Mixing and CP Violation in Charm Decays at LHCb

Adam Davis
On behalf of the LHCb Collaboration

August 4, 2016
Outline

NEW

Measurement of $CP$ asymmetry in $D^0 \rightarrow K^- K^+$ decays
LHCb-PAPER-2016-035 (in preparation)

NEW

Search for Mixing and CP Violation with WS $D^0 \rightarrow K\pi$ from $\bar{B} \rightarrow \mu D^* X$
LHCb-PAPER-2016-033 (in preparation)
Some Theory and Expectations

Mixing in a Nutshell

- Mixing in Neutral Mesons: mass≠flavor eigenstates
- Mass Eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, $|p|^2 + |q|^2 = 1$
  \[ x = \frac{m_2 - m_1}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}, \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2} \]

CP Violation

- Direct CPV: $\left| \frac{\bar{A}_f}{A_f} \right| \neq 1$
  \[ A_f = \langle f|\mathcal{H}|D\rangle, \quad \bar{A}_f = \langle \bar{f}|\mathcal{H}|\bar{D}\rangle \]
- CPV in Mixing: $\left| \frac{q}{p} \right| \neq 1$
  Weak Phase: $\phi = \arg\left( \frac{q}{p} \right) \neq 0$
- CPV in Interference between Mixing and Decay: $\arg\left( \frac{q}{p} \bar{A}_f \right) \neq 0$

Expectations

- Only up-type quark system with mixing
- Mixing enters at 1 loop level in SM, GIM and CKM suppressed
- Non-perturbative long-range effects may dominate short-range interactions, difficult to calculate
- $x, y$ expected to be $\lesssim 0.5\%$
- CPV expected to be $\mathcal{O}(10^{-3})$ in SM
- If enhancement of CPV is seen, could be caused by New Physics

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LHCb

- LHCb acceptance: $2 < \eta < 5$
- Reconstructed 1.4 billion charm hadron decays in 2011-2015

LHCb-CONF-2016-005

- Today’s presentation: $3 \text{ fb}^{-1}$ collected in Run I of LHC
LHCb acceptance: $2 < \eta < 5$

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A. Davis

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![Graph showing the mass distribution of \(K\pi^+\) candidates per 19 keV/c\(^2\). Signal: 445 million candidates per 19 keV/c\(^2\).]

LHCb

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LHCb-CONF-2016-005

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LHCb Preliminary
2012 data
Signal: 445 million

$K^+\pi^-$ mass [MeV/c$^2$]

Candidates per 19 keV/c

0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
6
10
×

TT & T Stations:
$\Delta p/p = 0.4\% - 0.6\%$
for 5 – 100 GeV Tracks

VELO:
20 \mu m IP resolution

RICH: $K/\pi$ Separation

Dipole Magnet:
Reversible Polarity

Muons:
Detection of $\mu^\mp$

$\Delta p/p = 0.4\% - 0.6\%$ for 5 – 100 GeV Tracks
LHCb

- LHCb acceptance: $2 < \eta < 5$
- Reconstructed 1.4 billion charm hadron decays in 2011-2015

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- RICH: $K/\pi$ Separation
- Dipole Magnet: Reversible Polarity
- Muon Stations: Detection of $\mu^{\pm}$
- TT & T Stations: $\Delta p/p = 0.4\% - 0.6\%$ for $5 - 100$ GeV Tracks
- VELO: $20 \mu m$ IP resolution

LHCb-CONF-2016-005
Measurement of $CP$ asymmetry in $D^0 \rightarrow K^- K^+$ decays
LHCb-PAPER-2016-035 (in preparation)
$A_{CP}(D^0 \to KK)$ Method

- Define $A_{raw}(D^0 \to f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\bar{D}^0 \to \bar{f})}$
- Measure $A_{CP}(D^0 \to KK)$, Tag using prompt $D^*+ \to D^0 \pi^+_s$ PV

\[
A_{CP}(D^0 \to KK) = A_{raw}(D^0 \to KK) - A_P(D^+) - A_D(\pi^+_s) + O(A^3)
\]

