CP violation and mixing in charm decays at LHCb

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On behalf of the LHCb collaboration

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Introduction

- In the Standard Model (SM), charge-parity violation (CPV) in the quark sector comes only from the complex phase in the CKM matrix
- Order of magnitudes too small to explain our matter dominated universe

$\rightarrow$ Look for other sources in New Physics (NP) processes that enhance CPV

CP violation

- CPV in the decay
  - Difference of decay rate between two *CP* conjugated states

$$|A(i \to f)|^2 \neq \left|A(\bar{i} \to \bar{f})\right|^2$$

- CPV in mixing
  - Difference of transition rate between two flavour eigenstates

$$\left|A(i \to \bar{i})\right|^2 \neq \left|A(\bar{i} \to i)\right|^2$$

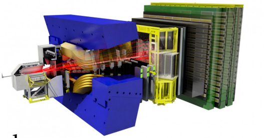
- CPV in the interference between mixing and decay
  - Interference between the decay with and without mixing

$$|A(i \to f)|^2 \neq \left|A(i \to \bar{i} \to f)\right|^2$$

CP violation in charm

Why look for CPV in charm ?

- Prediction of CPV in charm from the SM are small
  $\rightarrow$ Lots of room for NP enhancement
- Only way to probe for CPV in up-type hadrons
  $\rightarrow$ Complementary to other searches in B or K



Why look for CPV in charm at LHCb ?

- Largest sample of charm decays
  - Large $c\bar{c}$ cross-section:
    $$\sigma(pp \rightarrow c\bar{c}X) = (2369 \pm 3 \pm 152 \pm 118)\,\mu\mathrm{b}\,,$$
    at $13\,\mathrm{TeV}$ and for $p_\mathrm{T} < 8\,\mathrm{GeV}/c$, $2.0 < y < 4.5$ [JHEP 03 (2016) 159]

  $\rightarrow$ Large charm yields ($\mathcal{O}(100\,\mathrm{M})$ $D^0 \rightarrow K^-\pi^+$ tagged decays)
- Good momentum resolution ($0.5 - 1\%$)
- Good tracking efficiency (over 95%) [Int. J. Mod. Phys A30 (2015) 1530022]
- Excellent vertex resolution (IP resolution $(15 + 29/p_\mathrm{T})\,\mu\mathrm{m}$)

Observation of *CP* violation in charm decays

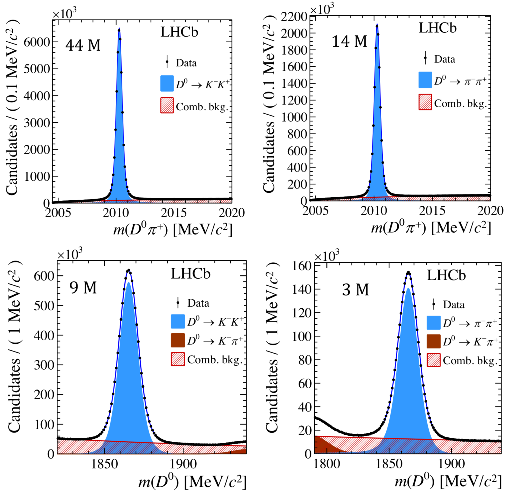
[Phys. Rev. Lett. 122 (2019) 211803]

- Dataset : 5.9 fb^{-1}, Run 2
- Comparison between 2 Cabibbo-suppressed decays :

$D^0 \to K^+K^-$ $\qquad$ $D^0 \to \pi^+\pi^-$

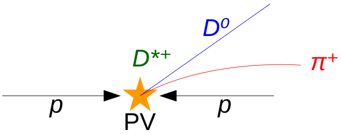
Prompt

Semileptonic

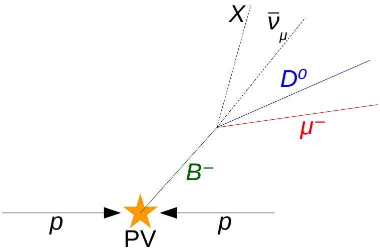


2 independent tagging methods are used :

Prompt
$D^{*+} \to D^0 \pi^+$



Semileptonic
$B^- \to D^0 \mu^- \overline{\nu}_\mu X$



Observation of CPV in charm [PRL 122 (2019) 211803]

The experimental observable is not directly A_{CP}, but A_{raw} :

$$A_{\mathrm{raw}} \approx A_{CP} + A_P + A_D + A_{\mathrm{tag}}$$

- The production asymmetry A_P : Potential asymmetry between the production of D^{*+} (B^+) and D^{*-} (B^-)
- The detection asymmetry A_D : Mesons and anti-mesons have different behaviours in matter ($=0$ in symmetric final states such as K^+K^- and $\pi^+\pi^-$)
- The tagging asymmetry A_{tag} : The tagging particle also has different behaviour in matter according to its charge
- The *CP* asymmetry A_{CP} : The interesting physical quantity

