CP Violation Measurement in
Wrong-Sign $D^0 \rightarrow K^+\pi^-$ Decays*

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(On behalf of the LHCb collaboration)

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Mixing and CPV in $D^0 - \bar{D}^0$

- Charm mixing: unique probe of mixing in the up-type quark system
  
  Mass eigenstates are related to their flavor eigenstates via
  
  $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle$, with $|q|^2 + |p|^2 = 1$

  - If indirect CPV is conserved, $|q/p| = 1$, $\phi \equiv \text{arg}(q/p) = 0$

  - Mixing parameters based on the mass and width differences:
    
    $x \equiv (m_2 - m_1)/\Gamma$, $y \equiv (\Gamma_2 - \Gamma_1)/2\Gamma$, with $\Gamma \equiv (\Gamma_2 + \Gamma_1)/2$

- In the SM, expecting
  
  - $x, y \sim 1\%$ or less
  
  - CPV $\sim 1\%$ or less

- Observation of enhanced CPV in the charm sector would be a clear indication of new physics

Short-distance contribution
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    $$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle, \text{ with } |q|^2 + |p|^2 \equiv 1$$
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Signal extraction of $D^0 \rightarrow K\pi$

$D^0$ flavor is tagged by the “soft” pion from $D^*$

$D^{*+} \rightarrow D^0 \pi^+_s$ 

$D^{*+} \rightarrow D^0 \pi^+_s$

right-sign events (RS)

wrong-sign events (WS)

$\times 10^6$

Candidates / (0.1 MeV/c^2)

LHCb @ 3 fb^-1

- Data
- Fit
- Background

RS mode:
54 M signal candidates

Computed with known $D^0$ and $\pi^+$ masses

$\times 10^3$

Candidates / (0.1 MeV/c^2)

LHCb @ 3 fb^-1

- Data
- Fit
- Background

WS mode:
0.23 M signal candidates

PRL 111,251801
Decay-time-dependent WS/RS ratios

- In the limit of $x, y \ll 1$, and assuming no CPV, the WS/RS yield ratio $R$ varies with $D^0$ decay time $t$ as:

$$R(t) \equiv \frac{N(WS)(t)}{N(RS)(t)} \approx R_D + \sqrt{R_D} \frac{y'}{\tau} \left( \frac{t}{\tau} \right)^2 + \frac{x'^2 + y'^2}{4} \left( \frac{t}{\tau} \right)^2$$

: known $D^0$ lifetime  
: $R_D$: the ratio of DCS to CF decay rates  
: $x' \equiv x \cos \delta + y \sin \delta$, $y' \equiv y \cos \delta - x \sin \delta$  
: $\delta$: strong phase difference between DCS and CF amplitudes

- We now write separately for $D^0 (R^+)$ and $\bar{D}^0 (R^-)$ to search for CPV:

$$R^\pm(t) \approx R_D^\pm + \sqrt{R_D^\pm} \frac{y'^\pm}{\tau} \left( \frac{t}{\tau} \right) + \frac{x'^2\pm + y'^2\pm}{4} \left( \frac{t}{\tau} \right)^2$$

- Mixing parameters ($R_D^\pm, x'^\pm, y'^\pm$) are measured separately in $D^0$ and $\bar{D}^0$ samples

Efficiency-corrected ratios accounting for the (decay-time-independent, $\sim 1\%$) asymmetry in detection efficiency between $K^+\pi^-$ and $K^-\pi^+$
Mixing results

LHCb mixing results are consistent with those from other experiments

PRL 111, 251801

All uncertainties incorporate systematic effects from secondary $D$ decays, etc

$R_D = 3.568 \pm 0.066$

$y' = 4.81 \pm 1.00$

$x'^2 = 5.5 \pm 4.9$

$\chi^2/\text{ndf} = 86.41/101$
Mixing and CPV results

Results are consistent with CP conservation

\[ A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} \]

