Charm mixing, CPV and Rare decays

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Outline

- Charm mixing, *CP* violation and Rare Decays:
  - Why important and challenging?
- Why charm is special?
- Where and how is charm studied?

- Mixing and *CP* violation:
  - Introduction & news
- Rare Decays:
  - Current status & news

- Summary

DISCLAIMER Charm spectroscopy not covered

Charm - Main Goals

- Test the robustness of the Standard Model
- Find and identify New Physics beyond SM

Where to look?

- Suppressed or Forbidden decays in SM
- Rare processes involving loop diagrams:

$D^0 - \bar{D}^0$ **mixing**

CP violation in charm

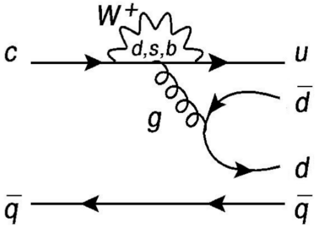
- New Particles may affect the loops

Charm - Key Features

- Down-type quarks in loops
  - **Complementary** to strange & beauty
- **Unique** access to (NP ?) currents coupling to up-type quarks
- Loops are highly suppressed
  - *CP* violation & Rare decays suppressed in SM
- QCD based calculations are difficult ($\sim 1/m_c$)

Hence we need

- Large & clean data samples
- Precise calculation of SM contributions



CKM suppression in *b* **loop**

$\sim V_{ub}V_{cb}(\frac{m_b}{m_W})^2 \sim 10^{-6}$

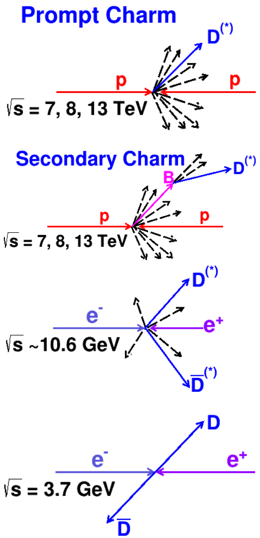
GIM suppression in *s* and *d* loops

$\sim \frac{(m_s^2 - m_d^2)}{m_W^2}$

complete cancellation in U-spin limit ($m_s = m_d$)

Charm - From Experiments

collider	Exp	$\sqrt{s}$	Lumi	$\sigma(c\bar{c})$	$N(c\bar{c})$
hadron			prompt charm		
	LHCb	13 TeV	6/fb	2.6 mb	16×10^{12}
		7, 8 TeV	3/fb	1.4 mb	4×10^{12}
	CDF	2 TeV	10/fb	0.1 mb	2.3×10^{11}
e^+e^-	B-Factories			continuum charm	
	Belle	10.6 GeV	1000/fb	1.3 nb	1.3×10^{9}
	BaBar		550/fb		0.7×10^{9}
	Belle2		200/fb		0.3×10^{9}
	Charm Factories @ $D\bar{D}$ threshold				
	BESIII	3.7 GeV	3/fb	3 nb	20×10^{6}
	Cleo-c		0.8/fb		5×10^{6}



Charm - Characteristics

LHCb

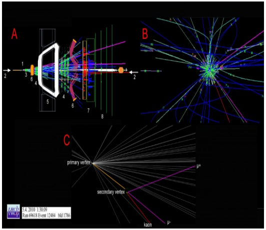
- Large cross-section
- Busy environment
- Non-trivial triggers with $\epsilon \sim \mathcal{O}(10^{-3} - 10^{-2})$
- Decays involving neutrals (γ, ν) are difficult
- D^0 flight distance $\sim$ 10 mm, $\sigma(t) \sim$ 50 fs

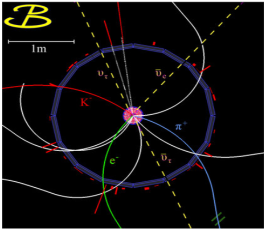
BELLE, Belle II, BABAR

- Cleaner environment
- No trigger, $\epsilon \sim 100\%$
- Good for decays involving neutrals
- D^0 flight distance $\sim 200 - 500\mu$m, $\sigma(t) \sim$ 250 fs (150 fs for Belle II)

BESIII

- Background free charm production
- No boost for $D \Rightarrow$ No time measurement
- Quantum-correlated charm production; $\Psi(3770) \to D\bar{D}$ and $CP(D) \times CP(\bar{D}) = -1$



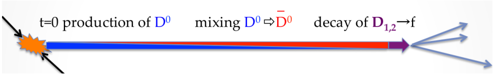


Mixing and CP violation

Why do Neutral Mesons Mix?

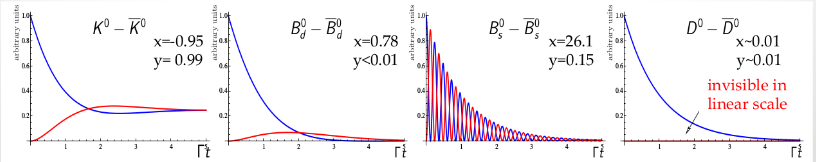
- Flavour eigenstates $D^0(c\bar{u})$ $\bar{D}^0(\bar{c}u) \neq$ Mass eigenstates $D_1(m_1,\Gamma_1)D_2(m_2,\Gamma_2)$

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



Mixing parameters $\boxed{\mathbf{x = \frac{m_2 - m_1}{\Gamma}; y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}}}$; $\mathbf{\Gamma = \frac{\Gamma_1+\Gamma_2}{2}}$

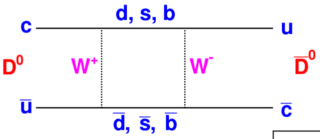
Probability that initial flavour ($t = 0$) changed/unchanged at time t



Understanding x and y

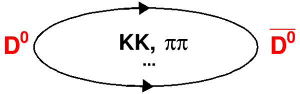
Standard Model contributions:

Short range quark-level mixing:



$\mathbf{x \sim 10^{-5}}$

Long range mixing via Final State Interactions:

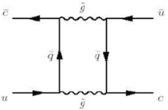


arXiv : hep – ph/0310076

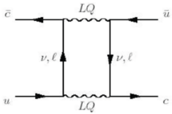
$\mathbf{x, y \sim 1\%}$

- Long range effects ⇒ difficult to calculate
- New Physics can affect **x**

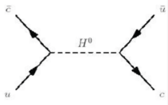
SUSY



Leptoquarks



Extended Higgs



- **Large uncertainties in SM mixing rate ⇒ Difficult to spot NP!**

How to find the flavour of D at its production ?

