Measurements of mixing and indirect CPV in two-body charm decays at LHCb

Kevin S. Maguire, on behalf of LHCb and University of Manchester

Charm at LHCb
Huge datasets of charm at LHCb, 630 million \(D^0 \rightarrow K^-\pi^+\) in 2011-2012 [LHCb-CONF-2016-005].

Must deal with acceptance effects and large backgrounds.

Probe CP in up-type quarks.

\(D^0\) mixing already established. CP violation not observed in \(D\) system.

https://cds.cern.ch/record/2200233?ln=en
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$D^0$ mixing already established.

$CP$ violation not observed in $D$ system.
1. $A_\Gamma$ measurements in $D^0 \to K^+K^-, \pi^+\pi^-$. 
2. Charm mixing and CPV ($R(t)^\pm$) in $D^0 \to K^\pm\pi^\mp$. 
$A_F$ measurements
Two Methods

1. Unbinned maximum likelihood of effective decay times [LHCb-CONF-2016-010].
   - 2 fb$^{-1}$ collected in 2012, and combined with a previous measurement on 1 fb$^{-1}$ from 2011 data [Phys. Rev. Lett., 112:041801, 2014].
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2. **Yield asymmetries in bins of decay time** [LHCb-CONF-2016-009].
   - Full 3 fb$^{-1}$ from 2011 and 2012.
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2. Yield asymmetries in bins of decay time [LHCb-CONF-2016-009].
   - Full 3 fb$^{-1}$ from 2011 and 2012.

- Both flavour tagged with $D^{*+} \to D^0 \pi^+$.
- Same dataset and selection, except for one condition.
- A paper including both measurements is in preparation.
Asymmetry of the effective decay widths, \( \hat{\Gamma}(D^0 \to f) \) to \( CP \)-eigenstates \( f \),

\[
A_{\Gamma} = \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(D^0 \to \bar{f})}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(D^0 \to \bar{f})}.
\]
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$f = K^+K^-, \pi^+\pi^-$. 
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- $f = K^+K^-, \pi^+\pi^-$.
- In the Standard model (SM), this quantity is predicted to be below $\mathcal{O}(10^{-3})$ [JHEP03(2010)009] [Phys.Rev.D 75,036008], which is a level now being reached by experimental precision.
Asymmetry of the effective decay widths, $\hat{\Gamma}(D^0 \to f)$ to $CP$-eigenstates $f$,

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- $f = K^+K^-, \pi^+\pi^-.$
- In the Standard model (SM), this quantity is predicted to be below $O(10^{-3})$ [JHEP03(2010)009] [Phys.Rev.D 75,036008], which is a level now being reached by experimental precision.
- Improvements in precision are now valuable for testing SM predictions.
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\[
a_m = -y \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) \frac{\cos(\phi)}{2},
\]

\[
a_i = x \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) \frac{\sin(\phi)}{2},
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\end{align*}

represent CPV in **mixing** and in the **interference** of decays.

$x$ and $y$ are the charm mixing parameters,

$\phi = \arg ((q\bar{A}_f)/(pA_f))$,  

where $A_f(\bar{A}_f)$ is the amplitude of $D^0 \to f(\bar{D}^0 \to f)$ decay,

$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$. 
Method 1: Maximum Likelihood Fit

Measure the $D^0$ and $\bar{D}^0$ effective lifetimes, $\hat{\tau} = 1/\hat{\Gamma}(D^0 \rightarrow f)$
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Unbinned maximum likelihood fit factorised into two stages.
Method 1: Maximum Likelihood Fit

- Measure the $D^0$ and $\bar{D}^0$ effective lifetimes, $\hat{\tau} = 1/\hat{\Gamma}(D^0 \rightarrow f)$
- Correct for lifetime biases with the Swimming algorithm.
- Unbinned maximum likelihood fit factorised into two stages.
- First stage:

\[
\Delta m = D^{*+} - D^0 \text{ mass difference}
\]

![Graph showing $D^0$ invariant mass](image1)

![Graph showing $\Delta m$](image2)
Event selection introduces a lifetime bias.
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\[ h + h' - \tau \]

\[ IP2 \]

\[ PV \]

\[ IP1 \]

\[ D,B \]

\[ h^+ \]

\[ h^- \]

\[ accepted? \]

\[ 1 = yes \]

\[ 0 = no \]

\[ \tau \]

\[ t_{\text{meas}} \]

\[ t_{\text{min}} \]
Event selection introduces a lifetime bias.