- Eliminate detection/production asymmetries using control channels $D^{*+} \to D^0 (\to K^- \pi^+), D^+ \to K^- \pi^+ \pi^+$ and $D^+ \to \bar{K}^0 \pi^+$

\[
A_{CP}(D^0 \to KK) = A_{raw}(D^0 \to KK) - A_{raw}(D^0 \to K^- \pi^+)
\]
\[
+ A_{raw}(D^+ \to K^- \pi^+ \pi^+) - A_{raw}(D^+ \to \bar{K}^0 \pi^+) + A_D(\bar{K}^0)
\]

- Also measure $A_{CP}(\pi^- \pi^+)$, derived from previous result PRL 116, 191601

\[
A_{CP}(\pi^- \pi^+) = A_{CP}(K^- K^+) - \Delta A_{CP}
\]

- Combine with muon tagged results JHEP (2014) 2014: 41
Yields and Weighting

- Extract yields with binned maximum likelihood fit to $\delta m$ for $D^*$ modes, or $m(D^+)$
- Simultaneous fit to $+/-$ tags
- Order weighting to cancel production asymmetry and maximize statistical sensitivity
  1. $D^+ \to K^-\pi^+\pi^+$ weighted to $D^+ \to K\pi^+$
  2. $D^0 \to K^-\pi^+$ weighted to $D^+ \to K^-\pi^+\pi^+$
  3. $D^0 \to KK$ weighted to $D^0 \to K^-\pi^+$

$\delta m$ Fit Model: Double Gaussian + Bifurcated Gaussian + Exponential
$D^+$ Fit Model: Triple Gaussian + Empirical Background

<table>
<thead>
<tr>
<th>Channel</th>
<th>Before Weighting</th>
<th>After Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to KK$</td>
<td>5.56 M</td>
<td>1.63 M</td>
</tr>
<tr>
<td>$D^0 \to K\pi$</td>
<td>32.4 M</td>
<td>2.61 M</td>
</tr>
<tr>
<td>$D^+ \to K\pi\pi$</td>
<td>37.5 M</td>
<td>13.7 M</td>
</tr>
<tr>
<td>$D^+ \to K^0\pi$</td>
<td>1.06 M</td>
<td>-</td>
</tr>
</tbody>
</table>
Results

$$A_{CP}(KK) = (+0.14 \pm 0.15 \pm 0.10\%)$$

- Using $\Delta(A_{CP})$ from PRL 116, 191601

$$A_{CP}(\pi\pi) = (0.24 \pm 0.15 \pm 0.11\%)$$

- Combine with muon tagged

$$A_{CP}^{\text{comb}}(KK,\pi\pi)$$ with full correlations

$$A_{CP}^{\text{comb}}(KK) = (0.04 \pm 0.12 \pm 0.10\%)$$

$$A_{CP}^{\text{comb}}(\pi\pi) = (0.07 \pm 0.14 \pm 0.11)$$

Consistent with CP Conservation
Search for Mixing and CP Violation with WS $D^0 \rightarrow K\pi$ from $\bar{B} \rightarrow \mu D^* X$
LHCb-PAPER-2016-033 (in preparation)
DT WS Mixing/CPV: Method

- Measure time dependent WS/RS ratio of $D^0 \to K\pi$
  
  \[ R(t)^\pm = \frac{WS(t)^\pm}{RS(t)^\pm} \simeq R_D^\pm + \sqrt{R_D^\pm} y^\prime \pm \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left( \frac{t}{\tau} \right)^2 \]

- Use:
  
  \[ \overline{B} \to \mu^- D^{*+} X \]
  
  \[ D^{*+} \to D^0 \pi^+_S \]
  
  \[ D^0 \to K\pi \]

- Doubly Tagged: $\mu^-$ and $\pi^+_S$ tag the $D^0$ production flavor

- Extremely clean

- Complements previous measurement using “prompt”
  
  \[ D^{*+} \to D^0 \pi^+_S \]

  \[ \text{PRL 111, 251801 (2013)} \]

- Goal: Measure Mixing/CPV parameters with DT only sample and combination of prompt and DT
Data Samples and Selection

- Extract $N_{RS, WS}$ from binned maximum likelihood fit to $D^*$ invariant mass
- Strategy:
  - Fit RS time integrated sample, fix signal shape
  - Split into $D^{*+}(D^0)$ and $D^{*-} (\bar{D}^0)$
  - fit RS and WS in each bin of decay time
- Subtract combinatoric $\mu$ background
- Veto candidates in both DT and prompt datasets
- Find decay time variation of RS $D^{*-}/D^{*+}$ ratio, account for in systematics