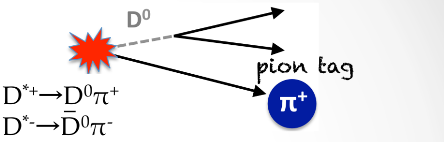
- Tag the flavour at the production
  - Find if D^0 or $\bar{D}^0$ produced at $t = 0$
- Mixing changes flavour at any time t

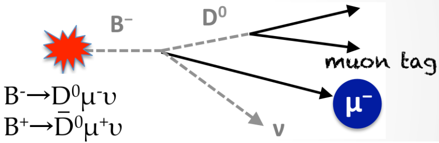
Prompt Charm: pp $\rightarrow$ D$^{*\pm}$

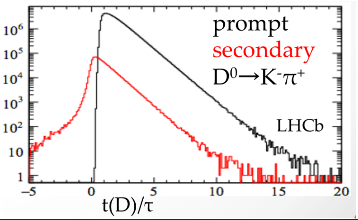
- $D^0/\bar{D}^0$ from soft-pion charge

Secondary Charm: pp $\rightarrow$ B $\rightarrow$ D

- $D^0/\bar{D}^0$ from muon charge
- Prompt Charm used at B-factories
- LHCb uses both data samples
- Full coverage of D decay time



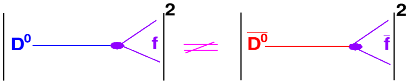




CP violation - Types & Observables

Direct CPV:

- **In Decay:**

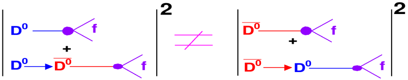


- $|\frac{\bar{A}_F}{A_F}| \neq 1$
- Difference in decay rates of D^0 and $\bar{D}^0$ $\Rightarrow$ $A_{CP} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\bar{D}^0 \to \bar{f})}$
- Depends on decay mode

Mixing induced CPV:

- **In Mixing:**

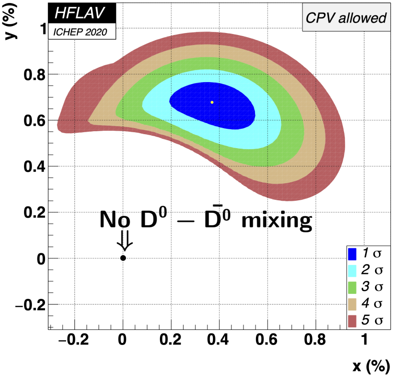
- $|\frac{q}{p}| \neq 1$
- **In Interference between Mixing and Decay:**



- $\phi \equiv \arg(\frac{q}{p}) \neq 0$
- Difference in decay rates as function of D decay time
- Independent of decay mode

Mixing & CPV: Time Dependent Studies

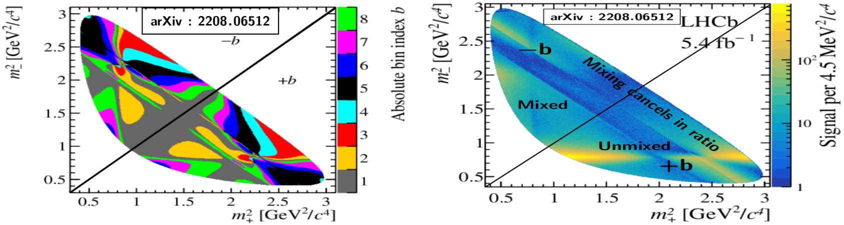
- Mixing & mixing induced CPV universal
- Don't depend on the decay mode
- Only in neutral D decays
- $D^0 - \bar{D}^0$ mixing observed in 2013 by LHCb[1]
- Significant non-zero value of x measured for the first time in 2021



[1]PRL **110**, 101802 (2013)

Model-independent Bin-Flip approach

PRD **99**, 012007 (2019)



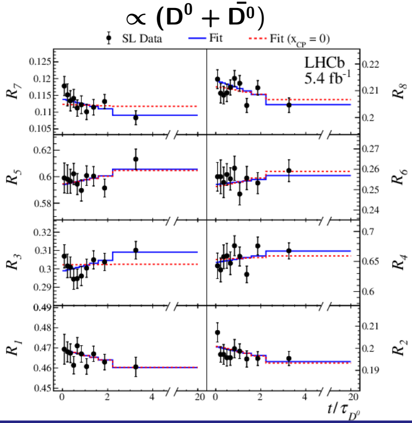
- Good sensitivity to $(\mathbf{x}, \mathbf{y}, \mathbf{q}, \mathbf{p})$ from interference between resonances contributing D^0 and $\bar{D}^0$ decays
- **Golden mode:** overlapping resonances, rich dynamics, and large statistics
- No need for Dalitz model or precise time & Dalitz acceptance $\Rightarrow$ Hard in LHCb
- Uses strong phases between $\mathbf{D^0}, \mathbf{\bar{D}^0} \rightarrow \mathbf{K^0_S \pi^+\pi^-}$ from CLEO-c & BESIII
  $\Rightarrow c_b = \cos\Delta\delta, s_b = \sin\Delta\delta$ PRD **101**, 112002 (2020) PRL **122**, 231802 (2019)
- Divide Dalitz plot into $\pm b$ bins; D decay time into j bins
- Measure ratio of signal in $-b$ and $+b$ in bin j

$$\mathbf{R^{\pm}_{bj}} \simeq \mathbf{r_b} - t_j\sqrt{\mathbf{r_b}}\left[(1-\mathbf{r_b})\, c_b y - (1+\mathbf{r_b})\, s_b x\right]$$

