Epiphany Conference 2021

Mixing and CP violation in charm mesons at LHCb

Edward Shields
on behalf of the LHCb collaboration
Univeristá di Milano-Bicocca & INFN
edward.brendan.shields@cern.ch

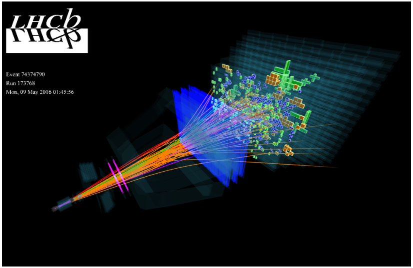
January 10, 2021

Mixing and CPV in Charm

Charge-Parity Violation (CPV) is a key requirement for the generation of the baryon-antibaryon asymmetry in the early Universe.
LHCb has observed direct CPV in Charm, but indirect CPV remains elusive.

Today, the following will be presented:

- Observation of CPV in Charm.
- Latest LHCb measurements.
- Outlook for Charm measurements at LHCb.



Mixing in Charm

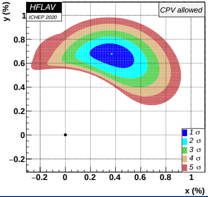
Mixing occurs because the mass eigenstates of neutral D mesons are superpositions of the flavour eigenstates:

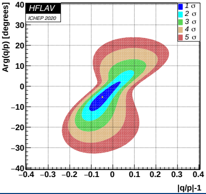
$$|D_{1,2}\rangle = p\left|D^0\right\rangle \pm q\left|\bar{D}^0\right\rangle$$

Mixing is governed by the mixing parameters, x & y, where:

$$x = \frac{m_2 - m_1}{\Gamma} \quad \& \quad y = \frac{\Gamma_2 - \Gamma_1}{\Gamma}$$

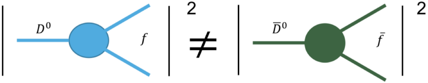
Mixing has been observed in Charm but currently there is no evidence for CPV in mixing or interference.



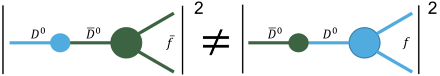


Direct CPV

- $|\bar{A}_{\bar{f}}/A_f| \neq 1$



Decay-time dependent CPV

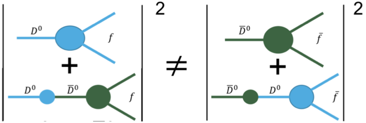


CPV in mixing

- $|q/p| \neq 1$

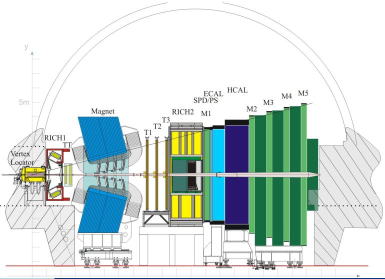
CPV in interference between mixing and decay

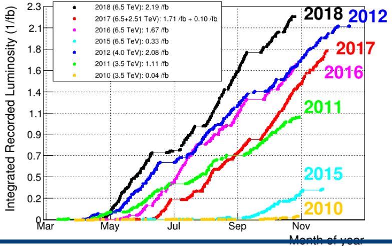
- $\phi \equiv \arg\left(\frac{q\bar{A}_{\bar{f}}}{pA_f}\right) \neq 0$



LHCb detector

- The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2<\eta<5$ equipped with charged-hadron identification detectors, calorimeters, and muon detectors.
- It is designed for the study of particles containing b or c quarks
- Excellent vertex resolution ($\sim(15+29/p_T)\,\mu m$ IP resol.) and tracking ($\sigma_p/p \sim 0.5-1\%@5-200\text{GeV}/c$).

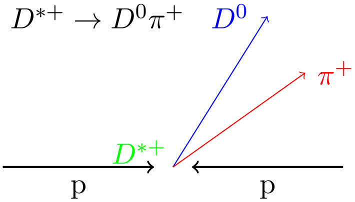


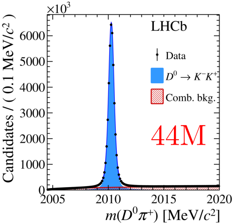


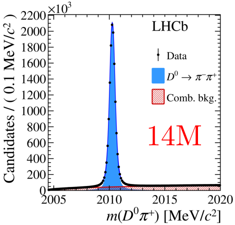
Observation of CPV at LHCb

Used $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays collected in Run II.