Fit Model: Triple Gaussian + Johnson + ARGUS like background

Fit $N_{RS} \approx 1.7 M$

Fit $N_{WS} \approx 6.7 K$
DT Only Result

\[ R(t) = \left( \frac{WS(t)}{RS(t)} \right)^{±} = R_D^{±} + \sqrt{R_D^{±} y' (\frac{t}{\tau}) + \frac{(x^{'+})^2 + (y^{−'})^2}{4} (\frac{t}{\tau})^2} \]

- Mixing Only:
  \[ R_D^+ = R_D^−, \ x'^+2 = x'^−2, \ y'^+ = y'^− \]
- No Direct CPV: \( R_D^+ = R_D^- \)
- All CPV allowed: All +/− free
- \( K\pi \) detection asymmetry, peaking backgrounds accounted for in fit
- Systematic uncertainties: combinatoric \( \mu \) subtraction, prompt veto, fit model variation and time dependent asymmetry
- Consistent with mixing only fit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No CPV</td>
<td></td>
</tr>
<tr>
<td>( R_D^{10^{-3}} )</td>
<td>3.48 ± 0.10 ± 0.01</td>
</tr>
<tr>
<td>( x'^{10^{-4}} )</td>
<td>0.28 ± 3.10 ± 0.11</td>
</tr>
<tr>
<td>( y'^{10^{-3}} )</td>
<td>4.60 ± 3.70 ± 0.18</td>
</tr>
<tr>
<td>( \chi^2/NDF )</td>
<td>6.293/7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No Direct CPV</th>
</tr>
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<tbody>
<tr>
<td>( R_D^{10^{-3}} )</td>
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<td>( \chi^2/NDF )</td>
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DT and Prompt combination

- Modify original fit to include both DT and prompt combinations
- Add errors in quadrature as original reported errors are not the same as here.
- Errors ~ 10 – 20% lower for combined fit
- Consistent with mixing only fit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DT + prompt combination</th>
<th>Prompt alone</th>
<th>% Error Improvement</th>
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<tbody>
<tr>
<td>$R_D[10^{-3}]$</td>
<td>3.533 ± 0.054</td>
<td>3.568 ± 0.067</td>
<td>19</td>
</tr>
<tr>
<td>$x^{2}/[10^{-5}]$</td>
<td>3.6 ± 4.3</td>
<td>5.5 ± 4.9</td>
<td>12</td>
</tr>
<tr>
<td>$y'[10^{-3}]$</td>
<td>5.23 ± 0.84</td>
<td>4.80 ± 0.94</td>
<td>11</td>
</tr>
<tr>
<td>$\chi^2/NDF$</td>
<td>96.594/111</td>
<td></td>
<td></td>
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<td>$x^{2}/[10^{-5}]$</td>
<td>4.9 ± 5.0</td>
<td>6.4 ± 5.6</td>
<td>11</td>
</tr>
<tr>
<td>$y'[10^{-3}]$</td>
<td>5.14 ± 0.91</td>
<td>4.80 ± 1.08</td>
<td>16</td>
</tr>
<tr>
<td>$\chi^2/NDF$</td>
<td>96.147/109</td>
<td></td>
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<tr>
<td>$R_D[10^{-3}]$</td>
<td>3.474 ± 0.081</td>
<td>3.545 ± 0.095</td>
<td>15</td>
</tr>
<tr>
<td>$x^{2}/[10^{-5}]$</td>
<td>1.1 ± 6.5</td>
<td>4.9 ± 7.0</td>
<td>7</td>
</tr>
<tr>
<td>$y'[10^{-3}]$</td>
<td>5.97 ± 1.25</td>
<td>5.10 ± 1.38</td>
<td>9</td>
</tr>
<tr>
<td>$\chi^2/NDF$</td>
<td>96.460/108</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusion

- **Today:**
  - Measurement of $CP$ asymmetry in $D^0 \to K^- K^+$ decays
    LHCb-PAPER-2016-035 (in preparation)
  - Search for Mixing and CP Violation with WS $D^0 \to K \pi$ from $\bar{B} \to \mu D^* X$
    LHCb-PAPER-2016-033 (in preparation)