$\mathbf{r_b}$ = ratio w/o mixing$(t=0)$

- LHCb Run 2 Data, **3.6 M** secondary charm ($B \to D^0\mu\nu$) signal events

arXiv : 2208.06512 (Submitted to PRD)



- $\mathbf{R^\pm}$ changes with time $\Rightarrow$ **Mixing**
- Simultaneous χ^2 fit to all bins:
  - Common Mixing/CPV parameters
  - Constrain strong phases

$$x = \left(4.6^{+1.5}_{-1.6}\right) \times 10^{-3}$$
$$y = \left(12.4^{+3.2}_{-3.3}\right) \times 10^{-3}$$

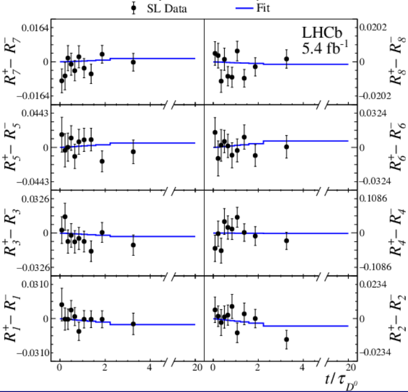
- ***x* is $\sim 3\sigma$ away from zero!**
- Statistically dominated!

$D^0 \to K_S^0\pi^+\pi^-$ Bin-Flip: Results from **secondary charm sample**

- LHCb Run 2 Data, **3.6 M** secondary charm ($B \to D^0\mu\nu$) signal events

arXiv : 2208.06512 (Submitted to PRD)

$\propto (\mathbf{D^0} - \mathbf{\bar{D}^0})$



- $\mathbf{R^+ \neq R^- \Rightarrow}$ **Mixing induced CPV**
- Simultaneous χ^2 fit to all bins:
  - Common Mixing/CPV parameters
  - Constrain strong phases

$$\left|\frac{q}{p}\right| = 1.21^{+0.21}_{-0.15}$$
$$\phi = \left(-0.132^{+0.088}_{-0.120}\right) \text{ rad}$$

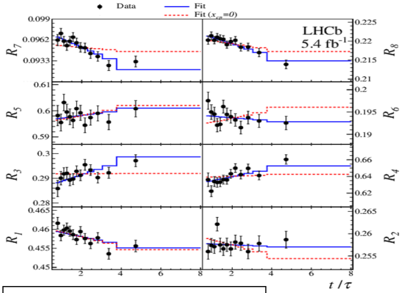
- No CPV is observed

$D^0 \to K_S^0\pi^+\pi^-$ Bin-Flip: Results from **prompt charm sample**

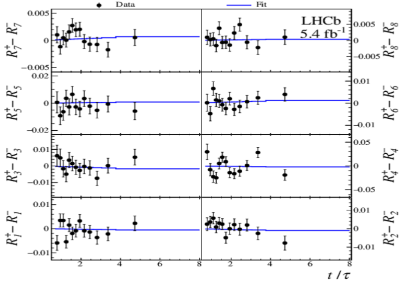
- LHCb Run 2 Data, **30.5 M** prompt charm ($D^* \to D^0\pi$) signal events
- **Statistically independent**, covering different D decay times

PRL **127**, 111801 (2021)

$\propto (\mathbf{D^0 + \bar{D}^0})$



$\propto (\mathbf{D^0 - \bar{D}^0})$



$$x = \left(3.98^{+0.56}_{-0.54}\right) \times 10^{-3}$$
$$y = \left(4.6^{+1.5}_{-1.4}\right) \times 10^{-3}$$

Statistically dominated

First observation of non-zero x! ($> 7\sigma$)

$$\left|\frac{q}{p}\right| = 0.996 \pm 0.052$$
$$\phi = \left(0.056^{+0.047}_{-0.051}\right) \text{ rad}$$

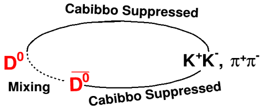
No CPV is observed

Measurement of $\mathbf{y_{CP}} - \mathbf{y_{CP}^{K\pi}}$

PRD **105**, 092013 (2022)

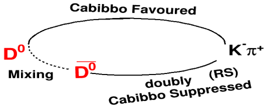
$$y_{CP} \propto y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)$$

$\mathbf{y_{CP} = y}$ if **no CPV** $\left(\phi = 0 \;\&\; \left|\frac{q}{p}\right| = 1\right)$



$$\mathbf{y_{CP}^{f}} - \mathbf{y_{CP}^{K\pi}} \approx y\left(1 + \sqrt{R_D}\right);$$

$$\mathbf{f = K^+K^-, \pi^+\pi^-} \qquad \sqrt{\mathbf{R_D}} = \sqrt{\frac{\mathbf{B}\left(\mathbf{D^0 \to K^+\pi^-}\right)_{\mathbf{DCS}}}{\mathbf{B}\left(\mathbf{D^0 \to K^-\pi^+}\right)_{\mathbf{CF}}}} \approx 6\%$$



- $y_{CP}^{K\pi} \approx -0.4 \times 10^{-3}$
- Direct constraint on y

Extraction of $y_{CP} - y_{CP}^{K\pi}$

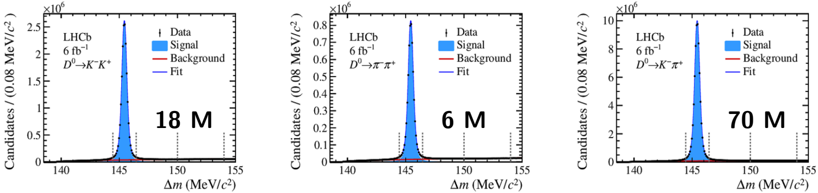
PRD **105**, 092013 (2022)