<table>
<thead>
<tr>
<th>Direct and indirect CP violation</th>
<th>no direct CP violation</th>
<th>no CP violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_D ) ([10^{-3}])</td>
<td>3.568 ± 0.066</td>
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</tr>
<tr>
<td>( A_D ) ([10^{-2}])</td>
<td>-0.7 ± 1.9</td>
<td></td>
</tr>
<tr>
<td>( y'^+ ) ([10^{-3}])</td>
<td>5.1 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>( x'^{2+} ) ([10^{-5}])</td>
<td>4.9 ± 7.0</td>
<td></td>
</tr>
<tr>
<td>( y'^- ) ([10^{-3}])</td>
<td>4.5 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>( x'^{2-} ) ([10^{-5}])</td>
<td>6.0 ± 6.8</td>
<td></td>
</tr>
<tr>
<td>( \chi^2/\text{ndf} )</td>
<td>85.87/98</td>
<td></td>
</tr>
</tbody>
</table>

All uncertainties incorporate systematic effects from \( K\pi \) detection asymmetry, secondary \( D \) decays, etc.
Interpretation of the LHCb results

- Using only the LHCb results, and with the constraints of:
  \[ x'^\pm = (|q/p|)^{\pm 1} (x' \cos \phi \pm y' \sin \phi) \]
  \[ y'^\pm = (|q/p|)^{\pm 1} (y' \cos \phi \mp x' \sin \phi) \]
  \[ \phi = \arg \left( \frac{q}{p} \right) \]

- The 68.3% C.L. constraints
  - 0.75 < |q/p| < 1.24 for all CPV allowed
  - 0.91 < |q/p| < 1.31 for the case without direct CPV

- The LHCb results contribute in the global fits for \(D^0 - \bar{D}^0\) mixing

- In the case without direct CPV, the superweak relationship* \(\phi = \tan^{-1} \left( \frac{1 - |q/p|^2 x}{1 + |q/p|^2 y} \right)\)
  is applicable, and |q/p| can be constrained with precision of ~1%

* A. L. Kagan, M. D. Sokoloff, PRD 80, 076008 (2009)
Summary

- LHCb now provides the WS mixing and CPV measurements with unprecedented level of precision.
- Neither direct CPV or CPV in $D^0$ – $\bar{D}^0$ mixing is observed, being consistent with SM.
- The LHCb CPV results are capable of playing an important role in constraining $|q/p|$.
Backup Slides
**WS/RS ratio versus $D^0$ decay time**

$$R^\pm(t) \approx R^\pm_D + \sqrt{R^\pm_D} y^\pm \frac{t}{\tau} + \frac{x'^2\pm + y'^2\pm}{4} \left(\frac{t}{\tau}\right)^2$$

$$x'^\pm = (|q/p|)^{\pm1} (x' \cos \phi \pm y' \sin \phi)$$

$$y'^\pm = (|q/p|)^{\pm1} (y' \cos \phi \mp x' \sin \phi)$$

- Fit the WS/RS ratio as a function of decay time under three hypotheses:
  - No CPV
    - $|q/p| = 1$, $\phi \equiv \arg(q/p) = 0$
    - $R_D^+ = R_D^-$, $x''^+ = x''^-$, $y'^+ = y'^-$
  - No direct CPV (CPV in mixing allowed)
    - $R_D^+ = R_D^-$
  - CPV allowed (for the direct and indirect CPV)
LHCb detector

Hardware trigger system for hadrons: based on large $E_T$ depositions in the hadron Cal.

Tracking system:
$\Delta p/p = 0.4-0.6\%$ @ 5-100 GeV/c, corresponding to $\sim 8$ MeV/c$^2$ mass resolution for $D \to K\pi$

Requiring $|M(K\pi) - M(D^0)| < 24$ MeV/c$^2$

RICH detectors:
Good $K/\pi$ separation for $p < 100$ GeV/c with mis-ID rate at a few percent

Silicon Vertex Locator:
20 $\mu$m impact parameter (IP) resolution, corresponding to $\sim 0.1\tau$ decay-time resolution for $D \to K\pi$