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

- Experimental asymmetries are difficult to measure
- They can be made independent of the D^0 decay by equalising the K^+K^- and $\pi^+\pi^-$ kinematics

$\rightarrow$ They can be subtracted

$$\begin{aligned}\Delta A_{CP} &= A_{\mathrm{raw}}(D^0 \to K^+K^-) - A_{\mathrm{raw}}(D^0 \to \pi^+\pi^-) \\ &= A_{CP}(D^0 \to K^+K^-) + A_P(D^{*+}) + A_{\mathrm{tag}}(\pi^+) \\ &\quad - A_{CP}(D^0 \to \pi^+\pi^-) - A_P(D^{*+}) - A_{\mathrm{tag}}(\pi^+) \\ &= A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)\end{aligned}$$

Similarly for the semileptonic sample

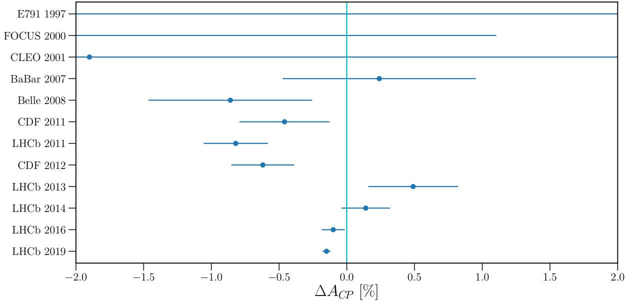
Results of this analysis

- $\Delta A_{CP}^{prompt} = [-18.2 \pm 3.2 \pm 0.9] \times 10^{-4}$
- $\Delta A_{CP}^{SL} = [-9 \pm 8 \pm 5] \times 10^{-4}$

Combination of the two, plus previous Run 1 analyses :

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

$\Rightarrow$ First observation of *CP* violation in charm at 5.3σ !



Search for time-dependent *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

Preliminary results

[LHCb-CONF-2019-001]

[LHCb-PAPER-2019-032]

Time-dependent CPV [LHCb-CONF-2019-001] [LHCb-PAPER-2019-032]

Prompt analysis [LHCb-CONF-2019-001]

- Dataset : 1.9 fb^{-1}, 2015-2016
- Production mode : $D^{*+} \to D^0 \pi^+$
- Yields : 17 M $D^0 \to K^+ K^-$, 5 M $D^0 \to \pi^+ \pi^-$

Semileptonic analysis [LHCb-PAPER-2019-032]

- Dataset : 5.4 fb^{-1}, 2016-2018
- Production mode : $B^- \to D^0 \mu X^-$
- Yields : 9 M $D^0 \to K^+ K^-$, 3 M $D^0 \to \pi^+ \pi^-$

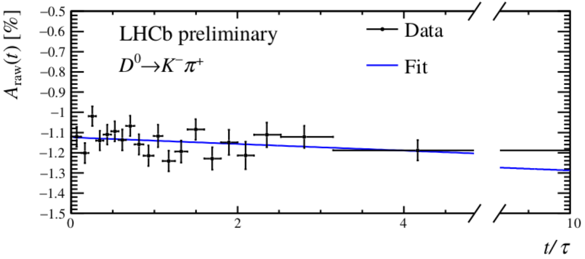
Formalism

$$A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})} \approx A_{CP}^{\rm dir} - A_{\Gamma}\frac{t}{\tau}$$

$$A_{\rm raw}(D^0 \to f; t) \approx A_{CP}(D^0 \to f; t) + A_P(B(D^*)) + A_D(\mu(\pi))$$

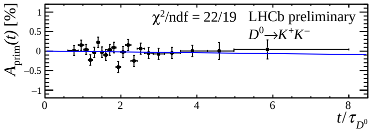
Control channel : $D^0 \to K^-\pi^+$

A_Γ expected to be well below experimental sensitivity



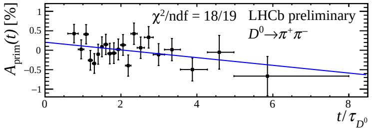
$$A_\Gamma = (1.6 \pm 1.2) \times 10^{-4}$$

Time-dependent CPV [LHCb-CONF-2019-001] [LHCb-PAPER-2019-032]