- Measured from fits to decay time ratios $R^f(f = K^+K^-, \pi^+\pi^-)$

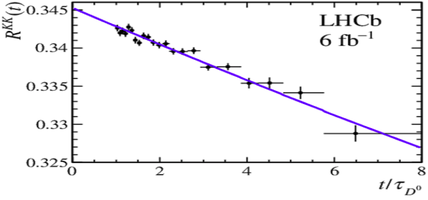
$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-\left(y_{CP}^f - y_{CP}^{K\pi}\right)\frac{t}{\tau_{D^0}}} \times \underbrace{\frac{\epsilon(f, t)}{\epsilon(K^-\pi^+, t)}}_{\text{Efficiencies}}$$

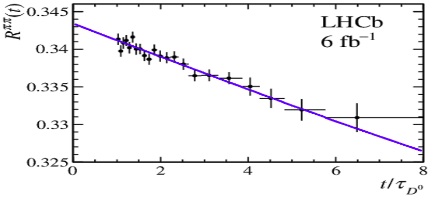
- LHCb Run 2 data, **prompt charm**

$$\Delta m = m_{h^+h^-\pi^\pm} - m_{h^+h^-} \; (h = K/\pi)$$



Extraction of $y_{CP} - y_{CP}^{K\pi}$: Results

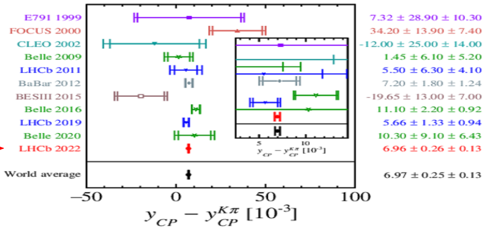




$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$

$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$



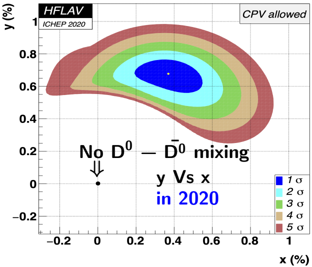
⇒

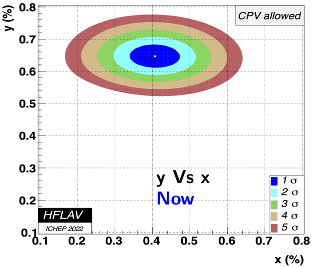
- **4 times precise** than previous World Average Value!

$$y = (6.46 \pm 0.24) \times 10^{-3}$$

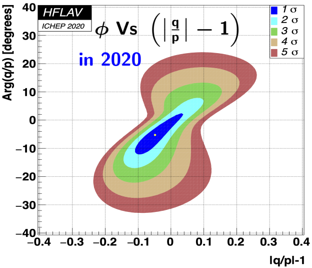
PRD **105**, 092013 (2022)

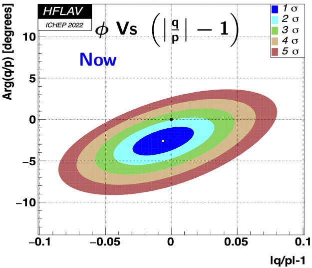
Mixing & CPV from global fit - **Past Vs Present**





$$x = (0.41 \pm 0.04)\%$$
$$y = (0.65 \pm 0.02)\%$$



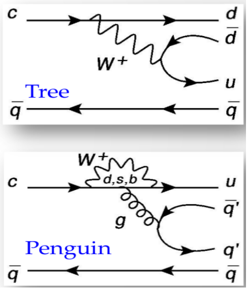


$$\left|\frac{q}{p}\right| = (0.99 \pm 0.02)$$
$$\phi \equiv \arg\left(\frac{q}{p}\right) = (-2.6 \pm 1.1)^\circ$$

Direct CPV (CPV in decays)

- **Time independent** measurements
- Depends on decay mode → **look at many modes**
- **Interference** between Tree & Penguin (SCS decays)
- Penguin in charm is tiny in SM
- Only significant observation of CPV is $\mathbf{\Delta A_{CP} = (-15 \pm 3) \times 10^{-4}}$

PRL **122**, 211803 (2019)



CP violation in charm observed in 2019 by LHCb

$$\Delta A_{CP} = A_{CP}\left(D^0 \to K^+K^-\right) - A_{CP}\left(D^0 \to \pi^+\pi^-\right)$$

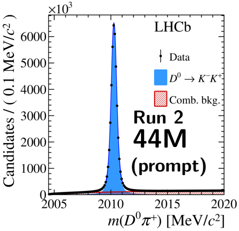
PRL **122**, 211803 (2019)

- Simple & sensitive measurement
- All nuisance asymmetries cancel out in the difference
- Full LHCb dataset (Run 1 + Run 2)

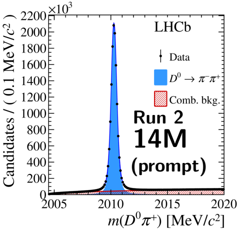
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

5.3σ from zero!

$D^0, \bar{D}^0 \to K^+K^-$



$D^0, \bar{D}^0 \to \pi^+\pi^-$



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

LHCB-PAPER-2022-024 (in preparation)

- A_{CP} and a_f^d related as:

$$\mathbf{A_{CP}(f)} \approx \mathbf{a}_f^d + \frac{\langle t \rangle_f}{\tau_{D^0}} \Delta Y$$

Average Decay time   Related to Mixing parameters[2]

- Need to measure $A_{CP}(D^0 \to K^+K^-)$ and $A_{CP}(D^0 \to \pi^+\pi^-)$ to understand the nature of observed CPV in charm
- Measure $\mathbf{A_{CP}}\left(\mathbf{D^0 \to K^+K^-}\right)$ and retrieve Direct CPV parameters $\mathbf{a^d_{KK}}$ and $\mathbf{a^d_{\pi\pi}}$ from the combination with ΔA_{CP}