- **Still no CPV in sight**

- **The future:**
  - 4.6 billion charm decays reconstructed in 2011-2015
  - LHC is running very efficiently
  - Datataking is ongoing
  - Expect many more exciting charm results to come!
  - Thanks for your attention!
$D^0 \rightarrow KK$ cancellation of asymmetries

- Control Channels to cancel:

\[
A_{CP}(D^0 \rightarrow KK) = A_{raw}(D^0 \rightarrow KK) - A_P(D^{*+}) - A_D(\pi_s^+) + O(A^3)
\]

\[
A_{raw}(D^0 \rightarrow K^- \pi^+) = A_P(D^{*+}) + A_D(\pi_s^+) + A_D(K^-) + A_D(\pi^+)
\]

\[
A_{raw}(D^+ \rightarrow K^- \pi^+ \pi^+) = A_P(D^+) + A_D(K^-) + A_D(\pi^+) + A_D(\pi^+)
\]

\[
A_{raw}(D^+ \rightarrow \overline{K^0} \pi^+) = A_P(D^+) + A_D(\overline{K^0}) + A_D(\pi^+)
\]
$A_{CP}(KK)$ Weighting checks

- Nominal weighting is in
  1. $D^+ \rightarrow K^- \pi^+ \pi^+$ weighted to $D^+ \rightarrow K^0 \pi^+$
  2. $D^0 \rightarrow K \pi$ weighted to $D^+ \rightarrow K^- \pi^+ \pi^+$
  3. $D^0 \rightarrow KK$ weighted to $D^0 \rightarrow K \pi$

- Variables weighted: $D^{*+}(p_T, \eta, \phi)$, $D^+(p_T, \eta), \pi_{\text{bachelor}}, \text{high} p\pi in K \pi \pi(\eta, \phi)$, $K, \pi(p_T, \eta, \phi)$

<table>
<thead>
<tr>
<th>Systematic check</th>
<th>$A_{CP}(K^- K^+)$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>0.143 ± 0.153</td>
</tr>
<tr>
<td>Weighting only in $p_T, \eta$</td>
<td>0.161 ± 0.144</td>
</tr>
<tr>
<td>Weighting with 15 bins</td>
<td>0.204 ± 0.150</td>
</tr>
<tr>
<td>Weighting with 25 bins</td>
<td>0.182 ± 0.154</td>
</tr>
<tr>
<td>Set high weights in each step to 1</td>
<td>0.143 ± 0.140</td>
</tr>
<tr>
<td><strong>Maximal difference</strong></td>
<td><strong>0.062</strong></td>
</tr>
</tbody>
</table>
Correlations for $A_{CP}(KK)$

- Statistical Correlation between Muon tagged and Pion tagged: 0.36
- Correlation between pion tagged $A_{CP}(D^0 \rightarrow KK)$ and $\Delta A_{CP} = 0.24$
Contours for \((x'^2, y')\)

DT Only

Prompt+DT

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Mixing and CP Violation in Charm Decays at LHCb
What do we measure?

- Assuming factorizable efficiencies, we measure
  \[ N_{RS}^{obs} = N_{D^{*+}} B(D^{*+} \to D^0 \pi^+_s) B(D^0 \to K^- \pi^+) \epsilon(\mu^-) \epsilon(\pi^+_s) \epsilon(K^- \pi^+) \]
  \[ N_{WS}^{obs} = N_{D^{*+}} B(D^{*+} \to D^0 \pi^+_s) B(D^0 \to K^+ \pi^-) \epsilon(\mu^-) \epsilon(\pi^+_s) \epsilon(K^+ \pi^-) \]
  \[ N_{RS}^{obs} = N_{D^{*-}} B(D^{*-} \to \overline{D}^0 \pi^-_s) B(\overline{D}^0 \to K^+ \pi^-) \epsilon(\mu^+) \epsilon(\pi^-_s) \epsilon(K^+ \pi^-) \]
  \[ N_{WS}^{obs} = N_{D^{*-}} B(D^{*-} \to \overline{D}^0 \pi^-_s) B(\overline{D}^0 \to K^- \pi^+) \epsilon(\mu^+) \epsilon(\pi^-_s) \epsilon(K^- \pi^+) \]

- The ratio then becomes
  \[ R^{obs\pm} = \frac{N_{WS}^{obs\pm}}{N_{RS}^{obs\pm}} = R^{\pm} \left( \frac{\epsilon(K^+ \pi^-)}{\epsilon(K^- \pi^+)} \right)^{\pm 1} \]