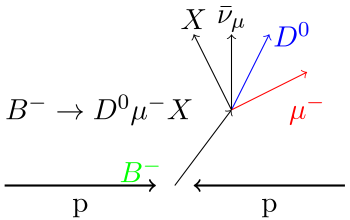
Prompt decays

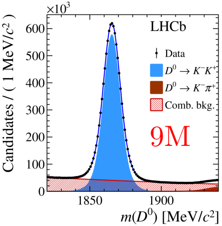


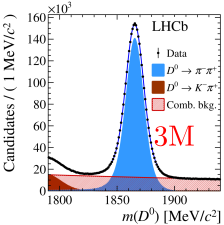




Semileptonic decays







$$A_{CP} = \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\bar{D}^0 \to f\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\bar{D}^0 \to f\right)}$$

What is measured at LHCb is:

$$A_{\text{raw}} \equiv \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$$

where

$$A_{\text{raw}} \approx A_{CP} + A_{\text{prod}} + A_{\text{det}}$$

- A_{prod} = Production asymmetry
- A_{det} = Detection asymmetry

Both A_{prod} and A_{det} are independent of the final state. Therefore they cancel out when the difference between A_{CP} for the K^+K^- and $\pi^+\pi^-$ final states are taken.

$$\Delta A_{CP} = A_{CP}\,(KK) - A_{CP}\,(\pi\pi)$$

A multidimensional reweighting procedure is applied to match kinematics of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ final states.

Run II results:

$$\Delta A_{CP}^{\text{Prompt}} = [-18.2 \pm 3.2\,(\text{stat}) \pm 0.9\,(\text{syst})] \times 10^{-4}$$
$$\Delta A_{CP}^{\text{Semileptonic}} = [-9 \pm 8\,(\text{stat}) \pm 5\,(\text{syst})] \times 10^{-4}$$

Run I results:

PRL 116 (2016) 191601 & JHEP 07 (2014) 041

$$\Delta A_{CP}^{\text{Prompt}} = [-10 \pm 8\,(\text{stat}) \pm 3\,(\text{syst})] \times 10^{-4}$$
$$\Delta A_{CP}^{\text{Semileptonic}} = [-14 \pm 16\,(\text{stat}) \pm 8\,(\text{syst})] \times 10^{-4}$$

Run I + Run II combination:

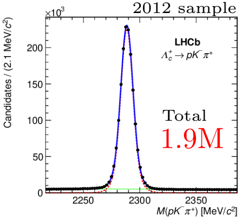
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

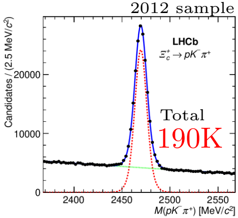
First observation of charm CPV at 5.3σ!

Latest LHCb measurements

Search for CPV in $\Xi_c^+ \to pK^-\pi^+$
Eur. Phys. J. C80 (2020) 986

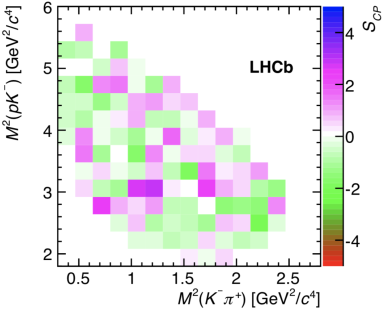
- A first search for CPV in the Cabibbo-suppressed $\Xi_c^+ \to pK^-\pi^+$ decay.
- $\Lambda_c^+ \to pK^-\pi^+$ Cabibbo favoured decay is used as a validation channel.
- Based on two amplitude model independent approaches.
- Used Run I data (2011 & 2012, 3.0fb^{-1}) from Prompt decays.