[2] PRD **103**, 053008 (2019)

Handling the Nuisance Asymmetries

- LHCb Run 2 data, **prompt charm** LHCB-PAPER-2022-024 (in preparation)

The measured asymmetry ($\mathbf{A_{raw}}$) includes both physics and detector effects:

$$\mathbf{A_{raw}} = \mathbf{A_{CP}} + \mathbf{A_{D}} + \mathbf{A_{P}}$$

$$\Downarrow$$

$$\frac{N(D^0 \to K^+K^-) - N(\bar{D}^0 \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\bar{D}^0 \to K^+K^-)}$$

Asymmetry of our interest

Detection asymmetry
$\sigma(K^-) > \sigma(K^+)$

Production asymmetry of D^*
$\sigma(D) \neq \sigma(\bar{D})$

B-factory experiments: $\mathbf{e^+e^- \to \gamma/Z^*}$ **interference** $= A_{FB}$

Result:

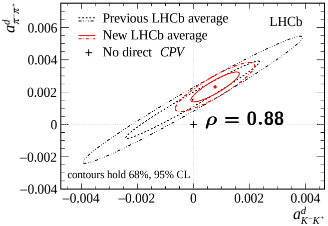
$$\mathbf{A_{CP}(D^0 \to K^+K^-) = [6.8 \pm 5.4 \pm 1.6] \times 10^{-4}}$$

A_{CP} in $D^0 \to K^+K^-$ decays: Results

LHCB-PAPER-2022-024 (in preparation)

$$\Delta A_{CP} = a^d_{KK} - a^d_{\pi\pi} - \frac{\langle t\rangle_{KK} - \langle t\rangle_{\pi\pi}}{\tau_{D^0}} \Delta Y$$

PRL 122, 211803 (2019) PRD 104, 072010 (2021)

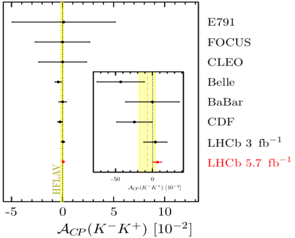


Run 1 + Run 2 Combined:

$$\mathbf{a^d_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4}}$$
$$\mathbf{a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4}}$$

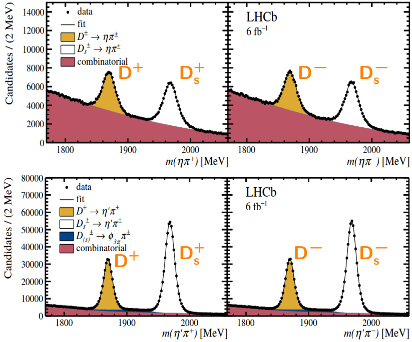
First evidence of direct CPV in $\mathbf{D^0 \to \pi^+\pi^-}$ decays at $\mathbf{3.8\sigma}$!

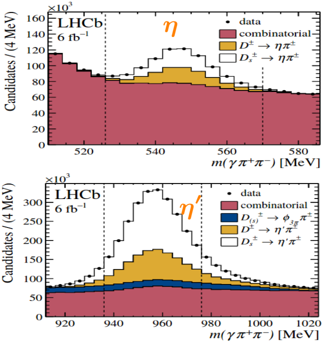
The most accurate measurement, still statistically dominated!



CP violation in $D^+_{(s)} \to \eta\pi^+$ & $D^+_{(s)} \to \eta'\pi^+$ decays

- LHCb Run 2 dataset arXiv:2204.12228 (submitted to JHEP)
- $D^\pm_{(s)} \to \eta(')\pi^\pm$, where $\eta(') \to \pi^+\pi^-\gamma$
- Nuisance asymmetries are subtracted using control channels
- **A$_{\text{CP}}$** $\Rightarrow$ from simultaneous fit between $m(\pi^+\pi^-\gamma)$ and $m(\eta(')\pi^\pm)$
- **0.5 M (1 M)** $D^\pm_{(s)} \to \eta'\pi^\pm$ & **1.1 M (1.3 M)** $D^\pm_{(s)} \to \eta\pi^\pm$ signal events





A_{CP} in $D_s^+ \to \eta\pi^+$ & $D_s^+ \to \eta'\pi^+$ decays: Results

Measured A_{CP} values in each decay channel: arXiv:2204.12228 (submitted to JHEP)

$$\mathbf{A_{CP}(D^+ \to \eta\pi^+) = (0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%^{(*)}}$$
$$\mathbf{A_{CP}(D_s^+ \to \eta\pi^+) = (0.32 \pm 0.51 \pm 0.12)\%}$$
$$\mathbf{A_{CP}(D^+ \to \eta'\pi^+) = (0.49 \pm 0.18 \pm 0.06 \pm 0.05)\%^{(*)}}$$
$$\mathbf{A_{CP}(D_s^+ \to \eta'\pi^+) = (0.01 \pm 0.12 \pm 0.08)\%^{(*)}}$$

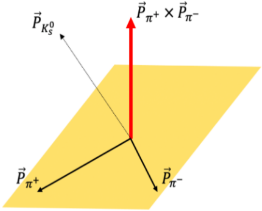
- $^{(*)}$Most precise measurement up to date!
- Results are consistent with no *CP* violation
- Statistically limited

CP violation in $D^0 \to K_S^0 K_S^0 \pi^+ \pi^-$ decays

BELLE

PRD **84**, 096013 (2011) | arXiv:hep-ph/0107102

Search for CPV using T-odd observable:
$\mathbf{C_T = \vec{p}_{K_S^0}.(\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})}$