Lower selection efficiency for candidates with very low decay times.

Move the PV along the momentum direction of the $D^0$ and recalculate the selection.
Irreducible background of $D^0$ from a long lived particle, like $B^0$. 
- Irreducible background of $D^0$ from a long lived particle, like $B^0$.
- Separated using $\ln(\chi^2_{IP})$. Where $\chi^2_{IP}$ is defined as the difference between the $\chi^2$ of the PV reconstructed with and without the considered particles.
Per-candidate probability density function (PDF) for prompt signal:

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f(t|\text{sig., prompt}) = \frac{1}{\tau} e^{-t'/\tau} \otimes R(t', t)
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Where \( R(t', t) \) is the detector decay-time resolution.
Per-candidate probability density function (PDF) for prompt signal:

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The per-candidates PDFs are normalised in the acceptance intervals.
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The per-candidates PDFs are normalised in the acceptance intervals.

Second Stage:
$A_{\Gamma}$ for the Cabibbo favoured mode $D^0 \rightarrow K^-\pi^+$ should be zero.
- $A_\Gamma$ for the Cabibbo favoured mode $D^0 \rightarrow K^{-}\pi^+$ should be zero.
- Result: pseudo-$A_\Gamma = (-0.07 \pm 0.15) \times 10^{-3}$.
- \( A_\Gamma \) for the Cabibbo favoured mode \( D^0 \rightarrow K^-\pi^+ \) should be zero.
- Result: pseudo-\( A_\Gamma = (-0.07 \pm 0.15) \times 10^{-3} \).

\[ \begin{align*}
K^+K^- \ 2 \text{ fb}^{-1} \text{ Result:} \\
&(-0.03 \pm 0.46 \pm 0.10) \times 10^{-3} \\

\pi^+\pi^- \ 2 \text{ fb}^{-1} \text{ Result:} \\
&(0.03 \pm 0.79 \pm 0.16) \times 10^{-3}
\end{align*} \]
- $A_{\Gamma}$ for the Cabibbo favoured mode $D^0 \rightarrow K^-\pi^+$ should be zero.
- Result: pseudo-$A_{\Gamma} = (-0.07 \pm 0.15) \times 10^{-3}$.

Main systematics from **mismodelling** of low decay-time, secondary contamination, ignored **correlations** and **combinatoric** backgrounds.
This result is combined with the previous LHCb measurement with 1 fb\(^{-1}\) \cite{PhysRevLett.112.041801}. 
Method 1: 3 fb$^{-1}$ Combination

- This result is combined with the previous LHCb measurement with 1 fb$^{-1}$ [Phys. Rev. Lett., 112:041801, 2014].
- New 2 fb$^{-1}$ systematics (mismodelling, correlations) assigned to 1 fb$^{-1}$. 

\[ \Gamma(D_0 \rightarrow K^+K^-) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3} \]

\[ \Gamma(D_0 \rightarrow \pi^+\pi^-) = (0.14 \pm 0.63 \pm 0.15) \times 10^{-3} \]

\[ \Delta \Gamma(D_0 \rightarrow K^+K^-) = (0.28 \pm 0.73 \pm 0.05) \times 10^{-3} \]

\[ \Gamma(D_0 \rightarrow \pi^+\pi^-) = (-0.07 \pm 0.32 \pm 0.11) \times 10^{-3} \]
This result is combined with the previous LHCb measurement with $1 \text{ fb}^{-1}$ \cite{PhysRevLett.112.041801, 2014}.