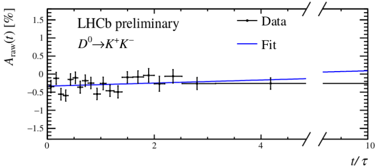


Prompt results :

$$A_\Gamma(D^0 \to K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4}$$

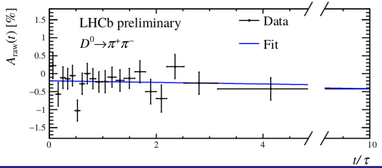


$$A_\Gamma(D^0 \to \pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}$$



Semileptonic results :

$$A_\Gamma(D^0 \to K^+K^-) = (-4.3 \pm 3.6 \pm 0.5) \times 10^{-4}$$



$$A_\Gamma(D^0 \to \pi^+\pi^-) = (2.2 \pm 7.0 \pm 0.8) \times 10^{-4}$$

Time-dependent CPV [LHCb-CONF-2019-001] [LHCb-PAPER-2019-032]

Prompt combination :

$$A_\Gamma(K^+K^- + \pi^+\pi^-) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}$$

Semileptonic combination

$$A_\Gamma(K^+K^- + \pi^+\pi^-) = (-2.9 \pm 2.0 \pm 0.6) \times 10^{-4}$$

SM prediction [A. Cerri et al., arxiv:1812.07638]

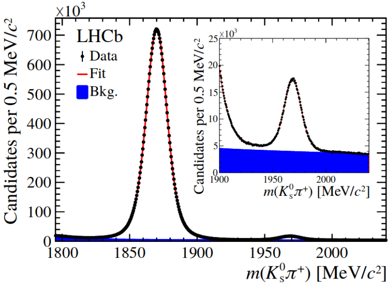
$$A_\Gamma \approx 3 \times 10^{-5}$$

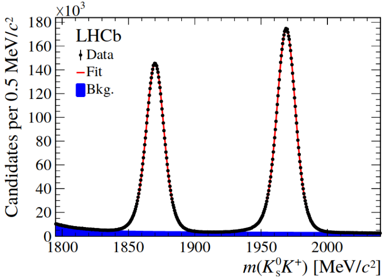
Search for *CP* violation in $D_s^+ \to K_S^0 \pi^+$, $D^+ \to K_S^0 K^+$ and $D^+ \to \phi \pi^+$ decays

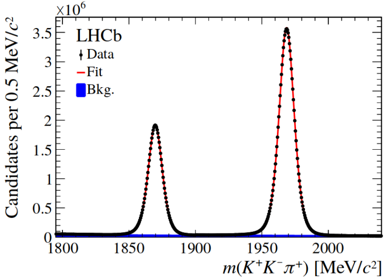
[Phys. Rev. Lett. 122 (2019) 191803]

Search for CPV in D_s^+ and D^+ decays [PRL 122 (2019) 191803]

- Dataset : 3.8 fb^{-1}, 2015-2017
- 3 decay modes
  - $D_s^+ \to K_S^0 \pi^+$: 600 k
  - $D^+ \to K_S^0 K^+$: 5.1 M
  - $D^+ \to \phi\pi^+$: 53.3 M
- 3 CF control samples
  - $D^+ \to K_S^0 \pi^+$: 30.5 M
  - $D_s^+ \to K_S^0 K^+$: 6.5 M
  - $D_s^+ \to \phi\pi^+$: 107 M







Search for CPV in D_s^+ and D^+ decays [PRL 122 (2019) 191803]

- *CP* asymmetry measured from raw asymmetry

$$A_{\mathrm{raw}}(D_{(s)}^+ \to f^+) \approx A_{CP}(D_{(s)}^+ \to f^+) + A_P(D_{(s)}^+) + A_D(f^+)$$

- Assume no CPV in CF control samples

$$A_{CP}(D_s^+ \to K_S^0\pi^+) \approx A_{\mathrm{raw}}(D_s^+ \to K_S^0\pi^+) - A_{\mathrm{raw}}(D_s^+ \to \phi\pi^+) - A_D(\overline{K}^0)$$

$$A_{CP}(D^+ \to K_S^0 K^+) \approx A_{\mathrm{raw}}(D^+ \to K_S^0 K^+) - A_{\mathrm{raw}}(D^+ \to K_S^0\pi^+) - A_{\mathrm{raw}}(D_s^+ \to K_S^0 K^+) + A_{\mathrm{raw}}(D_s^+ \to \phi\pi^+) - A_D(\overline{K}^0)$$

$$A_{CP}(D^+ \to \phi\pi^+) \approx A_{\mathrm{raw}}(D^+ \to \phi\pi^+) - A_{\mathrm{raw}}(D^+ \to K_S^0\pi^+)$$

