MIXING AND TIME-DEPENDENT CPV SEARCHES IN CHARM AT LHCb

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Because of the severe GIM suppression, mixing is slow and CPV small (according to SM).

- $m_c$ is (quite) close to the hadronic scale $\Lambda_{\text{QCD}} \rightarrow \Lambda_{\text{QCD}}/m_c$
  - Perturbative expansion tricky

- Strong coupling $\alpha_s(m_c)$ is large $\rightarrow$ higher order contributions and/or non-perturbative effects can be significant

- Long distance contributions are important
- Precise theoretical predictions are difficult
- Experimental input crucial to constrain charm dynamics
- Potential for measurable New Physics is great
CPV IN CHARM

- The only up-type quark decays where CPV can be studied
- Complementary to $K$ and $B$
- All three types of CPV are realized in charm
  - Decay ($|A_f|^2 \neq |\bar{A}_f|^2$)
  - Pure mixing ($|q/p| \neq 1$)
  - Decay-mixing interference ($\phi_{\lambda_f} = \text{arg}(\frac{q\bar{A}_f}{pA_f}) \neq 0$)
• Mixing comes from a mismatch between flavour and mass eigenstates
  \[ |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \]

• Usually described by
  \[ x = \Delta m_D / \Gamma_D \quad \text{and} \quad y = \Delta \Gamma_D / 2 \Gamma_D \]

• In case of CPV \( |q/p| \) and \( \phi \approx \phi_{\lambda f} \) or
  \[
  \Delta x = \frac{1}{2} \left[ x \cos \phi \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) + y \sin \phi \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) \right] \\
  \Delta y = \frac{1}{2} \left[ y \cos \phi \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) - x \sin \phi \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) \right]
  \]
**Search for Time-Dependent CPV in \( D^0 \rightarrow h^+h^- (h \in \{K, \pi\}) \)**

- Same channels as \( \Delta A_{CP} \) discovery

\[
A_{CP} = \frac{\Gamma(D^0(t) \rightarrow f) - \Gamma(\bar{D}^0(t) \rightarrow f)}{\Gamma(D^0(t) \rightarrow f) + \Gamma(\bar{D}^0(t) \rightarrow f)} = a_f^d + \Delta Y_f \frac{t}{\tau_D} + \mathcal{O}(x^2, y^2, xy)
\]

- SM prediction is very small \( \sim 10^{-5} \) (Kagan & Silvestrini, 2020, Li & Umeeda, 2020)

- We don’t observe \( A_{CP} \)

\[
A_{\text{raw}} = \frac{N(D^0(t) \rightarrow f) - N(\bar{D}^0(t) \rightarrow f)}{N(D^0(t) \rightarrow f) + N(\bar{D}^0(t) \rightarrow f)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_D} + A_{\text{prod}}(f, t) + A_{\text{det}}(f, t)
\]

\[\Delta Y_f \approx x \phi \chi_f - y \left( \left| \frac{q}{p} \right| - 1 \right) + y a_f^d \approx -\Delta y\]

\[\Delta Y_{K^+K^-} \] needed to measure CPV in decay from time-integrated \( D^0 \rightarrow K^+K^- \)
SEARCH FOR TIME-DEPENDENT CPV IN $D^0 \rightarrow h^+h^-$

- $D^0$ from $D^{*+} \rightarrow D^0 \pi^+_{\text{tag}}$
- At $\sqrt{s} = 13$ TeV with $\mathcal{L} = 5.7$ fb$^{-1}$
- $58M \ D^0 \rightarrow K^+K^-$, $18M \ D^0 \rightarrow \pi^+\pi^-$, purity $\sim 95\%$

- Residual combinatorial background subtracted using sidebands
- Momentum-dependent detection asymmetries $A_{\text{det}}$ based on magnet field polarity and charge of $\pi_{\text{tag}}$
- $A_{\text{det}} + A_{\text{prod}} \rightarrow D^0/\bar{D}^0$ momentum asym.
- Trigger correlates $D^0$ decay time with kinematics $\rightarrow A_{\text{det}}(t), A_{\text{prod}}(t)$ become time-dependent
- Solution: equalize $D^0$ and $\bar{D}^0$ kinematics

After reweighting
$\Delta Y_{K^-\pi^+} \approx 0$
(control channel)

Before reweighting
$\Delta Y_{K^-\pi^+} \neq 0$
Search for time-dependent CPV in $D^0 \rightarrow h^+ h^-$

\[ \Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4} \]
\[ \Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4} \]

- $\Delta Y_{K^+K^-}$ and $\Delta Y_{\pi^+\pi^-}$ agree within 0.5\(\sigma\)
- Compatible with no CPV within 2\(\sigma\)

PRD 104, 072010 (2021)
Search for time-dependent CPV in $D^0 \rightarrow h^+ h^-$

Table 1: Summary of the systematic uncertainties, in units of $10^{-4}$. The statistical uncertainties are reported for comparison.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta Y_{K^+ K^-}$ [$10^{-4}$]</th>
<th>$\Delta Y_{\pi^+ \pi^-}$ [$10^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtraction of the $m(D^0_{\pi^+_\text{tag}})$ background</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Flavour-dependent shift of $D^*$-mass peak</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$D^{**}$ from $B$-meson decays</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$m(h^+ h^-)$ background</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Kinematic weighting</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>1.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

