Charm mixing and *CP* violation at LHCb

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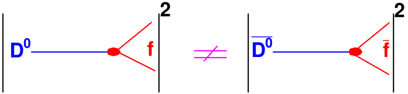
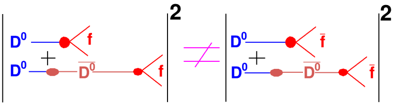
Outline

- **Direct CPV:**



  - Observation of *CP* violation in neutral charm meson decays $\Rightarrow$ the ΔA_{CP} measurement
  - Search for *CP* violation in $D^+ \to K^0_S K^+$, $D^+_s \to K^0_S \pi^+$, and $D^+ \to \phi \pi^+$ decays

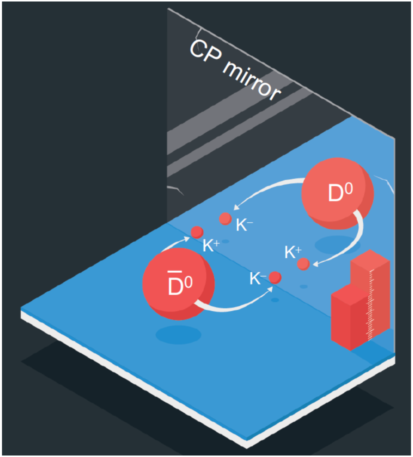
- **Mixing and indirect CPV:**



  - Time dependent CPV in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays $\Rightarrow$ the A_Γ measurement
  - Model-independent Bin-flip method for $D^0 \to K^0_S \pi^+\pi^-$ decays

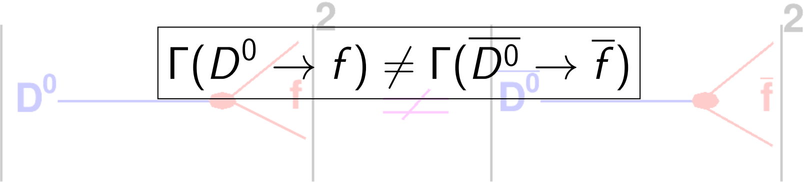
CPV in charm decays

- Complementary to CPV in beauty or kaon systems
- Prediction $\rightarrow$ very small $\left[\mathcal{O}(10^{-4})–\mathcal{O}(10^{-3})\right]$ [1]
- New physics can be hidden in loops
- Large production cross section in LHCb allows us to reach the desired sensitivity to observe charm CPV
- CPV is finally discovered in charm decays at LHCb in 2019



[1] https://arxiv.org/abs/hep-ph/0609178
https://arxiv.org/abs/1706.07780 [hep-ph]
https://arxiv.org/abs/1112.5451 [hep-ph]