- Results

$$A_{CP}(D_s^+ \to K_S^0\pi^+) = (1.6 \pm 1.7 \pm 0.5) \times 10^{-3}$$

$$A_{CP}(D^+ \to K_S^0 K^+) = (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3}$$

$$A_{CP}(D^+ \to \phi\pi^+) = (0.03 \pm 0.40 \pm 0.29) \times 10^{-3}$$

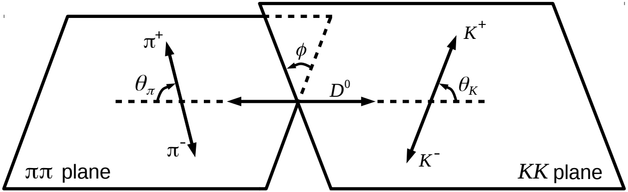
$\rightarrow$ Compatible with *CP* conservation

Search for *CP* violation through an amplitude analysis of $D^0 \to K^+K^-\pi^+\pi^-$ decays

[JHEP 02 (2019) 126]

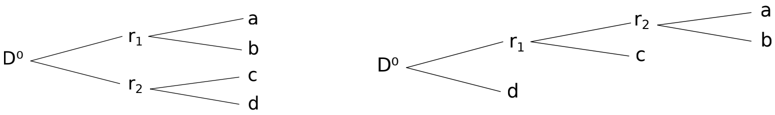
$D^0 \to K^+K^-\pi^+\pi^-$ amplitude analysis [JHEP 02 (2019) 126]

- Dataset : 3.0 fb^{-1}, Run 1
- Production mode : $B^- \to D^0\mu^-\overline{\nu}_\mu X$
- Yield : 160 k signal candidates
- Large number of interfering amplitudes could enhance CPV
- 4-body spinless decay $\to$ 5D phase space
  - $m(K^+K^-)$, $m(\pi^+\pi^-)$, $\cos(\theta_K)$, $\cos(\theta_\pi)$, $\phi_{KK,\pi\pi}$



$D^0 \to K^+K^-\pi^+\pi^-$ amplitude analysis [JHEP 02 (2019) 126]

- Use the isobar model to describe the signal PDF



- The signal PDF

$$a(\boldsymbol{x};\boldsymbol{c}) = \frac{\epsilon_s(\boldsymbol{x})S(\boldsymbol{x};\boldsymbol{c})\mathcal{R}_4(\boldsymbol{x})}{\int \epsilon_s(\boldsymbol{x})S(\boldsymbol{x};\boldsymbol{c})\mathcal{R}_4(\boldsymbol{x})d^5\boldsymbol{x}} \quad \text{with} \quad S(\boldsymbol{x};\boldsymbol{c}) = \left|\sum_k c_k A_k(\boldsymbol{x})\right|^2$$

- The background PDF

$b(\boldsymbol{x})$ is taken from the D^0 mass sidebands

$D^0 \to K^+K^-\pi^+\pi^-$ amplitude analysis [JHEP 02 (2019) 126]

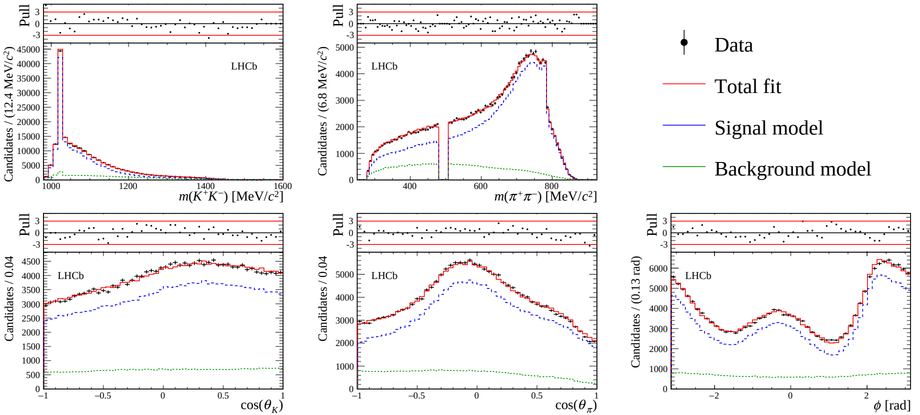
Model Building Method

1. Create a list of all possible amplitudes
2. Start with following minimal model :
   - $D^0 \to \phi(1020)^0[K^+, K^-](\rho - \omega)^0[\pi^+, \pi^-]$ in S,P & D waves
   - $D^0 \to K^*(892)^0[K^+, \pi^-]\overline{K}^*(892)^0[K^-, \pi^+]$ in S,P & D waves
3. Fit model + 1 new amplitude from the list
4. Add to the model the amplitude that produces the largest decrease in $-2\ln(\mathcal{L})$
5. Iterate steps 3 & 4