- Allowing for background contributions, this becomes
  \[ R^{obs\pm} = R^{\pm} \left( 1 - \Delta_p^{\pm} \right) \left( \frac{\epsilon(K^+ \pi^-)}{\epsilon(K^- \pi^+)} \right)^{\pm 1} + p^{\pm}_{\text{other}} \]

**What we want**

\[ \propto \text{Fraction of Prompt in DT Sample} \]

**K\pi Detection Efficiency**

Double MisID, other peaking
Selection Criteria and Backgrounds from $B$

- Kinematically constrain daughter $K, \pi$ to same vertex, constrain $\mu, \pi_{S}$ and $D^{0}$ to come from same vertex
- Veto candidates which appear in both Prompt and DT samples
- Extract random muon and muon mistag shape from $B \rightarrow \mu^{+}D^{*+}X$ (Unphysical)
- Call this the Same Sign (SS) sample.
- Scale to sideband in $5.6 < m(\mu D^{*}) < 6.0 \text{GeV}$ in each decay time bin
- Gauge systematic uncertainty by setting scaling factor to 1

\[ R^{\text{obs} \pm} = R^{\pm} \left( 1 - \left( \frac{\Delta p}{p} \right)^{0} \left( \frac{\epsilon(K^{+}\pi^{-})}{\epsilon(K^{-}\pi^{+})} \right) \right)^{\pm 1} + p_{\text{other}}^{\pm} \]
Multiple Candidates

- To understand multiple candidates, match explicitly momenta of final state particles, varying individually to find differences.
- Find 109,484 multiple candidates, almost all are due to a slow pion being wrong.
- Wrong $\mu$ subtracted.
- Different $D^0$ daughters will not peak in $m(D^*)$, same with different $D^0$ or different $\mu$ and $\pi_S$.
- Explicitly use all multiple candidates.
- Look for $\pi_S$ candidates consistent with being a clone: momentum vectors aligned within 0.6 mrad.
- Choose one clone randomly.
Extraction of Peaking Backgrounds

- WS peaking background not well described by double misID alone
- Divide $D^0$ sidebands into 6 regions for low and high sidebands
- Fit $m(D^*)$ in each bin, extract the number of peaking events
- Extract number of events in the signal region. Total: $128 \pm 31$
- Due to limited statistics, can only do integrated over decay time
- Fraction of doubly misidentified $D^0$ to WS yield $(1.9 \pm 0.7)\%$
- Fraction of doubly misidentified $D^0$ to RS yield: $(7.4 \pm 1.8) \times 10^{-5} \equiv \rho_{\text{other}}$

\[\chi^2_{\text{ndf}} = 10.45 / 9 \quad \text{Prob} = 0.3151 \quad p_0 = 18.64 \pm 8326 \quad p_1 = 0.01191 \pm 8.944 \quad p_2 = 5.384e^{-5} \pm 0.002398\]
The strategy for $A_{K\pi}$

- Calculate Instrumental $K\pi$ asymmetry as

$$A_{K\pi} = \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi^+)}$$

$$\approx A(K^0_{S}\pi) - A(K\pi\pi) - A(\bar{K}^0) + A_{L0\;Muons} + \mathcal{O}(10^{-6})$$

- $A(\bar{K}^0) = -(0.05 \pm 0.01)\%$ from previous measurements
- Use $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^0_{S}\pi^+$ to extract $A(K\pi\pi)$ and $A(K^0_{S}\pi)$
- Calculate $A_{L0\;Muons}$ directly from DT data
- Extract asymmetry of each sample from simultaneous fit to $D^\pm$ mass
- To cancel $D^\pm$ production asymmetry, must reweight
Reweighting Plots