New $2 \text{ fb}^{-1}$ systematics (mismodelling, correlations) assigned to $1 \text{ fb}^{-1}$.

Preliminary: \cite{LHCb-CONF-2016-010}

\[
A_\Gamma(D^0 \rightarrow K^+ K^-) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3},
\]

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Method 1: 3 fb$^{-1}$ Combination

- This result is combined with the previous LHCb measurement with 1 fb$^{-1}$ [Phys. Rev. Lett., 112:041801, 2014].
- New 2 fb$^{-1}$ systematics (mismodelling, correlations) assigned to 1 fb$^{-1}$.

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\Delta A_{\Gamma} = (0.28 \pm 0.73 \pm 0.05) \times 10^{-3},
\]
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A_{\Gamma} = (-0.07 \pm 0.32 \pm 0.11) \times 10^{-3},
\]
Method 2: Binned yield asymmetry

- Simple counting experiment in bins of decay time.

\[ A^i_{\text{raw}} = \frac{n_i(D^0 \rightarrow f) - n_i(D^0 \rightarrow f)}{n_i(D^0 \rightarrow f) + n_i(D^0 \rightarrow f)} \quad i = 1, \ldots, m \]
Method 2: Binned yield asymmetry

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\[ A_{\text{raw}}^i = \frac{n_i(D^0 \rightarrow f) - n_i(D^0 \rightarrow f)}{n_i(D^0 \rightarrow f) + n_i(D^0 \rightarrow f)} \quad i = 1, \ldots, m \]

- Straight line fit.

\[ A_{\text{raw}}(t) = A_0 - \frac{t}{\tau_{D^0}} A_\Gamma \]
Sideband subtraction of the random “soft” pion from $\Delta m$ fit.
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Candidates in signal and sideband region used in the analyses.
Sideband subtraction of the random “soft” pion from $\Delta m$ fit.

- Candidates in signal and sideband region used in the analyses.
- Candidates in the sideband region are given negative weights.
Sideband subtraction of the random “soft” pion from $\Delta m$ fit.

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Candidates in the sideband region are given negative weights.

Cut on $\ln(\chi^2_{IP}) < 2$ removes secondaries.
Systematic assigned for residual contamination.
Momentum dependent charge-asymmetry in detection of “soft” pions creates a time-dependent detection asymmetry.

Due to $D^0$ momentum and decay-time correlation.
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\[ k = \frac{1}{\sqrt{p_x^2 + p_y^2}}, \]
\[ \theta_x = \arctan\left(\frac{p_x}{p_y}\right), \]
\[ \theta_y = \arctan\left(\frac{p_y}{p_z}\right), \]
- Momentum dependent charge-asymmetry in detection of “soft” pions creates a time-dependent detection asymmetry.
- Due to $D^0$ momentum and decay-time correlation.

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\[ \theta_y = \arctan\left(\frac{p_y}{p_z}\right) \]

- Equalise the asymmetries with $(k, \theta_x, \theta_y)$.
- \[ R = \frac{(k, \theta_x, \theta_y)_\pi^+}{(k, \theta_x, \theta_y)_\pi^-} \]
- Reweight $R$ to 1.
Pseudo-$A_{T}$

Preliminary: Before Correction: [LHCb-CONF-2016-009]
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Kevin S. Maguire  
CKM2016  
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Pseudo-$A_\Gamma$

**Preliminary: Before Correction:** [LHCb-CONF-2016-009]

![Graph showing $A_{K\pi}^{raw}(t)$ for 2011 and 2012 data, with error bars and chi-squared values for each bin.]

