



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 $D^{*+} \rightarrow D^0 \pi^+$ and $D^{*-} \rightarrow \bar{D}^0 \pi^-$ where $D^0 \rightarrow K^- K^+$ or $D^0 \rightarrow \pi^- \pi^+$. 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^* meson. By studying the differences between D^{*+} and D^{*-} decays we can estimate the CP asymmetry. Specifically, we are interested in

$$\begin{aligned} D^{*+} &\rightarrow D^0 \pi^+ \text{ and } D^{*-} \rightarrow \bar{D}^0 \pi^-, \\ D^0 &\rightarrow K^- K^+ \text{ and } D^0 \rightarrow \pi^- \pi^+ \end{aligned} \quad (1)$$

decay modes where we refer to the π^\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 (π_s^\pm).

We can calculate the *total asymmetry* by

$$A_{\text{total}} = \frac{A_{CP} + A_D}{1 + A_{CP} A_D}, \quad (2)$$

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

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

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

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

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* based on D^0 kinematics

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

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^* 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 from $K^- K^+$ or $\pi^- \pi^+$, thus, the weighting is not affected by the detection asymmetry that occurs from the soft pions. This weighting function reads

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

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 $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ 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 $D^{*\pm} \rightarrow D^0 \pi^\pm$ 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 $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ 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 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.

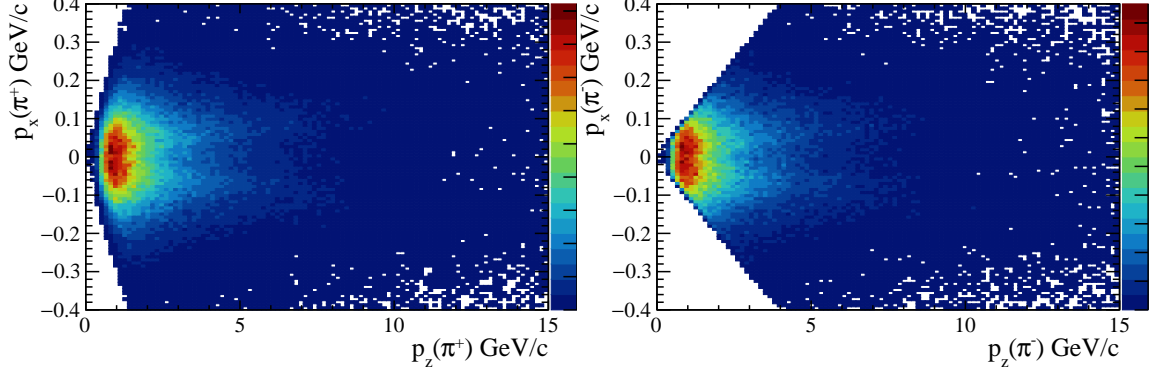


Figure 1: Positive and negative soft pion $p_x - p_z$ momentum plane for the $D^0 \rightarrow k^- K^+$ sample. We remove negative soft pions from kinematic regions associated with $A_D(\vec{p}) = 1$.

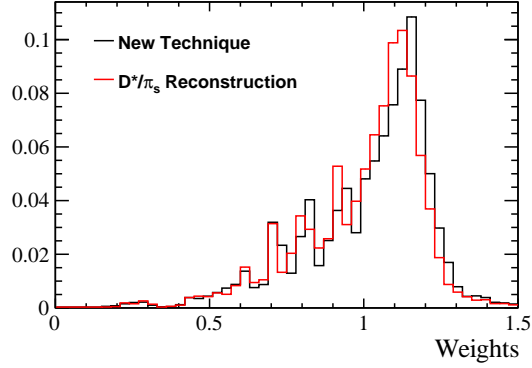


Figure 2: Distribution of weighting function values. The black histogram represents the new technique where we reconstruct D^0 candidates from either $K^- K^+$ or $\pi^- \pi^+$ while the red histogram represents the old weighting function where D^0 candidates were reconstructed using the D^* and the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

