Gun samples.

From the analysis of the RapidSim data we observe a reduction in the deviation of $\Delta A_{\mathrm{total}}$ when applying the old weighting function (reconstruction with $D^{\star}\pi_s$), 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 (reconstruction with K^-K^+ or $\pi^-\pi^+$) is much more effective than the previously used one.

Furthermore, we employed the weighting functions to Particle Gun data in order to study a more realistic scenario. The old weighting function slightly reduces the $\Delta A_{\mathrm{total}}$ deviation but the new technique decreases the deviation by more than 20 times.

In conclusion, the new weighting function we examined can be effectively used in further analyses using LHCb data that were discarded in previous measurement due to large detection asymmetries, thus increasing the statistics and improving the accuracy of our results.

References

[1] G. A. Cowan, D. C. Craik, and M. D. Needham. "RapidSim: an application for the fast simulation of heavy-quark hadron decays". In: *Comput. Phys. Commun.* 214 (2017), pp. 239–246. DOI: `10.1016/j.cpc.2017.01.029`. arXiv: `1612.07489 [hep-ex]`.

[2] Roel Aaij et al. "LHCb Detector Performance". In: *Int. J. Mod. Phys. A* 30.07 (2015), p. 1530022. DOI: `10.1142/S0217751X15300227`. arXiv: `1412.6352 [hep-ex]`.

[3] Roel Aaij et al. "Observation of CP Violation in Charm Decays". In: *Phys. Rev. Lett.* 122.21 (2019), p. 211803. DOI: `10.1103/PhysRevLett.122.211803`. arXiv: `1903.08726 [hep-ex]`.

[4] Federico Betti. "CP violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays and lepton-flavour universality test with the decay $B^0 \to D^{*-}\tau^+\nu_\tau$". PhD thesis. Bologna U., 2019. DOI: `10.6092/unibo/amsdottorato/8769`.