- 2011 Up: $+1.65 \pm 0.30$, $\chi^2/ndf = 36.17/27$
- 2011 Down: $-0.11 \pm 0.25$, $\chi^2/ndf = 12.81/27$
- 2012 Up: $+0.77 \pm 0.18$, $\chi^2/ndf = 57.10/27$
- 2012 Down: $-0.06 \pm 0.17$, $\chi^2/ndf = 28.87/27$
- Average: $+0.41 \pm 0.19$, $\chi^2/ndf = 33.05/3$
Pseudo-$A_{\Gamma}$

Preliminary: Before Correction: [LHCb-CONF-2016-009]
Pseudo-$A_{\pi}$

**Preliminary: Before Correction:** [LHCb-CONF-2016-009]

1. $A_{\pi}^K(t)$
   - LHCb preliminary
   - 2011 Up
   - 2011 Down
   - 2012 Up
   - 2012 Down

2. $A_{\pi}^{\text{raw}}(t)$

**Preliminary: After Correction:**

1. $A_{\pi}^K(t)$
   - LHCb preliminary
   - 2011 Up
   - 2011 Down
   - 2012 Up
   - 2012 Down

2. $A_{\pi}^{\text{corr}}(t)$

**Results:**
- $A_{\pi}^{\text{raw}}(t)$
  - $A_{\pi}^{\text{corr}}(t)$

- $A_{\pi}^K(t)$
  - 11Up
  - 11Dw
  - 12Up
  - 12Dw
  - avg.

- $A_{\pi}^{\text{corr}}(t)$
  - 11Up
  - 11Dw
  - 12Up
  - 12Dw
  - avg.

- $\chi^2/\text{ndf}$
  - 11Up: $+1.65 \pm 0.30$ ($\chi^2/\text{ndf} = 36.17/27$)
  - 11Dw: $-0.11 \pm 0.25$ ($\chi^2/\text{ndf} = 12.81/27$)
  - 12Up: $+0.77 \pm 0.18$ ($\chi^2/\text{ndf} = 57.10/27$)
  - 12Dw: $-0.06 \pm 0.17$ ($\chi^2/\text{ndf} = 28.87/27$)
  - avg.: $+0.41 \pm 0.10$ ($\chi^2/\text{ndf} = 22.07/3$)

- $\chi^2/\text{ndf}$
  - 11Up: $+0.56 \pm 0.30$ ($\chi^2/\text{ndf} = 19.53/27$)
  - 11Dw: $+0.04 \pm 0.25$ ($\chi^2/\text{ndf} = 12.31/27$)
  - 12Up: $-0.01 \pm 0.18$ ($\chi^2/\text{ndf} = 29.47/27$)
  - 12Dw: $+0.23 \pm 0.18$ ($\chi^2/\text{ndf} = 29.64/27$)
  - avg.: $+0.16 \pm 0.10$ ($\chi^2/\text{ndf} = 3.01/3$)
Preliminary: Before Correction: [LHCb-CONF-2016-009]

Preliminary: After Correction:
Method 2: Results

\[ D^0 \rightarrow K^+K^- \]

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\[ D^0 \rightarrow \pi^+\pi^- \]
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Preliminary:

\[
\begin{align*}
A_\Gamma(D^0 \rightarrow K^+ K^-) &= (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}, \\
A_\Gamma(D^0 \rightarrow \pi^+ \pi^-) &= (0.46 \pm 0.58 \pm 0.12) \times 10^{-3},
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World’s best measurement!
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**World’s best measurement!**

\[
\Delta A_\Gamma = (-0.76 \pm 0.66 \pm 0.04) \times 10^{-3},
\]

\[
A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3},
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Yield asymmetry in bins (more accurate) [LHCb-CONF-2016-009]

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- The more accurate yield asymmetry in bins is taken as the final result.