2.3 Asymmetry calculation

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

$$A_{\text{total}} = \frac{N_+ - N_-}{N_+ + N_-} \quad (7)$$

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

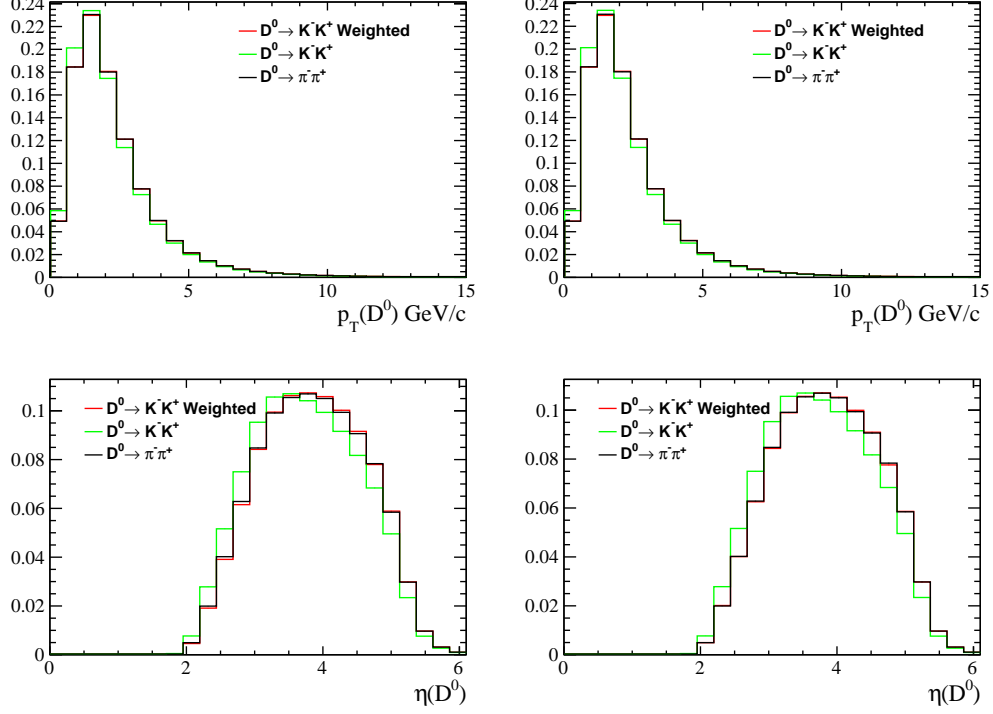


Figure 3: Comparison of D^0 kinematics with and without weighting. On the left column we present we new weighting technique with D^0 candidates reconstructed from $K^- K^+$ and on the right the baseline technique.

weighted samples, we have

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

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

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

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

Technique	Weighted	Unweighted
Not associated	$A_{\text{total}} = 0.14726 \pm 0.00066$	$A_{\text{total}} = 0.16268 \pm 0.00064$
Associated with π_s	$A_{\text{total}} = 0.14994 \pm 0.00066$	

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

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

$$A_{\text{total}} = 0.24571 \pm 0.00067 \quad (10)$$

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 ± 0.00094	-0.08303 ± 0.00093
	Deviation (σ)	1.65	18.2
Associated with π_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 in 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.

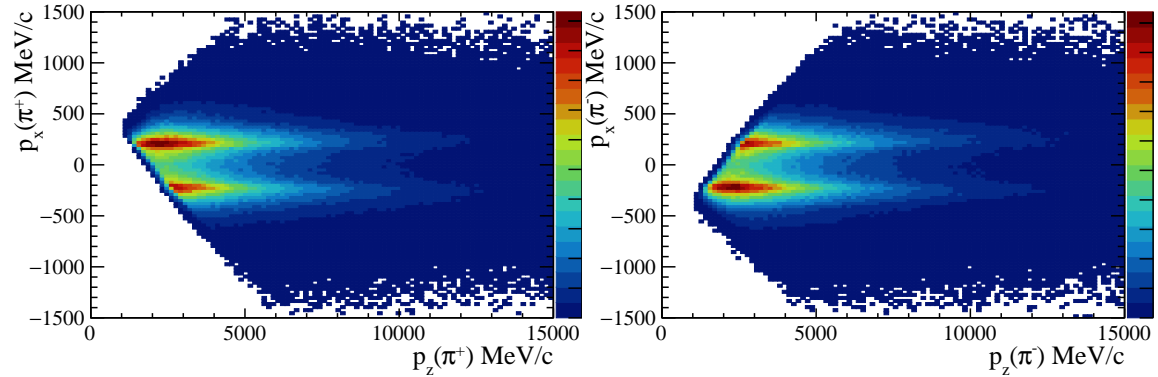


Figure 4: We present the positive (left) and negative (right) soft pion $p_x - p_z$ momentum planes for the 2018 $D^0 \rightarrow K^- K^+$ with up magnet polarity sample generated using Particle Gun.

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

Year	Polarity	A_{total}
2015	Down	0.00284 ± 0.00049
	Up	-0.00033 ± 0.00069
2016	Down	0.00296 ± 0.00069
	Up	-0.00130 ± 0.00069
2017	Down	0.00349 ± 0.00075
	Up	-0.00091 ± 0.00074
2018	Down	0.00260 ± 0.00075
	Up	-0.00024 ± 0.00074

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

Polarity	Technique	Weighted	Unweighted
Down	Not associated	$A_{\text{total}} = 0.00300 \pm 0.00075$	$A_{\text{total}} = 0.00272 \pm 0.00074$
	Associated with π_s	$A_{\text{total}} = 0.00306 \pm 0.00075$	
Up	Not associated	$A_{\text{total}} = -0.00063 \pm 0.00074$	$A_{\text{total}} = -0.00018 \pm 0.00074$
	Associated with π_s	$A_{\text{total}} = -0.00031 \pm 0.00074$	