Stopping criteria

- Goodness of fit : χ^2
- Sum of fit fractions : interference

26 amplitudes have been selected to describe the signal



$D^0 \to K^+K^-\pi^+\pi^-$ amplitude analysis [JHEP 02 (2019) 126]

- Simultaneous fit of D^0 and $\bar{D}^0$ decays
- CPV parametrisation :

$$\overline{|c_k|} = \frac{|c_k|_{D^0} + |c_k|_{\bar{D}^0}}{2} \qquad A_{|c_k|} = \frac{|c_k|_{D^0} - |c_k|_{\bar{D}^0}}{|c_k|_{D^0} + |c_k|_{\bar{D}^0}}$$

$$\overline{\arg(c_k)} = \frac{\arg(c_k)_{D^0} + \arg(c_k)_{\bar{D}^0}}{2} \qquad \Delta\arg(c_k) = \frac{\arg(c_k)_{D^0} - \arg(c_k)_{\bar{D}^0}}{2}$$

- Fit fraction asymmetry:

$$A_{\mathcal{F}_k} = \frac{\mathcal{F}_k^{D^0} - \mathcal{F}_k^{\bar{D}^0}}{\mathcal{F}_k^{D^0} + \mathcal{F}_k^{\bar{D}^0}}$$

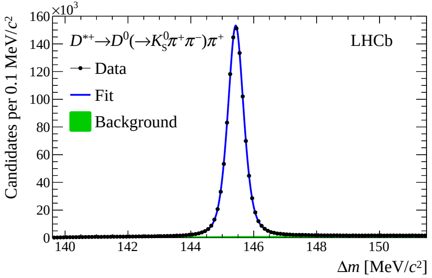
- Consistent with *CP* conservation with a sensitivity ranging from 1% to 15%

Measurement of the mass difference between neutral charm-meson eigenstates in $D^0 \to K^0_S \pi^+ \pi^-$ decays

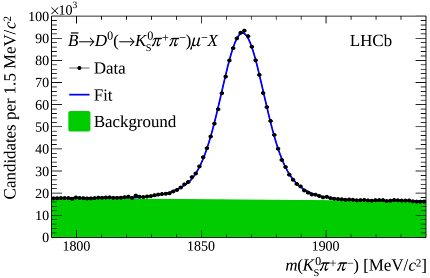
[Phys. Rev. Lett. 122 (2019) 231802]

- Dataset : 3.0 fb^{-1}, Run 1
- Production modes :
  - $D^{*+} \to D^0 \pi^+$: 1.3 M signal candidates
  - $B \to D^0 \mu^- X$: 1 M signal candidates

Prompt



Semileptonic



- Mass eigenstates

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

- Mixing parameters

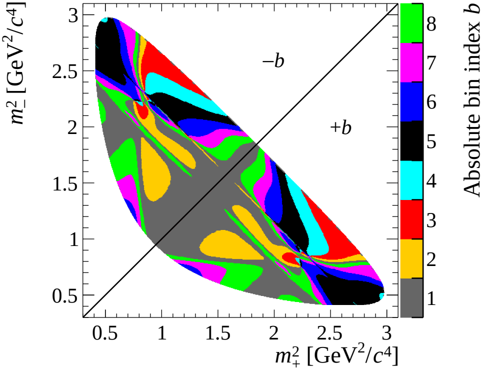
$$x \equiv \frac{m_1 - m_2}{\Gamma}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \quad \text{with } \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- CPV parametrisation

$$x_{CP} \equiv -\mathrm{Im}(z_{CP}), \qquad y_{CP} \equiv -\mathrm{Re}(z_{CP})$$
$$\Delta x \equiv -\mathrm{Im}(\Delta z), \qquad \Delta y \equiv -\mathrm{Re}(\Delta z)$$
$$\text{with} \quad z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y + ix)$$

The bin-flip method [A. Di Canto et al., PRD 99 (2019) 012007]

- Description of the phase space
- Bins of nearly constant strong-phase difference between D^0 & $\bar{D}^0$
- Simultaneous least-square fit of yields in all phase space and decay time bins