- Combinatorial background subtraction
SEARCH FOR TIME-DEPENDENT CPV IN $D^0 \rightarrow h^+h^-$

- Previous world average $\Delta Y = (3.0 \pm 2.0 \pm 0.5) \times 10^{-4}$
- Precision improved by a factor of two
- Small systematic uncertainty → great prospects for future LHCb measurements
  ($\sigma$ approaching SM prediction $\mathcal{O}(10^{-5})$, LHCB-TDR-023-001)
Search for time-dependent CPV in $D^0 \rightarrow h^+h^-$

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The $\Gamma$ difference ($y \neq 0$) between neutral charm-meson eigenstates has been established in the past years (PRL 122, 011802 (2019), PRD 97, 031101 (2017), PLB 753 (2016), PRD 87, 012004 (2013)).

The mass difference ($x \neq 0$) has so far been elusive; the previous most precise measurement by LHCb reported $x_{CP} = (2.7 \pm 1.6) \times 10^{-3}$ (PRL 122, 231802 (2019)).

- $D^{*+} \to D^0 \pi^+_\text{tag}$
- $D^0 \to K^0_S \pi^+ \pi^-$
- $\mathcal{L} = 5.4$ fb$^{-1}$
- 30.6M signal events
- Exploits multi-body final state; sensitive to mixing and CPV via time-dep. variations across phase-space

![Graph showing candidates per 0.1 MeV/c$^2$]
Rich resonant structure

Many interfering amplitudes

- $D^0 \xrightarrow{DCS} K^* \pi^+ \rightarrow K_S^0 \pi^+ \pi^-$
- $D^0 \xrightarrow{mix} \bar{D}^0 \xrightarrow{CF} K^* \pi^- \rightarrow K_S^0 \pi^+ \pi^-$
- $D^0 \xrightarrow{CF} K^* \pi^+ \rightarrow K_S^0 \pi^+ \pi^-$
- $D^0 \xrightarrow{CP} K_S^0 \rho^0 \rightarrow K_S^0 \pi^+ \pi^-$

- Dalitz plot divided into ± bins; strong-phase difference is \(\sim\) constant in each bin

- Strong-phases constrained using quantum-correlated $D^0 - \bar{D}^0$ pairs (CLEO [PRD 82, 112006 (2010)] and BES-III [PRD 101, 112002 (2020)] inputs)
Bin-flip method

- Measure a time-dep. ratio for each
  ± bin; “bin-flip” (PRD 99, 012007 (2019))
- Slightly lower sensitivity than amplitude
  analysis
- Model-independent & most detector
  effects cancel

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

- \( b \) — Dalitz bin, \( j \) — time bin
- \( r_b \) ratio at \( t = 0 \)
- \( X_b = c_b - i s_b \)
- \( z_{CP} = -y_{CP} - i x_{CP} \), \( \Delta z = -\Delta y - i \Delta x \)

At leading order

\[
R_{bj}^\pm \approx r_b + \sqrt{r_b} \left[ (1 + r_b)(x_{CP} \pm \Delta x)c_b - (1 - r_b)(y_{CP} \pm \Delta y)s_b \right] \langle t \rangle_j
\]
• Ratios of ± bins
• Deviations from constant values due to mixing
• Red lines are fit projections where $x_{CP} \equiv 0 \rightarrow y_{CP}$ alone can’t reproduce observation

$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$
$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$

• First measurement of non-zero $x$ ($> 7\sigma$)
• Difference of ratios for $D^0$ and $\bar{D}^0$

• No CPV observed (slope)

\[ \Delta x = (0.27 \pm 0.18 \pm 0.01) \times 10^{-3} \]
\[ \Delta y = (0.20 \pm 0.36 \pm 0.13) \times 10^{-3} \]

• Limits on $\Delta x$ significantly improved
Uncertainties

Table 2: Point estimates and 95.5% confidence-level (CL) intervals for $x$, $y$, $|q/p|$ and $\phi$. The uncertainties include statistical and systematic contributions.

<table>
<thead>
<tr>
<th>Source</th>
<th>$x_{CP}$</th>
<th>$y_{CP}$</th>
<th>$\Delta x$</th>
<th>$\Delta y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction and selection</td>
<td>0.199</td>
<td>0.757</td>
<td>0.009</td>
<td>0.044</td>
</tr>
<tr>
<td>Secondary charm decays</td>
<td>0.208</td>
<td>0.154</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Detection asymmetry</td>
<td>0.000</td>
<td>0.001</td>
<td>0.004</td>
<td>0.102</td>
</tr>
<tr>
<td>Mass-fit model</td>
<td>0.045</td>
<td>0.361</td>
<td>0.003</td>
<td>0.009</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.291</td>
<td>0.852</td>
<td>0.010</td>
<td>0.110</td>
</tr>
</tbody>
</table>