- Construct Asymmetries A_T (for D^0)and $\bar{A}_T$ (for $\bar{D}^0$) with

$$A_T \xrightarrow{\mathbf{CP}} \bar{A}_T,\ C_T \xrightarrow{\mathbf{C}} C_T;\ C_T \xrightarrow{\mathbf{P}} -\bar{C}_T$$

$$\mathbf{(A_T)_{D^0}} = \frac{N_1(C_T > 0) - N_2(C_T < 0)}{N_1(C_T > 0) - N_2(C_T < 0)}; \quad \left(\mathbf{\bar{A}_T}\right)_{\mathbf{\bar{D}^0}} = \frac{N_3(-\bar{C}_T > 0) - N_4(-\bar{C}_T < 0)}{N_3(-\bar{C}_T > 0) - N_4(-\bar{C}_T < 0)}$$

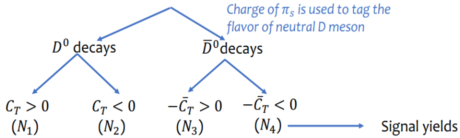
The difference $$\boxed{\mathbf{a_{CP}^T = \frac{1}{2}\left[(A_T)_{D^0} - \left(\bar{A}_T\right)_{\bar{D}^0}\right]}}$$

is sensitive to **CPV**

- Remove effects from strong phases
- Complementary measurement to A_{CP}

arXiv:2207.07555 [hep-ex] (submitted to PRDL)

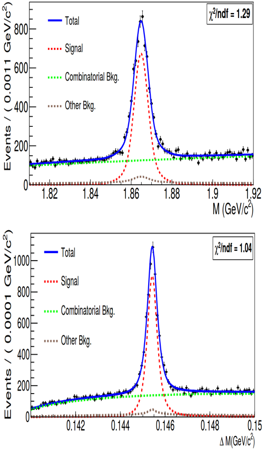
- Belle dataset of integrated luminosity 922 fb^{-1}
- $\mathbf{a^T_{CP}}$ from 2D simultaneous fit between M_D and Δm to four categories:



$$\mathbf{a^T_{CP}} = \left[-1.95 \pm 1.42^{+0.14}_{-0.12}\right] \%$$

- **First measurement of $\mathbf{a^T_{CP}}$ for the mode**
- Result is consistent with no CPV

6095 ± 95 events

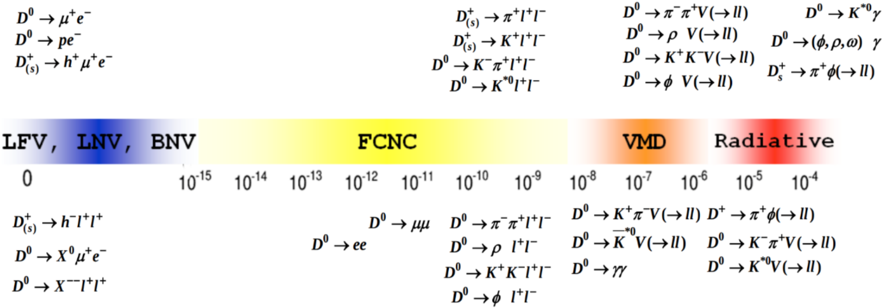


$$\mathbf{A_{CP}} = \left[-2.51 \pm 1.44^{+0.35}_{-0.52}\right] \%$$ Consistent with no CPV

Rare Decays

Spectrum of Charm Decays

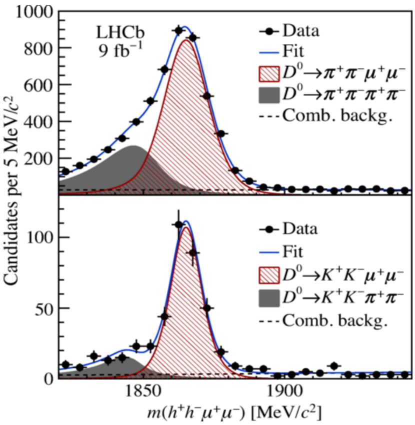
- SM null tests with search for rare and forbidden charm decays



$D^0 \to h^+h^-\mu^+\mu^-$ decays

PRL **128**, 221801 (2022)

- Four-body decays $\to$ larger branching fractions than 2-body decays, rich observables
- First observation of **rarest charm decays** using LHCb Run 1 data
  PRL **119** 181805 (2017)
  - Analysis done in $m(\mu^+\mu^-)$ regions
- Resonance tail may contribute
- Branching Fractions aren't clean test of SM
- First full angular analysis with LHCb **Run 1 + Run 2** data
- Resonance regions $\to$ SM null-tests



- $N(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 3500$
- $N(D^0 \to K^+K^-\mu^+\mu^-) \sim 300$

$D^0 \to h^+h^-\mu^+\mu^-$ decays: Observables

PRL **128**, 221801 (2022)

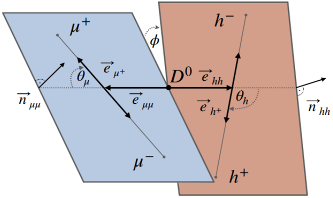
- Five independent kinematic variables:

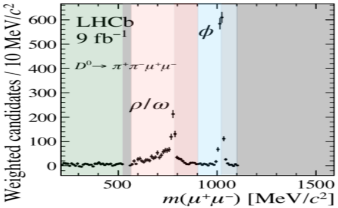
$$p^2\left[\mathbf{m(h^+h^-)}\right], q^2\left[\mathbf{m(\mu^+\mu^-)}\right], \theta_\mu, \theta_h$$
and ϕ

- Differential decay rate is expressed as the sum of nine angular observables I_{1-9}
- *CP* average & Asymmetry:

$$\langle S_i\rangle = \frac{1}{2}\left[\langle I_i\rangle (+)(-) \langle \bar{I}_i\rangle\right]; \quad \left\langle S^{SM}_{5-7}\right\rangle = 0$$
$$\langle A_i\rangle = \frac{1}{2}\left[\langle I_i\rangle (-)(+) \langle \bar{I}_i\rangle\right]; \quad \left\langle A^{SM}_{i}\right\rangle = 0$$