Results of *CP* parameters

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

Derived mixing parameters

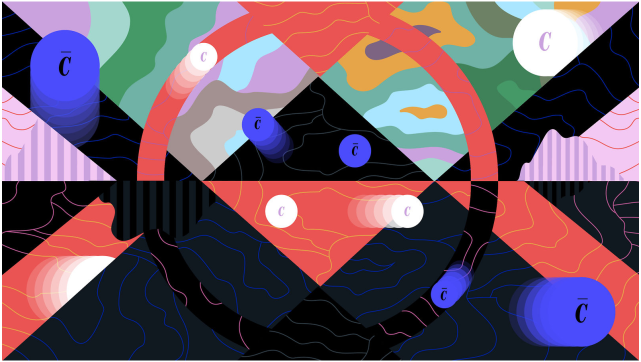
Parameter	Value	95.5% CL interval
x $[10^{-2}]$	$0.27\,^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
y $[10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p \rvert$	$1.05\,^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09\,^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

Combination with world average on x

$x = (3.9^{+1.1}_{-1.2}) \times 10^{-3}$ $\rightarrow$ first evidence for mass difference !

Conclusion

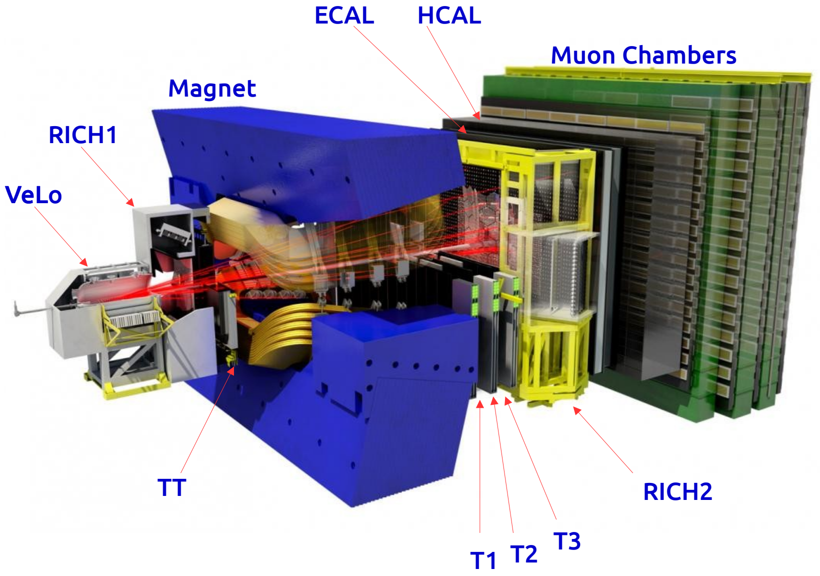
- Highlight of recent analyses from LHCb
- CPV has been observed for the first time in charm decays
- Many other analyses ongoing to complete the picture
- Working hard on Run 2 analyses and towards the upgrade for even better results



Artwork by Sandbox Studio, Chicago with Ana Kova

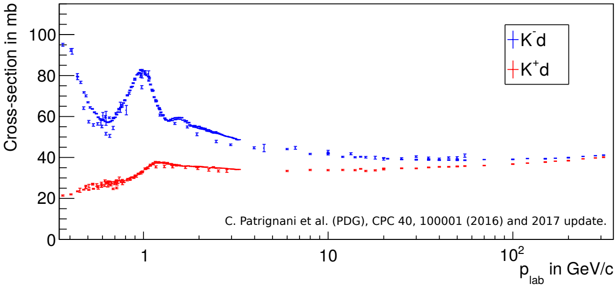
BACKUP

The LHCb detector



Detection asymmetry

- Detection asymmetry reduced by flipping magnet polarity regularly
- Residual detection asymmetry due to intrinsic different cross-section between particles of opposite charge when interacting with the detector's material



Signal PDF $D^0 \to K^+K^-\pi^+\pi^-$

$$a(\boldsymbol{x};\boldsymbol{c}) = \frac{\epsilon_s(\boldsymbol{x})S(\boldsymbol{x};\boldsymbol{c})\mathcal{R}_4(\boldsymbol{x})}{\int \epsilon_s(\boldsymbol{x})S(\boldsymbol{x};\boldsymbol{c})\mathcal{R}_4(\boldsymbol{x})d^5\boldsymbol{x}} \quad \text{with} \quad S(\boldsymbol{x};\boldsymbol{c}) = \left|\sum_k c_k A_k(\boldsymbol{x})\right|^2$$

- The normalisation integral is done by summing over a MC sample
- The efficiencies are taken care of by using a fully-simulated MC sample that has been reconstructed like the data sample
- Breit-Wigner, Flatté and K-matrix formalisms for the lineshapes
- Covariant formalism used for the spin factors