Direct CPV



$$\boxed{\Gamma(D^0 \to f) \neq \Gamma(\overline{D^0} \to \bar{f})}$$

$$\boxed{\mid A_f \mid \neq \mid \overline{A}_{\bar{f}} \mid}$$

Search for A_{CP} in two-body decays

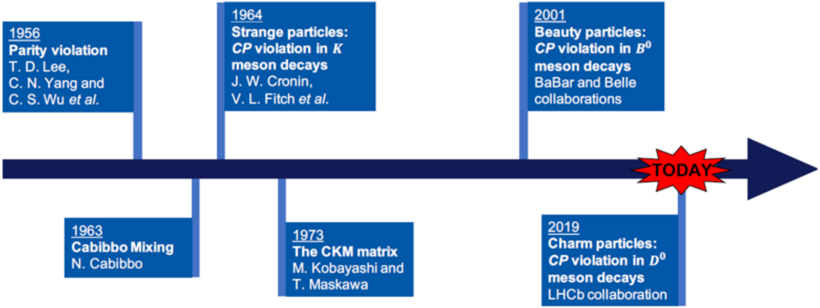
Most precise

https://hflav-eos.web.cern.ch/hflav-eos/charm/

	LHCb Run I	Belle	BABAR	BESIII
Modes	**A_{CP}(%)**			
$D^0 \to K^+K^-$	$0.04 \pm 0.12 \pm 0.10$	$-0.32 \pm 0.21 \pm 0.09$	$0.00 \pm 0.34 \pm 0.13$	
$D^0 \to \pi^+\pi^-$	$0.07 \pm 0.14 \pm 0.11$	$0.55 \pm 0.36 \pm 0.09$	$-0.24 \pm 0.52 \pm 0.22$	
$D^0 \to K^0_S K^0_S$	$-2.9 \pm 5.2 \pm 2.2$	$0.00 \pm 1.53 \pm 0.17$		
$D^0 \to \pi^0\pi^0$		$-0.03 \pm 0.64 \pm 0.10$		
$D^+ \to \pi^+\pi^0$		$2.31 \pm 1.24 \pm 0.23$		
$D^+ \to K^0_S K^+$	$0.03 \pm 0.17 \pm 0.14$	$0.08 \pm 0.28 \pm 0.14$	$0.46 \pm 0.36 \pm 0.25$	$-1.5 \pm 2.8 \pm 1.6$
$D^+ \to \phi\pi^+$	$-0.04 \pm 0.14 \pm 0.14$	$0.51 \pm 0.28 \pm 0.05$		
$D^+_s \to K^0_S\pi^+$	$0.38 \pm 0.46 \pm 0.17$	$5.45 \pm 2.50 \pm 0.33$	$0.3 \pm 2.0 \pm 0.3$	
$D^+ \to \eta'\pi^+$	$-0.61 \pm 0.72 \pm 0.55 \pm 0.12$	$-0.12 \pm 1.12 \pm 0.17$		
$D^+_s \to \eta'\pi^+$ . . .	$-0.82 \pm 0.36 \pm 0.24 \pm 0.27$			

- All results are consistent with no CP violation hypothesis

Observation of CPV in neutral charm meson decays



Observation of CPV in charm-ΔA_{CP} measurement

- Data sample: Full Run II data of 5.9 fb^{-1} Phys. Rev. Lett. **122**, 211803
- Charm tagging:
  - **Prompt:** coming from primary vertex, *i.e.* $D^{*\pm} \to D\pi^{\pm}$
  - **Semileptonic:** coming from B-decays, *i.e.* $B \to D\mu^{\pm}X$

The measured asymmetry ($\mathbf{A_{raw}}$) in $\mathbf{D \to h^+h^-}$ decays ($h = K$ or π) includes both physics and detector effects:

$$\mathbf{A_{raw} = A_{CP} + A_D + A_P}$$

$$\Downarrow$$

$$\frac{N(D^0 \to h^+h^-) - N(\overline{D^0} \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\overline{D^0} \to h^+h^-)}$$

Asymmetry of our interest

Detection asymmetry from π (prompt) or μ (semileptonic)

Production asymmetry of D^* (prompt) or B (semileptonic)

To eliminate $\mathbf{A}_D$ and $\mathbf{A_P}$:

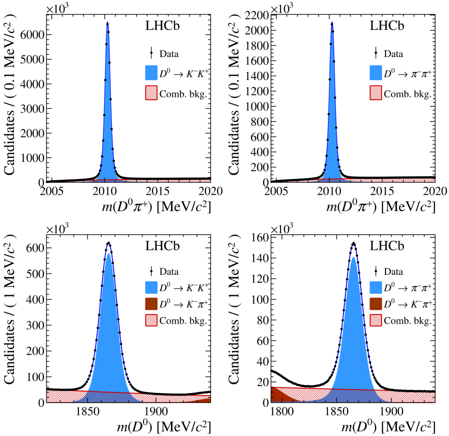
$$\mathbf{\Delta A_{CP} = A_{K^+K^-} - A_{\pi^+\pi^-} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)}$$

ΔA_{CP} measurement: fits and yields

Phys. Rev. Lett. **122**, 211803

- Fit $m(D^0\pi)$ (prompt) or $m(D^0)$ (semileptomic) $\Rightarrow$ **A_{raw}**
- Signal events from **prompt** decay:
  - **44 million** for $D \to K^+K^-$
  - **14 million** for $D \to \pi^+\pi^-$
- Signal events from **semileptonic** decay:
  - **9 million** for $D \to K^+K^-$
  - **3 million** for $D \to \pi^+\pi^-$

Prompt (top) and **semileptonic (bottom):**



ΔA_{CP} measurement: systematic uncertainties

Phys. Rev. Lett. **122**, 211803

$(\times 10^{-4})$

Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
Peaking background	0.5	–
B fractions	–	1
B reco. efficiency	–	2
Total	0.9	5