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<tr>
<th>Source</th>
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<th>$y_{CP}$</th>
<th>$\Delta x$</th>
<th>$\Delta y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong phase inputs</td>
<td>0.23</td>
<td>0.66</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>Detection asymmetry inputs</td>
<td>0.00</td>
<td>0.00</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>Statistical (w/o inputs)</td>
<td>0.40</td>
<td>1.00</td>
<td>0.18</td>
<td>0.35</td>
</tr>
<tr>
<td>Total statistical uncertainty</td>
<td>0.46</td>
<td>1.20</td>
<td>0.18</td>
<td>0.36</td>
</tr>
</tbody>
</table>

- Trigger-induced efficiency correlations
- Possible bias due to charm from $B \rightarrow D$
- Inputs from CLEO and BES III; new strong-phase measurements from BES III of great interest for Run 3 measurement
- Especially $\Delta x$ and $\Delta y$ statistically dominated $\rightarrow$ future improvement
- WA significantly improved for both mixing and CPV
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- Very complementary with the $D^0 \rightarrow h^+ h^-$ analysis
- $\Delta x$ improvement shrinks uncertainty on diagonal
- $\Delta y$ improvement shrinks uncertainty on diagonal
"Simultaneous determination of CKM angle $\gamma$ and charm mixing parameters" \hspace{1mm} (arXiv:2110.02350)

- Provides the most precise determination of $\gamma$ from a single experiment; $\gamma = (65^{+3.8}_{-4.2})^\circ$; see talks by Anna, Arnau, and Fidan
- Improves the precision on $y$ by a \textbf{factor of two} w.r.t. the current WA!
- $y = (0.630^{+0.033}_{-0.030})\%$

![Diagram showing the two-dimensional profile likelihood contours for $(x, y)$ and $(\phi, |q/p|)$ parameters.](image)

The charm mixing parameters, $x$ and $y$, are determined simultaneously with $\gamma$ in this combination for the first time. The precision on $x$ is driven by the recent measurement described in Ref. [50]. The result $y = (0.630^{+0.033}_{-0.030})\%$ is more precise than the world average, $y = (0.603^{+0.057}_{-0.056})\%$ [18], by approximately a factor of two, driven entirely by the improved measurement of $\delta_{K\pi}$ from the beauty system and the simultaneous averaging methodology employed in this article. The correlation between $\delta_{K\pi}$ and $\delta_{DK\pm B\pm}$ is $-57\%$, highlighting $B\pm \to DK\pm$ decays as the source of this improvement.

The beauty part of the combination is cross-checked with an independent framework using a Bayesian statistical treatment. A flat prior is used for $\gamma$ and the relevant hadronic parameters and results in a value of $\gamma = (65^{+3.6}_{-3.7})^\circ$, in agreement with the default frequentist results. Good agreement between the frequentist and Bayesian interpretations is also seen for the other hadronic parameters. A second cross-check using an independent fitting framework with frequentist interpretation gives consistent results to better than 1% precision. Finally, the charm sector of the combination was validated by accurately reproducing the HFLAV results [18].

The relative impact of systematic uncertainties on the input observables is studied, and found to contribute approximately 1.4\° to the result for $\gamma$, demonstrating that the uncertainty of this combination is still dominated by the data sample size.

In previous combinations, the experimental input from $B^0 \to D^{\pm} \pi^{\pm}$ decays was included with an external theoretical prediction of $r_{D^{\pm} \pi^{\pm}} = 0.0182 \pm 0.0038$ [35]. This prediction assumes SU(3) symmetry, and was the only input from theory. This external input is no longer used, and the combination gives an experimental determination...
LHCb collected the largest sample of charm decays; leading to **new world-best measurements**

- Time-integrated CP asymmetries (including channels with neutrals; see Andrea Contu’s talk)
- Time-dependent CP asymmetries and mixing parameters (including **first observation of a mass difference** between neutral $D$ mass eigenstates)
More interesting Run 2 analyses in the pipeline
  - $y_{CP}$ from $D^0 \rightarrow h^+ h^-$
  - $x, y$ from semi-leptonic $D^0 \rightarrow K_S \pi \pi$
  - Time-dep amplitude analysis of $D^0 \rightarrow K_S \pi \pi$
  - Update WS/RS(t) measurement of $D^0 \rightarrow K \pi$ with full Run2 sample

Other approaches under investigation
  - Four-body final states
  - ...

Precision of the measurements is mostly limited by statistics → improvement expected

Run 3 (starting next year) - higher luminosity, upgraded trigger and detector

↓

Stay tuned!
THANK YOU!
- Improvement on y driven almost entirely by $\delta_D^{K\pi}$ from beauty
- Correlation of $\delta_D^{K\pi}$ and $\delta_B^{DK\pm}$ is $\sim 57\% \rightarrow B^\pm \rightarrow DK^\pm$ dominates
\[ \Delta Y_{K\pi} = (0.4 \pm 0.5 \text{ (stat)} \pm 0.2 \text{ (syst)}) \times 10^{-4} \]

- From global fit: \( |\Delta Y_{K\pi}| < 0.3 \times 10^{-4} \) at 90\% CL