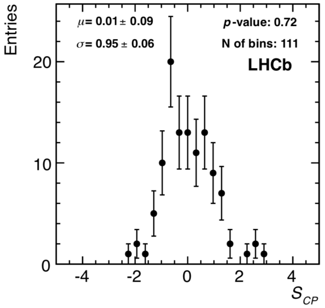




S_{CP} is the significance of the difference between baryons and anti-baryons.

$\mathbf{S_{CP}}$ Result





No evidence of CPV found.

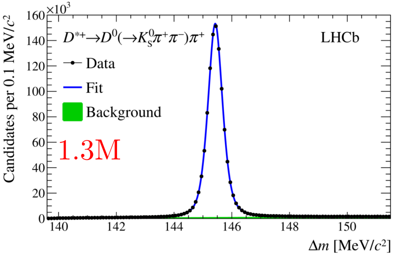
Used 2.3×10^6 $D^0 \to K^0_S \pi^+\pi^-$ decays collected in Run I to measure mixing parameters.

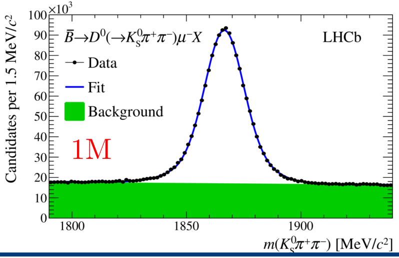
$$x_{CP} = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta x = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

$$y_{CP} = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta y = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$





In the limit of CP symmetry (i.e. $\phi = 0$ & $|q/p|$=1) then $x_{CP} = x$, $\Delta x = 0$, $y_{CP} = y$, and $\Delta y = 0$.
Any significant discrepancy between x_{CP}, y_{CP} and x, y would indicate CPV.

The measured values are:

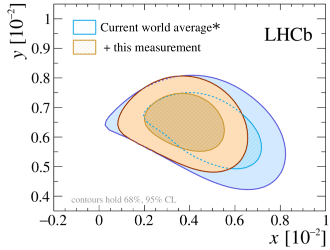
$$x_{CP} = [2.7 \pm 1.6\,(\text{stat}) \pm 0.4\,(\text{syst})] \times 10^{-3}$$
$$y_{CP} = [7.4 \pm 3.6\,(\text{stat}) \pm 1.1\,(\text{syst})] \times 10^{-3}$$
$$\Delta x = [-0.53 \pm 0.70\,(\text{stat}) \pm 0.22\,(\text{syst})] \times 10^{-3}$$
$$\Delta y = [0.6 \pm 1.6\,(\text{stat}) \pm 0.3\,(\text{syst})] \times 10^{-3}$$

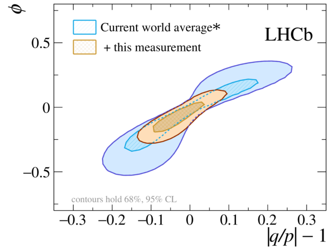
we can derive x from this:

$$x = \left(2.7^{+1.7}_{-1.5}\right) \times 10^{-3}$$

When this is combined with the world average, there is evidence of a mass difference between the neutral charm-meson eigenstates.

$$x = \left(3.9^{+1.1}_{-1.2}\right) \times 10^{-3}$$





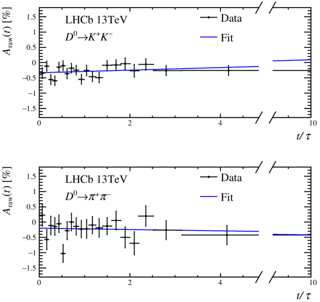
* world average as of 2019.

Measurement of parameter A_Γ with $D^0 \to \pi^+\pi^-/K^+K^-$ decays.

With Run II Semileptonic data (5.4fb^{-1})

$$A_{CP}(f,t) \equiv \frac{\Gamma\left(D^0 \to f,t\right) - \Gamma\left(\bar{D}^0 \to f,t\right)}{\Gamma\left(D^0 \to f,t\right) + \Gamma\left(\bar{D}^0 \to f,t\right)}$$
$$\approx a_{CP}^{dir}(f) - \frac{t}{\tau_D^0} A_\Gamma(f)$$

SM predictions $\approx 3 \times 10^{-5}$.