- Dominant systematic uncertainty:
  - **Prompt:**
    - **fit model:** evaluated by pseudo-experiments
    - **peaking ($m(D^0\pi)$) background ($D^0 \to K^-\pi^+\pi^0$, $D^0 \to \pi^-\ell^+\nu_\ell$):** evaluated via measuring yields and background asymmetries in $m(D^0)$ distributions
  - **Semileptonic:**
    - **Mistag** evaluated from $B \to D^0(K^-\pi^+)\mu X$ sample

ΔA_{CP} measurement: results

Phys. Rev. Lett. **122**, 211803

- From Run II:

$$\Delta A_{CP}^{\pi-tag} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4},$$
$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8 \pm 5) \times 10^{-4}$$

- Combine with LHCb Run I data:

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

Observation of CP violation with 5.3σ significance!

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

- CPV can arise from interference between $c \to d\bar{d}u$ and $c \to s\bar{s}u$
- Run II data set of 3.8 fb^{-1}

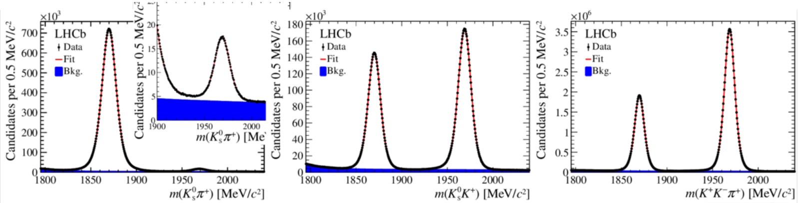
Phys. Rev. Lett. **122**, 191803

$$A_{CP}(D_s^+ \to K_S^0\pi^+) \approx A(D_s^+ \to K_S^0\pi^+) - A(D_s^+ \to \phi\pi^+)$$

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

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

- Simultaneous fit is performed to extract raw asymmetries
- Signal yield varies from 0.6 to 53 million



Search for CPV in $D^+ \to K^0_S K^+$, $D^+_s \to K^0_S \pi^+$, and $D^+ \to \phi\pi^+$ decays

Phys. Rev. Lett. **122**, 191803

Systematic uncertainties:

$(\times 10^{-3})$

Source	$\mathcal{A}_{CP}(D_s^+ \to K^0_S\pi^+)$	$\mathcal{A}_{CP}(D^+ \to K^0_S K^+)$	$\mathcal{A}_{CP}(D^+ \to \phi\pi^+)$
Fit model	0.39	0.44	0.24
Secondary decays	0.30	0.12	0.03
Kinematic differences	0.09	0.09	0.04
Neutral kaon asymmetry	0.05	0.05	0.04
Charged kaon asymmetry	0.08	0.09	0.15
Total	0.51	0.48	0.29

- Dominant source is the fit model
- Secondary charm contribution (from semileptonic B decays) is also non-negligible

Search for CPV in $D^+ \to K^0_S K^+$, $D^+_s \to K^0_S \pi^+$, and $D^+ \to \phi\pi^+$ decays

Results:

Phys. Rev. Lett. **122**, 191803

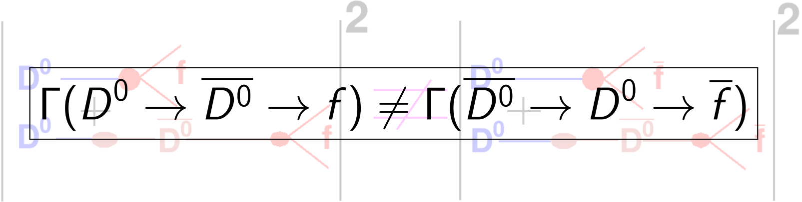
$$\mathbf{A_{CP}(D^+_s \to K^0_S \pi^+) = (1.3 \pm 1.9 \pm 0.5) \times 10^{-3}}$$
$$\mathbf{A_{CP}(D^+ \to K^0_S K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3}}$$
$$\mathbf{A_{CP}(D^+ \to \phi\pi^+) = (0.05 \pm 0.42 \pm 0.29) \times 10^{-3}}$$

- **Best measurements of A_{CP} on these modes!**

Results with Run I + Run II:

$$\mathbf{A_{CP}(D^+_s \to K^0_S \pi^+) = (1.6 \pm 1.7 \pm 0.5) \times 10^{-3}}$$
$$\mathbf{A_{CP}(D^+ \to K^0_S K^+) = (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3}}$$
$$\mathbf{A_{CP}(D^+ \to \phi\pi^+) = (0.03 \pm 0.40 \pm 0.29) \times 10^{-3}}$$