MD 2012, LHCb Preliminary

A. Davis

Mixing and CP Violation in Charm Decays at LHCb
A(Kπ) Results

<table>
<thead>
<tr>
<th>Sample</th>
<th>A(Kππ)[%]</th>
<th>A(K₀π)[%]</th>
<th>A_{L0\mu}on[%]</th>
<th>A(Kπ)[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 Mag Down</td>
<td>−1.31 ± 0.27</td>
<td>−0.85 ± 0.31</td>
<td>−0.01 ± 0.01</td>
<td>0.50 ± 0.41</td>
</tr>
<tr>
<td>2011 Mag Up</td>
<td>−1.43 ± 0.28</td>
<td>−0.794 ± 0.36</td>
<td>0.02 ± 0.01</td>
<td>0.71 ± 0.45</td>
</tr>
<tr>
<td>2012 Mag Down</td>
<td>−1.81 ± 0.17</td>
<td>−0.647 ± 0.27</td>
<td>0.00 ± 0.01</td>
<td>1.22 ± 0.32</td>
</tr>
<tr>
<td>2012 Mag Up</td>
<td>−1.79 ± 0.21</td>
<td>−0.929 ± 0.25</td>
<td>0.00 ± 0.01</td>
<td>0.91 ± 0.33</td>
</tr>
<tr>
<td>Total</td>
<td>−1.67 ± 0.11</td>
<td>−0.81 ± 0.14</td>
<td>0.00 ± 0.01</td>
<td>0.90 ± 0.18</td>
</tr>
</tbody>
</table>

- Search for decay time variation by splitting DT sample by decay time, reweight in each of 5 bins
- See no variation with respect to decay time, take offset as systematic

\[ A(K\pi) = [0.90 \pm 0.18 \pm 0.10]\% \]
Cross checks and Systematic Uncertainties

- **Cross Checks**
  - Split by magnet polarity
  - Split by data-taking year
  - Split by polarity and year
  - Split by kaon momentum
  - Split by slow pion $p_T$
  - Split by muon $p_T$
  - **All consistent with statistical fluctuations**

- **Systematic Uncertainties**
  - No scaling of the SS background,
  - Allowing the RS fit model to be different for each decay time bin.
  - Variation of the $K\pi$ asymmetry as a function of decay time,
  - Fit coverage using $2\sigma$ possible bands of $x$ and $y$ from HFAG
  - **Differences from nominal taken as systematic uncertainty, correlations taken into account**
  - All cross-checks performed on blinded data, systematic uncertainties calculated before unblinding.
Time dependence of $K\pi$ asymmetry

- Know that $A(K\pi)$ does not depend on decay time
- Know we have a time dependent charge asymmetry
- Vary $A(K\pi) \rightarrow A(K\pi)(t) = A(K\pi) + \delta(A_{K\pi}) + \alpha + \beta t$.
- $\alpha, \beta$ terms taken from fit to the asymmetry of the RSD$^{*\pm}$
- $\delta(A_{K\pi}) = -0.0110$ chosen such that $\int dt \ A(K\pi)(t) = A(K\pi)$

### Mixing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$R_D[10^{-3}]$</th>
<th>$y'[10^{-3}]$</th>
<th>$x'^2[10^{-4}]$</th>
<th>$y'[10^{-3}]$</th>
<th>$x'^2[10^{-4}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic Uncertainty</td>
<td>0.01</td>
<td>0.07</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### No DCPV

<table>
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<th>$R_D[10^{-3}]$</th>
<th>$y'[10^{-3}]$</th>
<th>$x'^2[10^{-4}]$</th>
<th>$y'[10^{-3}]$</th>
<th>$x'^2[10^{-4}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic Uncertainty</td>
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<td>1.17</td>
<td>0.98</td>
<td>1.64</td>
<td>1.67</td>
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### All CPV

<table>
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<th>$R_D[10^{-3}]$</th>
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<th>$x'^2[10^{-4}]$</th>
<th>$R_D[10^{-3}]$</th>
<th>$y'[10^{-3}]$</th>
<th>$x'^2[10^{-4}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic Uncertainty</td>
<td>0.06</td>
<td>0.25</td>
<td>0.03</td>
<td>0.07</td>
<td>0.28</td>
<td>0.03</td>
</tr>
</tbody>
</table>
No Mixing Fit for DT alone

- In fit, set $x^2 = y' = 0$
- Result: $R_D = (3.76 \pm 0.05) \times 10^{-3}$
- $\chi^2/\text{ndf} = 31.953/9$
- $\Delta \chi^2 = 22.66$, NDF = 2, $p = 2.68 \times 10^{-6}$
- Inconsistent with no mixing at 4.6$\sigma$

A. Davis
Mixing and CP Violation in Charm Decays at LHCb
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