CP even (*CP* odd) coefficients

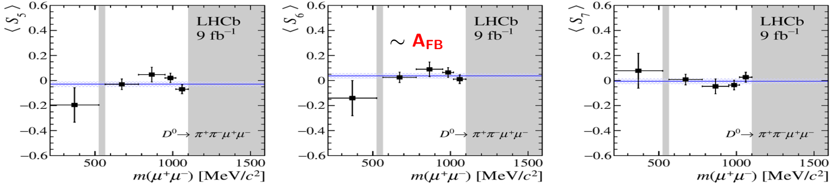




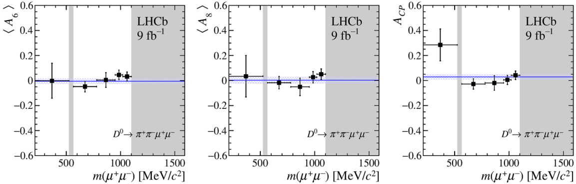
$D^0 \to h^+h^-\mu^+\mu^-$ decays: Results

SM null-tests ($\langle S_{5-7} \rangle$) **consistent with zero**:

PRL **128**, 221801 (2022)



Examples of $\langle A_6 \rangle$, $\langle A_8 \rangle$ &A_{CP}:



$m(\mu^+\mu^-)$ [MeV/c^2]	A_{CP} [%]
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	
< 525	$28 \pm 13 \pm 1$
525–565	—
565–780	$-2.7 \pm 4.1 \pm 0.4$
780–950	$-1.9 \pm 5.8 \pm 0.4$
950–1020	$0.5 \pm 3.7 \pm 0.4$
1020–1100	$4.2 \pm 3.4 \pm 0.4$
> 1100	—
Full range	$2.9 \pm 2.1 \pm 0.4$
$D^0 \to K^+K^-\mu^+\mu^-$	
< 525	$4 \pm 15 \pm 1$
525–565	—
> 565	$-2.5 \pm 6.8 \pm 0.6$
Full range	$-2.3 \pm 6.3 \pm 0.6$

- Measurements are consistent with SM & *CP* symmetry
- Statistically dominated

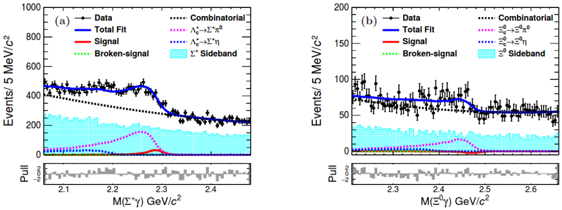
Search for $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$

arXiv:2206.12517 (accepted in PRD)

Best results for $D^0 \to \phi\gamma$ and $D^0 \to \rho\gamma$ are from Belle PRL **118**, 051811 (2017)

First search for **radiative charmed baryon decay**

BF can reach upto $\mathcal{O}(10^{-4})$ due to long range effects



Normalisation channels

$$\frac{\mathbf{BF}(\Lambda_c^+ \to \Sigma^+\gamma)}{\mathbf{BF}(\Lambda_c^+ \to pK^-\pi^+)} < 4 \times 10^{-3}$$

$$\frac{\mathbf{BF}(\Xi_c^0 \to \Xi^0\gamma)}{\mathbf{BF}(\Xi_c^0 \to \Xi^-\pi^+)} < 1.2 \times 10^{-2}$$ at 90% CL

Absolute branching fractions at 90% CL:

$$\mathbf{BF}(\Lambda_c^+ \to \Sigma^+\gamma) < 2.6 \times 10^{-4}$$

$$\mathbf{BF}(\Xi_c^0 \to \Xi^0\gamma) < 1.7 \times 10^{-4}$$

$D^0 \to \mu^+\mu^-$ decays

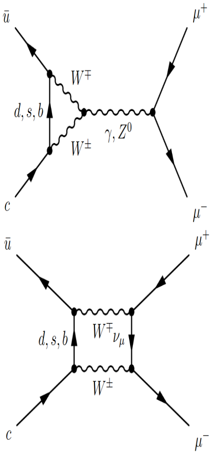
LHCb-PAPER-2022-029 (in Preparation)

- FCNC + Helicity suppression $\left[\mathrm{BF} \sim \mathcal{O}(10^{-12})\right]$
- Key in constraining NP
  - Lepto-quarks in tree-level
- Both short distance $\left[\mathcal{O}(10^{-18})\right]$ & long distance $\left[\mathcal{O}(10^{-11})\right]$ contributions within SM

  PRD **93** 074001 (2016)
- Current upper limit

  $\mathrm{BF}(\mathrm{D}^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ 90% CL

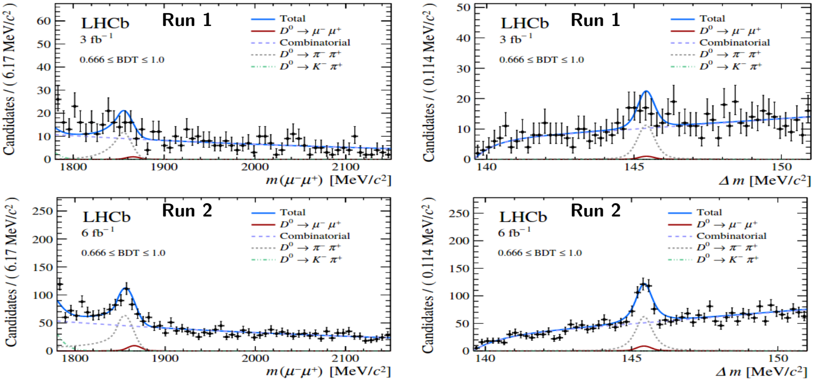
  PLB **725** 16 (2013)



Analysis Strategy:

- LHCb Run 1 + Run 2 dataset, prompt charm
- Simultaneous fit in three intervals of BDT output variable
- Normalisation channels: $D^0 \to \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays