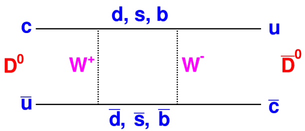
Mixing and indirect CPV



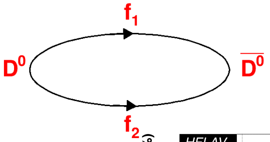
$$\Gamma(D^0 \to \overline{D^0} \to f) \neq \Gamma(\overline{D^0} \to D^0 \to \overline{f})$$

$D^0 - \overline{D^0}$ mixing

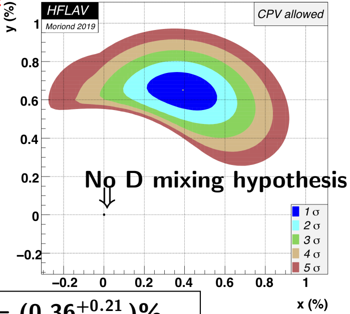
Short range



Long range



Formalism



Mass eigenstates:

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

$m_{1,2}$, $\Gamma_{1,2}$ are masses and widths of $D_{1,2}$

Mixing parameters:

$$x \equiv \frac{m_1 - m_2}{\Gamma};\ y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

$$x = (0.36^{+0.21}_{-0.16})\%$$
$$y = (0.67^{+0.26}_{-0.17})\%$$

Search for TD CPV in $D^0 \to h^+h^-$ decays ($h = K, \pi$)

LHCb-CONF-2019-001

- Standard model prediction is smaller than current experimental precision

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

$$\Downarrow \text{ (since } x, y << 1)$$

$$A_{CP}(f,t) \approx A_{CP}^{\text{decay}}(f) - \boxed{\mathbf{A_\Gamma}} \frac{t}{\tau_{D^0}}$$

- Perform a linear fit to the values of A_{CP} calculated from bins of D^0 decay time
  - The slope parameter is $\mathbf{A_\Gamma}$
  - $\mathbf{A_\Gamma = -a_{CP}^{indir}}$
- Data sample $\approx 2\ \text{fb}^{-1}$ from Run II

Search for TD CPV in $D^0 \to h^+h^-$ decays ($h = K, \pi$)

- A_Γ is from 21 bins of D decay time LHCb-CONF-2019-001
- Dataset: 17 million for $D^0 \to K^+K^-$ and 5 million for $D^0 \to \pi^+\pi^-$
- Validated measurement with $D^0 \to K^-\pi^+$

Results:

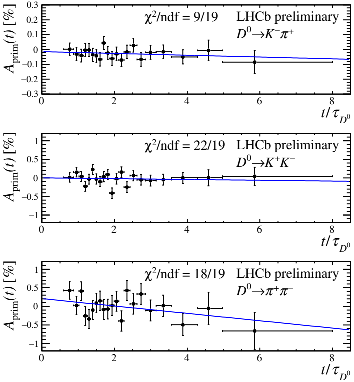
$$\mathbf{A_\Gamma(D^0 \to K^-\pi^+) = (0.7 \pm 1.1) \times 10^{-4}}$$
$$\mathbf{A_\Gamma(D^0 \to K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4}}$$
$$\mathbf{A_\Gamma(D^0 \to \pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}}$$

A_Γ does not depend on D decay channel and two values can be combined

$$\mathbf{A_\Gamma(D^0 \to h^+h^-) = (3.4 \pm 3.1 \pm 0.6) \times 10^{-4}} \quad (h = K, \pi)$$

Combining with Run I data:

$$\mathbf{A_\Gamma(D^0 \to h^+h^-) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}} \quad (h = K, \pi)$$

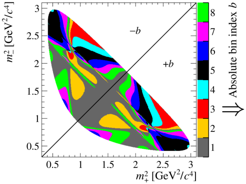


A_Γ is consistent with SM!