When combined with Run I results:

JHEP 04 (2015) 043 & Phys. Rev. Lett. 118 (2017) 261803

$$A_\Gamma\left(K^+K^-\right) = (-4.4 \pm 2.3 \pm 0.6) \times 10^{-4}$$
$$A_\Gamma\left(\pi^+\pi^-\right) = (2.5 \pm 4.3 \pm 0.7) \times 10^{-4}$$

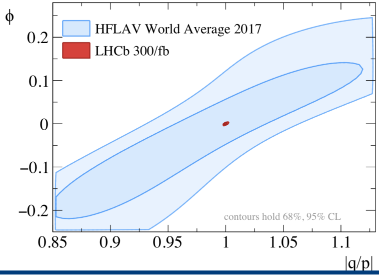
Outlook

Run III

- Run III will begin in 2022 and provide 5-10 times the sensitivity to direct and indirect CPV in Charm.
- For decay-time dependent CPV in particular, effects not deriving from the Standard Model could be highlighted.
- A new detector and trigger system will help with greater efficiency in some channels.

Upgrade II

- Upgrade II will come with a huge gain in statistics.
- Will allow measurements with incredible precision of CP violating parameters.



Mixing and CPV in $D^0 \to K^0_S \pi^+\pi^-$

Sample (lumi $\mathcal{L}$)	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(\|q/p\|)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL	10M	0.07%	0.05%	0.07	4.6°
	Prompt	36M	0.05%	0.05%	0.04	1.8°
Run 1–3 (23 fb^{-1})	SL	33M	0.036%	0.030%	0.036	2.5°
	Prompt	200M	0.020%	0.020%	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	78M	0.024%	0.019%	0.024	1.7°
	Prompt	520M	0.012%	0.013%	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

A_Γ

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

Conclusion

- LHCb continues to provide a wide range of excellent physics results.
- Incredible precision could be reached on mixing and CPV parameters in the coming years.

Keep an eye out for:

- New A_Γ measurement with full Run II Prompt data sample.
- Measurement of mixing and CPV parameters with Run II $D^0 \to K_S^0\pi^+\pi^-$ data sample.

Coming soon!

BACKUP

Mixing in Charm

The mass eigenstates of neutral D mesons are not flavour eigenstates. But they can be written in terms of the flavour eigenstates:

$$|D_{1,2}\rangle = p\left|D^0\right\rangle \pm q\left|\bar{D}^0\right\rangle$$

The time evolution of the flavour eigenstates is then given by

$$\left|D^0(t)\right\rangle = g_+(t)\left|D^0\right\rangle + \frac{q}{p}g_-(t)\left|\bar{D}^0\right\rangle$$

$$\left|\bar{D}^0(t)\right\rangle = \frac{p}{q}g_-(t)\left|D^0\right\rangle + g_+(t)\left|\bar{D}^0\right\rangle$$

where $g_\pm(t) = e^{-iMt}e^{i\Gamma t/2}\left[{}^{\cos}_{\sin}\left(-i(x+iy)\Gamma t/2\right)\right]$.

Binned $\mathbf{S_{CP}}$ method

- Tests for localised asymmetries in the phase-space of $H_c^+ \to pK^-\pi^+$.
- Based on a bin-by-bin comparison of H_c^+ and H_c^- baryons.
- For each bin i, the significance of the difference between number of H_c^+ and H_c^- baryons is

$$S_{CP}^i = \frac{n_+^i - \alpha n_-^i}{\sqrt{\alpha \left(n_+^i - n_-^i\right)}}$$

where $\alpha = n_+/n_-$ which is the total number of $H_c^{\pm}$ candidates.

- In the hypothesis of no CPV, S_{CP} values are expected to be distributed according to a normal distribution.