$D^0 \to K^+K^-\pi^+\pi^-$ signal model

Amplitude	$\lvert c_k \rvert$	$\arg(c_k)$ [rad]	Fit fraction [%]	σ
$D^0 \to \phi(1020)^0(\rho-\omega)^0$	1	0	$23.82 \pm 0.38 \pm 0.50$	> 40
$D^0 \to K_1(1400)^+K^-$	$0.614 \pm 0.011 \pm 0.031$	$1.05 \pm 0.02 \pm 0.05$	$19.08 \pm 0.60 \pm 1.46$	> 40
$D^0 \to [K^-\pi^+]_{L=0}[K^+\pi^-]_{L=0}$	$0.282 \pm 0.004 \pm 0.008$	$-0.60 \pm 0.02 \pm 0.10$	$18.46 \pm 0.35 \pm 0.94$	> 40
$D^0 \to K_1(1270)^+K^-$	$0.452 \pm 0.011 \pm 0.017$	$2.02 \pm 0.03 \pm 0.05$	$18.05 \pm 0.52 \pm 0.98$	> 40
$D^0 \to K^*(892)^0\overline{K}^*(892)^0$	$0.259 \pm 0.004 \pm 0.018$	$-0.27 \pm 0.02 \pm 0.03$	$9.18 \pm 0.21 \pm 0.28$	> 40
$D^0 \to K^*(1680)^0[K^-\pi^+]_{L=0}$	$2.359 \pm 0.036 \pm 0.624$	$0.44 \pm 0.02 \pm 0.03$	$6.61 \pm 0.15 \pm 0.37$	> 40
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=1}$	$0.249 \pm 0.005 \pm 0.017$	$1.22 \pm 0.02 \pm 0.03$	$4.90 \pm 0.16 \pm 0.18$	> 40
$D^0 \to K_1(1270)^-K^+$	$0.220 \pm 0.006 \pm 0.011$	$2.09 \pm 0.03 \pm 0.07$	$4.29 \pm 0.18 \pm 0.41$	> 40
$D^0 \to [K^+K^-]_{L=0}[\pi^+\pi^-]_{L=0}$	$0.120 \pm 0.003 \pm 0.018$	$-2.49 \pm 0.03 \pm 0.16$	$3.14 \pm 0.17 \pm 0.72$	37
$D^0 \to K_1(1400)^-K^+$	$0.236 \pm 0.008 \pm 0.018$	$0.04 \pm 0.04 \pm 0.09$	$2.82 \pm 0.19 \pm 0.39$	33
$D^0 \to K^*(1680)^0\overline{K}^*(892)^0$	$0.823 \pm 0.023 \pm 0.218$	$2.99 \pm 0.03 \pm 0.05$	$2.75 \pm 0.15 \pm 0.19$	37
$D^0 \to [\overline{K}^*(1680)^0K^*(892)^0]_{L=1}$	$1.009 \pm 0.022 \pm 0.276$	$-2.76 \pm 0.02 \pm 0.03$	$2.70 \pm 0.11 \pm 0.09$	> 40
$D^0 \to \overline{K}^*(1680)^0[K^+\pi^-]_{L=0}$	$1.379 \pm 0.029 \pm 0.373$	$1.06 \pm 0.02 \pm 0.03$	$2.41 \pm 0.09 \pm 0.27$	> 40
$D^0 \to [\phi(1020)^0(\rho-\omega)^0]_{L=2}$	$1.311 \pm 0.031 \pm 0.018$	$0.54 \pm 0.02 \pm 0.02$	$2.29 \pm 0.08 \pm 0.08$	> 40
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=2}$	$0.652 \pm 0.018 \pm 0.043$	$2.85 \pm 0.03 \pm 0.04$	$1.85 \pm 0.09 \pm 0.10$	> 40
$D^0 \to \phi(1020)^0[\pi^+\pi^-]_{L=0}$	$0.049 \pm 0.001 \pm 0.004$	$-1.71 \pm 0.04 \pm 0.37$	$1.49 \pm 0.09 \pm 0.33$	30
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=1}$	$0.747 \pm 0.021 \pm 0.203$	$0.14 \pm 0.03 \pm 0.04$	$1.48 \pm 0.08 \pm 0.10$	> 40
$D^0 \to [\phi(1020)^0\rho(1450)^0]_{L=1}$	$0.762 \pm 0.035 \pm 0.068$	$1.17 \pm 0.04 \pm 0.04$	$0.98 \pm 0.09 \pm 0.05$	24
$D^0 \to a_0(980)^0f_2(1270)^0$	$1.524 \pm 0.058 \pm 0.189$	$0.21 \pm 0.04 \pm 0.19$	$0.70 \pm 0.05 \pm 0.08$	27
$D^0 \to a_1(1260)^+\pi^-$	$0.189 \pm 0.011 \pm 0.042$	$-2.84 \pm 0.07 \pm 0.38$	$0.46 \pm 0.05 \pm 0.22$	17
$D^0 \to a_1(1260)^-\pi^+$	$0.188 \pm 0.014 \pm 0.031$	$0.18 \pm 0.06 \pm 0.43$	$0.45 \pm 0.06 \pm 0.16$	14
$D^0 \to [\phi(1020)^0(\rho-\omega)^0]_{L=1}$	$0.160 \pm 0.011 \pm 0.005$	$0.28 \pm 0.07 \pm 0.03$	$0.43 \pm 0.05 \pm 0.03$	18
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=2}$	$1.218 \pm 0.089 \pm 0.354$	$-2.44 \pm 0.08 \pm 0.15$	$0.33 \pm 0.05 \pm 0.06$	14
$D^0 \to [K^+K^-]_{L=0}(\rho-\omega)^0$	$0.195 \pm 0.015 \pm 0.035$	$2.95 \pm 0.08 \pm 0.29$	$0.27 \pm 0.04 \pm 0.05$	15
$D^0 \to \phi(1020)^0f_2(1270)^0$	$1.388 \pm 0.095 \pm 0.257$	$1.71 \pm 0.06 \pm 0.37$	$0.18 \pm 0.02 \pm 0.07$	14
$D^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	$1.530 \pm 0.086 \pm 0.131$	$2.01 \pm 0.07 \pm 0.09$	$0.18 \pm 0.02 \pm 0.02$	20
		Sum of fit fractions	$129.32 \pm 1.09 \pm 2.38$	
		χ^2/ndf	$9242/8121 = 1.14$	