Measurement of the mass difference between neutral charm meson eigenstates

- Used $D^0 \to K^0_S \pi^+\pi^-$ decays $\Rightarrow$ rich resonance structures
- Good sensitivity due to interference between D^0 and $\overline{D^0}$ decays
- Challenges in LHCb:
  - **Decay time acceptance & distortions in Dalitz** $\Rightarrow$ difficult to model
  - $\mathbf{K^0_S}$ **reconstruction** $\Rightarrow$ different Dalitz-acceptance & resolution at different regions of its decay
  - **Separation of semileptonic** D (≈ 1 million) from prompt (≈ 1.3 million)

Phys. Rev. D. **99**, 012007 (2019)



$\Rightarrow$ **Equal $\Delta\delta_D$ binning**

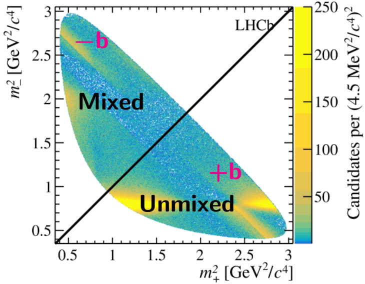
$\Downarrow$

- Model-independent **Bin-flip** approach
- Simpler than Dalitz analysis
- To avoid efficiency modeling and dynamics of D^0 decay

Model-independent Bin-flip method

- Used c_b, s_b from CLEO-c

Phys. Rev. Lett. **122**, 231802



- Bin Dalitz into $\pm b$ about $m_+^2 = m_-^2$
- D decay time into bins j
- Measure ratio of signal in $-b$ and $+b$ in bin j

$$R_{bj}^{\pm} = \frac{r_b \left[1 + \frac{1}{4} t_j^2 Re(z_{CP}^2 - \Delta z^2)\right] + \frac{1}{4} t_j^2 \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b} t_j Re\left[\mathbf{X}_b^* (z_{CP} \pm \Delta z)\right]}{\left[1 + \frac{1}{4} t_j^2 Re(z_{CP}^2 - \Delta z^2)\right] + r_b \frac{1}{4} t_j^2 \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b} t_j Re\left[\mathbf{X}_b^* (z_{CP} \pm \Delta z)\right]},$$

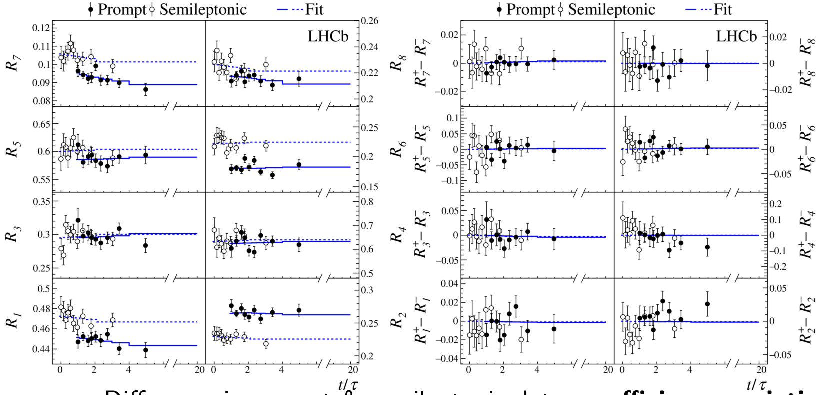
where $z_{CP} \pm \Delta z = -\left(\frac{q}{p}\right)^{\pm}(y + ix)$ and r_b is ratio without mixing $\mathbf{X_b} = \mathbf{c_b} - \mathbf{is_b}$

$R^{\pm}$ **changes with time** $\Rightarrow$ **Mixing**
$R^+ \neq R^-$ $\Rightarrow$ **Indirect CPV**

Model-independent Bin-flip method: results (Run I data)

Phys. Rev. Lett. **122**, 231802

$\propto (\mathbf{D^0} + \overline{\mathbf{D^0}})$ $\quad$ $(\mathbf{D^0} - \overline{\mathbf{D^0}})$



- Difference in prompt & semileptonic data $\Rightarrow$ **efficiency variation across Dalitz**
- The slope indicates the *D*-mixing

Results and world average

Phys. Rev. Lett. **122**, 231802

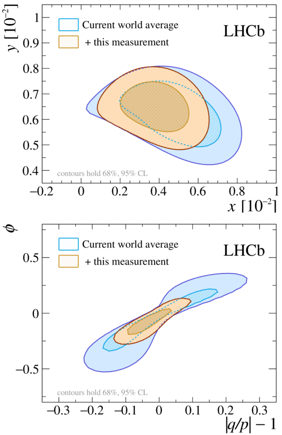
$y_{CP} = (0.74 \pm 0.36 \pm 0.11)\%$
$\Delta y = (-0.06 \pm 0.16 \pm 0.03)\%$
$x_{CP} = (0.27 \pm 0.16 \pm 0.04)\%$
$\Delta x = (-0.053 \pm 0.070 \pm 0.022)\%$