$D^0 \to \mu^+\mu^-$ decays: Results



- No significant signal observed (79 ± 45) LHCb-PAPER-2022-029 (in Preparation)
- $\mathbf{BF(D^0 \to \mu^+\mu^-) < 2.9(3.3) \times 10^{-9}}$ 90(95)% CL
- **Factor of two improvement!**
- **Most stringent limit on FCNC in charm**

Summary

- Reaching an era of increasing precisions in charm measurements
- Non-zero mass difference between charm mass eigenstates now firmly established
- **Evidence of Direct CPV** in $D^0 \to \pi^+\pi^-$ decays
- **Upper Limit for BF($\mathbf{D^0 \to \mu^+\mu^-}$)** is below $B_s^0 \to \mu^+\mu^-$
- Many charm analyses using LHCb Run 2 data ongoing
- More data coming from Belle II & LHCb upgrade; exciting times ahead

Backup slides

Angular observables for $D^0 \to h^+ h^- \mu^+ \mu^-$ decays

- Differential decay rate is expressed as a sum of nine angular coefficients I_{1-9} as

$$\frac{d^5\Gamma}{dp^2 dq^2 d\vec{\Omega}} = \frac{1}{2\pi} \sum_{i=1}^{9} c_i(\theta_\mu, \phi) I_i(q^2, p^2, \cos\theta_h),$$

where $\vec{\Omega} \equiv (\cos\theta_\mu, \cos\theta_h, \phi)$ and

$$\begin{aligned} c_1 &= 1, & c_2 &= \cos 2\mu, & c_3 &= \sin^2\theta_\mu \cos 2\phi, \\ c_4 &= \sin 2\mu \cos\phi, & c_5 &= \sin\theta_\mu \cos\phi, & c_6 &= \cos\theta_\mu, \\ c_7 &= \sin\theta_\mu \sin\phi, & c_8 &= \sin 2\theta_\mu \sin\phi, & c_9 &= \sin^2\theta_\mu \sin 2\phi \end{aligned}$$

- I_1 provides normalisation factor

$$I_2 = \int_{-\pi}^{\pi} d\phi \left[\int_{-1}^{-0.5} d\cos\theta_\mu + \int_{0.5}^{1} d\cos\theta_\mu - \int_{-0.5}^{0.5} d\cos\theta_\mu\right] \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}},$$

$$I_3 = \frac{3\pi}{8}\left[\int_{-\pi}^{-\frac{3\pi}{4}} d\phi + \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} d\phi + \int_{\frac{3\pi}{4}}^{\pi} d\phi - \int_{-\frac{3\pi}{4}}^{-\frac{\pi}{4}} d\phi - \int_{\frac{\pi}{4}}^{\frac{3\pi}{4}} d\phi\right] \int_{-1}^{1} d\cos\theta_\mu \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}},$$

$$I_4 = \frac{3\pi}{8}\left[\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi - \int_{-\pi}^{-\frac{\pi}{2}} d\phi - \int_{\frac{\pi}{2}}^{\pi} d\phi\right]\left[\int_{0}^{1} d\cos\theta_\mu - \int_{-1}^{0} d\cos\theta_\mu\right] \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}},$$

$$I_5 = \left[\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi - \int_{-\pi}^{-\frac{\pi}{2}} d\phi - \int_{\frac{\pi}{2}}^{\pi} d\phi\right] \int_{-1}^{1} d\cos\theta_\mu \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}},$$

$$I_6 = \int_{-\pi}^{\pi} d\phi \left[\int_{0}^{1} d\cos\theta_\mu - \int_{-1}^{0} d\cos\theta_\mu\right] \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}},$$

$$I_7 = \left[\int_{0}^{\pi} d\phi - \int_{-\pi}^{0} d\phi\right] \int_{-1}^{1} d\cos\theta_\mu \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}},$$

$$I_8 = \frac{3\pi}{8}\left[\int_{0}^{\pi} d\phi - \int_{-\pi}^{0} d\phi\right]\left[\int_{0}^{1} d\cos\theta_\mu - \int_{-1}^{0} d\cos\theta_\mu\right] \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}},$$

$$I_9 = \frac{3\pi}{8}\left[\int_{-\pi}^{-\frac{\pi}{2}} d\phi + \int_{0}^{\frac{\pi}{2}} d\phi - \int_{-\frac{\pi}{2}}^{0} d\phi - \int_{\frac{\pi}{2}}^{\pi} d\phi\right] \int_{-1}^{1} d\cos\theta_\mu \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}}.$$

Normalised angular observables for $D^0 \to h^+h^-\mu^+\mu^-$ decays

The normalised and integrated observables $\langle I_i \rangle$ are defined as

$$\langle I_{2,3,6,9} \rangle = \frac{1}{\Gamma} \int_{q^2_{\min}}^{q^2_{\max}} dq^2 \int_{p^2_{\min}}^{p^2_{\max}} dp^2 \int_{-1}^{+1} d\cos\theta_h \, I_{2,3,6,9} \, ,$$

$$\langle I_{4,5,7,8} \rangle = \frac{1}{\Gamma} \int_{q^2_{\min}}^{q^2_{\max}} dq^2 \int_{p^2_{\min}}^{p^2_{\max}} dp^2 \left[\int_{0}^{+1} d\cos\theta_h - \int_{-1}^{0} d\cos\theta_h \right] I_{4,5,7,8}$$

- Observable I_{1-9} separately measured for $D^0 \, [\langle I_i \rangle]$ and $\bar{D}^0 \, [\langle \bar{I}_i \rangle]$
- $\langle S_i \rangle$ and $\langle A_i \rangle$ are defined as:

$$\langle S_i \rangle = \frac{1}{2} \left[\langle I_i \rangle (+)(-) \langle \bar{I}_i \rangle \right] ;$$

$$\langle A_i \rangle = \frac{1}{2} \left[\langle I_i \rangle (-)(+) \langle \bar{I}_i \rangle \right] ;$$

CP even ($I_{2,3,4,7}$) & *CP* odd ($I_{5,6,8,9}$) coefficients