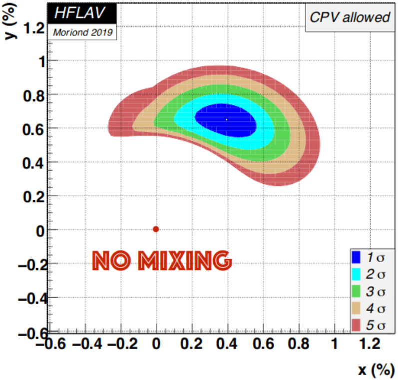
Mass difference measurement details

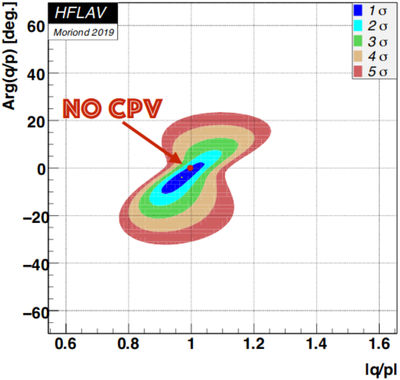
$$\chi^2 \equiv \sum_{\mathrm{pr,sl}} \sum_{\mathrm{l,d}} \sum_{+,-} \sum_{b,j} \frac{(N^{\pm}_{-bj} - N^{\pm}_{+bj} R^{\pm}_{+bj})^2}{(\sigma^{\pm}_{-bj})^2 + (\sigma^{\pm}_{+bj} R^{\pm}_{+bj})^2}$$
$$+ \sum_{b,b'} \left(X_b^{\mathrm{CLEO}} - X_b\right) (V^{-1}_{\mathrm{CLEO}})_{bb'} \left(X_{b'}^{\mathrm{CLEO}} - X_{b'}\right) .$$

$$R^{\pm}_{bj} \approx \frac{r_b + \frac{1}{4} r_b \langle t^2 \rangle_j \,\mathrm{Re}(z_{CP}^2 - \Delta z^2) + \frac{1}{4} \langle t^2 \rangle_j \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b} \langle t \rangle_j \,\mathrm{Re}[X_b^*(z_{CP} \pm \Delta z)]}{1 + \frac{1}{4} \langle t^2 \rangle_j \,\mathrm{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{1}{4} \langle t^2 \rangle_j \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b} \langle t \rangle_j \,\mathrm{Re}[X_b(z_{CP} \pm \Delta z)]} .$$

N are the yields and σ are the yields uncertainties. X_b are the strong phase difference in each phase space bin and r_b are the yields ratios in these bins.

World average





$$x = \left(0.39^{+0.11}_{-0.12}\right)\%$$

$$y = \left(0.651^{+0.063}_{-0.069}\right)\%$$

$$|q/p| = \left(0.969^{+0.050}_{-0.045}\right)$$

$$\phi = \left(-3.9^{+4.5}_{-4.6}\right)^{\circ}$$