From Belle: Phys. Rev. D. **89**, 091103 (2014)

$x = (0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08})\%$
$y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07})\%$

For no CPV hypothesis:
$x_{CP} = x,\ y_{CP} = y,\ \Delta x = \Delta y = 0$

- Best precision on x from a single measurement!
- Statistically dominated
- Dominant systematics → semileptonic contamination



$x > 0$ at 3σ!

Summary

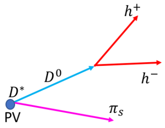
- Plenty of charm data have been collected at LHCb from Run I and Run II
- *CP* **violation in charm decays has been observed for the first time**
- Bin-flip method allows us to perform **the most precise measurement of** x
- **First evidence of** $x > 0$
- Many interesting charm analyses are going on with the full LHCb dataset
- Stay tuned...

Backup slides

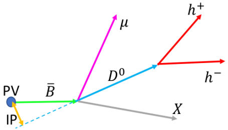
Determining the flavor of D meson

Two ways to distinguish D^0 and $\overline{D^0}$:

- From prompt: use "slow" pion charge
- From secondary: use the charge of muon



Prompt tag – IP ~ 0



Semileptonic tag – IP > 0

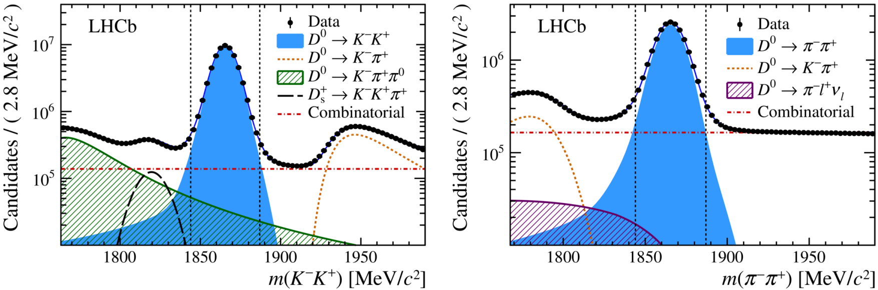
ΔA_{CP} future prospects

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^-K^+$	Yield $D^0 \to \pi^-\pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

- Huge improvement in precision

ΔA_{CP} peaking backgrounds

- From $m(K^+K^-)$ and $m(\pi^+\pi^-)$ fits and then extrapolated into the signal region



A_Γ measurement-systematic uncertainties

$(\times 10^{-4})$

Source	$A_\Gamma(D^0 \to K^+K^-)$	$A_\Gamma(D^0 \to \pi^+\pi^-)$
Secondary decays	0.4	0.4
Δm background	0.3	0.5
$m(h^+h^-)$ background	0.3	0.2
Kinematic weighting	0.3	0.3
Sum in quadrature	0.7	0.8

New world average

$$\mathbf{\Delta A_{CP} \simeq \Delta a_{CP}^{dir}\left(1 + \frac{\langle \bar{t} \rangle}{\tau_{D^0}} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau_{D^0}} a_{CP}^{ind}}$$

$$\Delta A_{CP} \approx a_{CP}^{dir} - \frac{\Delta \langle t \rangle}{\tau_{D^0}} A_{\Gamma}$$

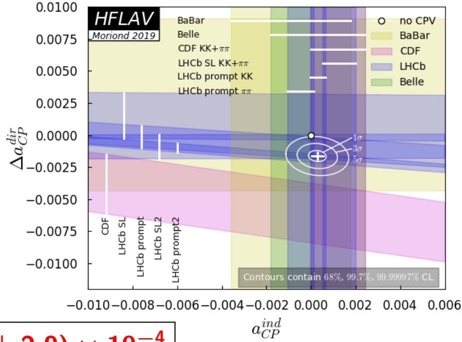
- $\langle \bar{t} \rangle \equiv \frac{\left(\langle t \rangle_{KK} + \langle t \rangle_{\pi\pi}\right)}{2}$

  $\Delta \langle t \rangle \equiv \langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}$