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

Polarity	Technique	Weighted	Unweighted
Down	Not associated	$A_{\text{total}} = 0.00359 \pm 0.00074$	$A_{\text{total}} = 0.00331 \pm 0.00074$
	Associated with π_s	$A_{\text{total}} = 0.00339 \pm 0.00074$	
Up	Not associated	$A_{\text{total}} = -0.00122 \pm 0.00074$	$A_{\text{total}} = -0.00082 \pm 0.00069$
	Associated with π_s	$A_{\text{total}} = -0.00105 \pm 0.00075$	

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

Polarity	Technique	Weighted	Unweighted
Down	Not associated	$A_{\text{total}} = 0.00208 \pm 0.00079$	$A_{\text{total}} = 0.00191 \pm 0.00079$
	Associated with π_s	$A_{\text{total}} = 0.00186 \pm 0.00079$	
Up	Not associated	$A_{\text{total}} = -0.00095 \pm 0.00080$	$A_{\text{total}} = -0.00059 \pm 0.00079$
	Associated with π_s	$A_{\text{total}} = -0.00109 \pm 0.00080$	

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

Polarity	Technique	Weighted	Unweighted
Down	Not associated	$A_{\text{total}} = 0.00265 \pm 0.00079$	$A_{\text{total}} = 0.00246 \pm 0.00079$
	Associated with π_s	$A_{\text{total}} = 0.00281 \pm 0.00079$	
Up	Not associated	$A_{\text{total}} = -0.00023 \pm 0.00079$	$A_{\text{total}} = 0.00002 \pm 0.00079$
	Associated with π_s	$A_{\text{total}} = -0.00002 \pm 0.00079$	

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

We calculate ΔA_{CP} 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} Deviation (σ)	0.00016 ± 0.00090 0.18	-0.00012 ± 0.00089 0.13
		Associated with π_s	ΔA_{total} Deviation (σ)	0.00022 ± 0.00090 0.24	
	Up	Not associated	ΔA_{total} Deviation (σ)	-0.00030 ± 0.00101 0.30	0.00015 ± 0.00101 0.15
		Associated with π_s	ΔA_{total} Deviation (σ)	0.00002 ± 0.00101 0.020	
2016	Down	Not associated	ΔA_{total} Deviation (σ)	0.00063 ± 0.00101 0.62	0.00035 ± 0.00101 0.35
		Associated with π_s	ΔA_{total} Deviation (σ)	0.00043 ± 0.00101 0.43	
	Up	Not associated	ΔA_{total} Deviation (σ)	0.00008 ± 0.00101 0.08	0.00048 ± 0.00098 0.49
		Associated with π_s	ΔA_{total} Deviation (σ)	0.00025 ± 0.00105 0.24	
2017	Down	Not associated	ΔA_{total} Deviation (σ)	-0.00141 ± 0.00109 1.30	-0.00158 ± 0.00109 1.45
		Associated with π_s	ΔA_{total} Deviation (σ)	-0.00163 ± 0.00109 1.50	
	Up	Not associated	ΔA_{total} Deviation (σ)	-0.00004 ± 0.00109 0.04	0.00032 ± 0.00108 0.30
		Associated with π_s	ΔA_{total} Deviation (σ)	-0.00018 ± 0.00109 0.17	
2018	Down	Not associated	ΔA_{total} Deviation (σ)	0.00004 ± 0.00109 0.05	-0.00014 ± 0.00109 0.13
		Associated with π_s	ΔA_{total} Deviation (σ)	0.00021 ± 0.00109 0.19	
	Up	Not associated	ΔA_{total} Deviation (σ)	0.00001 ± 0.00108 0.009	0.00026 ± 0.00108 0.24
		Associated with π_s	ΔA_{total} Deviation (σ)	0.00022 ± 0.00108 0.20	

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

Year	Polarity	Technique		Weighted	Unweighted
Average	Both	Not associated	ΔA_{total} Deviation (σ)	-0.00083 ± 0.00036 2.31	-0.00028 ± 0.00036 0.78
		Associated with π_s	ΔA_{total} Deviation (σ)	-0.00046 ± 0.00037 1.24	

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

From the analysis of the RapidSim data we observe a reduction in the deviation of ΔA_{total} when applying the old weighting function (reconstruction with $D^*\pi_s$), 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. For these specific datasets we noticed that both weighting functions do not improve the ΔA_{total} result

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, thus, more conclusive study regarding the new weighting technique could be done using a more accurate simulation by generate full events from pp collisions.

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 $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays and lepton-flavour universality test with the decay $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ ”. PhD thesis. Bologna U., 2019. DOI: 10.6092/unibo/amsdottorato/8769.