Unbinned kNN method

- This method is based on the concept of a set of nearest neighbour candidates (n_k) in a combined sample of two datasets: baryons and antibaryons.
- A test statistic T for the null hypothesis is defined as

$$T = \frac{1}{n_k \left(n_+ + n_-\right)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I\left(i, k\right),$$

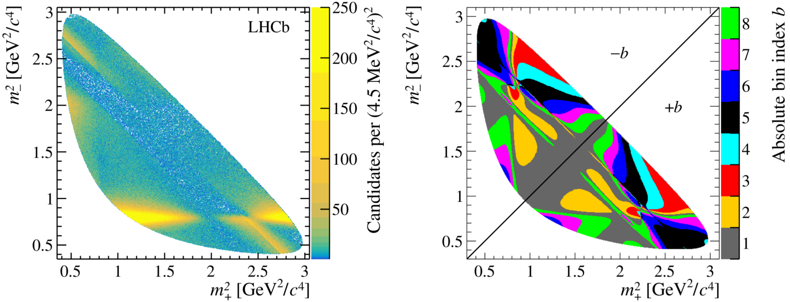
where $I\left(i, k\right) = 1$ if the i^{th} candidate and k^{th} nearest neighbour have the same charge and $I\left(i, k\right) = 0$ otherwise.

- In the hypothesis of no CPV, T is distributed as a Gaussian with well known mean and variance (μ_T, σ_T).

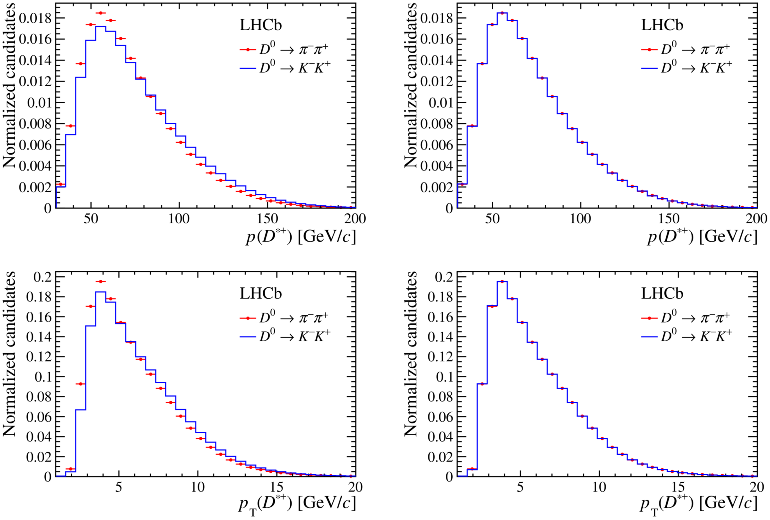
'Bin-flip' method for $D^0 \to K_S^0 \pi^+ \pi^-$

Phys. Rev. Lett. 122 (2019) 231802

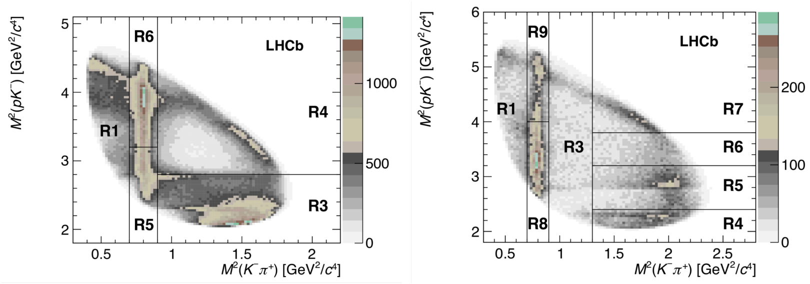
- Partition the Dalitz plot into bins that have nearly constant phase-space differences $\Delta\delta\left(m_-^2, m_+^2\right)$ between the D^0 and $\bar{D}^0$ amplitudes within each bin.
- The bins are organised symmetrically about the Dalitz plots principal bisector, and given indices $\pm b$.
- Take the ratio of events between initally produced D^0 ($\bar{D}^0$) mesons in the $+b$ and $-b$ bins.



Reweighting in ΔA_{CP} measurement



Binning scheme for $H_c^+ \to pK^-\pi^+$



Left is $\Lambda_c^+ \to pK^-\pi^+$, right is $\Xi_c^+ \to pK^-\pi^+$.