- $\frac{\langle \bar{t} \rangle}{\tau_{D^0}}$, $\frac{\Delta \langle t \rangle}{\tau_{D^0}}$ are from full dataset
- LHCb averages for

  $y_{CP} = (5.7 \pm 1.5) \times 10^{-3}$;

  $a_{CP}^{ind} = (-2.8 \pm 2.8) \times 10^{-4}$



$$\mathbf{\Delta a_{CP}^{dir} = (-15.6 \pm 2.9) \times 10^{-4}}$$

confirms that ΔA_{CP} is **mainly sensitive to direct CPV**

Bin-flip method

Advantages:

- Does not require to model Dalitz
- Time and Dalitz acceptance modeling not required

Limitations:

- Cleo-c input can be limiting factor for Run II
- *CP*-eigenstates cancel in ratios $\rightarrow$ less sensitive to y, Δy
- Treats time & Dalitz are uncorrelated $\rightarrow$ further reduces the sensitivity to $y, \Delta y$

Comparison with Belle

- Belle dataset: 1.2 million signal events Phys. Rev. D. **89**, 091103 (2014)
- LHCb dataset: 2.3 million signal events

Belle:

$$x = (0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08})\%$$
$$y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07})\%$$

- Statistically dominated
- Significant modeling uncertainty

LHCb Run I:

$$x = (0.27 \pm 0.16 \pm 0.04)\%$$
$$y = (0.74 \pm 0.36 \pm 0.11)\%$$

- Statistically dominated
- Dominant systematic uncertainties are Dalitz model and acceptance

Bin-flip method-systematic uncertainties

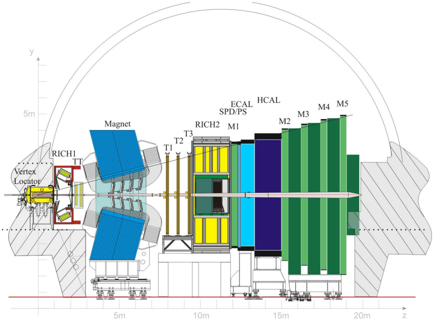
$(\times 10^{-3})$

Source	x_{CP}	y_{CP}	Δx	Δy
Secondary charm decays	0.24(0.44)(0.00)	0.36(0.65)(0.00)	< 0.01	< 0.01
Unrelated $D^0\mu^-$ combinations	0.34(0.00)(0.94)	0.31(0.00)(0.60)	< 0.01	< 0.01
Reconstruction and selection biases	0.08(0.24)(0.08)	0.94(1.37)(0.21)	0.22(0.24)(0.28)	0.25(0.29)(0.22)
Mass-fit model	0.04(0.02)(0.10)	0.03(0.08)(0.15)	< 0.01	0.03(0.04)(< 0.01)
VELO length scale	< 0.01	< 0.01	< 0.01	< 0.01
Input D^0 lifetime	< 0.01	< 0.01	< 0.01	< 0.01
Total systematic	0.43(0.50)(0.95)	1.05(1.52)(0.65)	0.22(0.24)(0.28)	0.25(0.29)(0.22)
CLEO inputs	0.70(0.65)(0.87)	1.22(1.54)(1.35)	0.19(0.25)(0.28)	0.26(0.36)(0.65)
Statistical (w/o CLEO inputs)	1.46(1.76)(2.64)	3.35(4.02)(6.12)	0.68(0.74)(1.67)	1.58(1.76)(3.93)
Statistical	1.62(1.87)(2.78)	3.57(4.30)(6.27)	0.70(0.78)(1.69)	1.60(1.80)(3.98)

The LHCb detector

J. Instrum. **3** (2008) S08005; Nucl.Phys. **B 871** (2013) 1-20; J. High Energ. Phys. **74** (2017)

Single-arm spectrometer covering pseudo-rapidity $\eta \in (2, 5)$



- **VE**etex **LO**cator: 20 μm IP resolution
- Tracking systems: $\frac{\Delta p}{p} = 0.4$–0.6% @ 5–100 GeV$/c$
- RICH: excellent particle identification; $>$95% efficiency & 5% mis-identification

Due to large cross-section, unprecedented amount of charm decays are collected during **Run I** ($\sqrt{s}$= **7 TeV** between Year 2011–2012) and **Run II** ($\sqrt{s}$= **13 TeV** between Year 2015–2018)