- Toy tests using both methods on datasets with randomised flavour tags show that the results are compatible.
$R^\pm(t)$ of $D^0 \rightarrow K^\pm \pi \pm$
\[ D^0 \rightarrow K^- \pi^+(\text{Right Sign})(CF), \]
$D^0 \rightarrow K^- \pi^+ (\text{Right Sign})(\text{CF}),$

$D^0 \rightarrow K^+ \pi^- (\text{Wrong Sign})(\text{DCS}),$
- Time dependent ratio of amplitudes for small $x$ and $y$ (sign indicates flavour tag):

\[
\frac{WS^\pm(t)}{RS^\pm(t)} := R^\pm(t) \approx R_D^\pm + \sqrt{R_D^\pm y'^\pm} \Gamma t + \frac{x'^\pm + y'^\pm}{4} (\Gamma t)^2
\]
Time dependent ratio of amplitudes for small $x$ and $y$ (sign indicates flavour tag):

$$\frac{WS^\pm(t)}{RS^\pm(t)} := R^\pm(t) \approx R^\pm_D + \sqrt{R^\pm_D}y'^\pm \Gamma t + \frac{x'^\pm 2 + y'^\pm 2}{4} (\Gamma t)^2$$

Three models

- **CP symmetry**: $R^+ = R^-, (x'^+)^2 = (x'^-)^2, y'^+ = y'^-.$
- **CP symmetry in decay amplitudes**: $R^+ = R^-.$
- All **CP violation** allowed.
- Single tag prompt with “soft” pion only

- Double tag (DT) secondary $B$ decays with muon and “soft” pion
  [arXiv:1611.06143].

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- Single tag prompt with “soft” pion only

- Double tag (DT) secondary $B$ decays with muon and “soft” pion
  [arXiv:1611.06143].

- DT cleaner and provides measurements at low decay times.

- Single tag has larger statistics and covers longer decay times.

- DT adds 3% of the statistics but removes 10%-20% from the errors.
- Make unphysical sample of 
  \( \bar{B} \rightarrow \mu^+ D^{*+} X \) (same sign).
- Remove muon mistags by reweighting with the same sign distributions.
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- Extract the signal yields from $\Delta m$ in bins of time.
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- Remove muon mistags by reweighting with the same sign distributions.
- Extract the signal yields from \( \Delta m \) in bins of time.
- One \( \Delta m \) fit of the time-integrated RS data is used to constrain the signal parameters for all bins.
- Do this for RS and WS and both flavours.
Use the three mixing hypotheses to fit the measured $R(t)^\pm$.

- **(top)**  The ratio of $D^0$ to WS over $\bar{D}^0$ to RS.

- **(middle)** The ratio of $\bar{D}^0$ to WS over $D^0$ to RS.

- **(bottom)** The difference of the two.
Use the three mixing hypotheses to fit the measured $R(t)^\pm$.

- **(top)** The ratio of $D^0$ to WS over $D^0$ to RS.
- **(middle)** The ratio of $\bar{D}^0$ to WS over $D^0$ to RS.
- **(bottom)** The difference of the two.

Consistent with the No CPV, mixing only hypothesis.
Conclusion
- Results of two complimentary $A_f$ measurements.
- World’s best measurement.
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- Results of two complimentary $A_T$ measurements.
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- Results from new DT and previously published prompt WS/RS ratio.
- Fits consistent with $CP$ symmetry and $CP$ violation hypothesis.
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- Fits consistent with $CP$ symmetry and $CP$ violation hypothesis.

All results consistent with No CPV in $D$. 
Backup
Swimming returns a tuple of turning points (TPs) which define decay-time acceptance intervals.

- Only the first acceptance interval is considered.
- The acceptance for each fit component is determined using an iterative process of unfolding.
- Validate by comparing the sum of the component TP distributions to data.

First TP, $TP_1$

First TP - Second TP, $TP_{\text{diff}}$
The per-candidate probability density functions (PDFs) are normalised in the accepted interval.

\[
f(t|TP_1, TP_{\text{diff}}, \text{class}) = \frac{f(t|\text{class})\Theta(t-TP_1)\Theta(TP_1+TP_{\text{diff}}-t)}{\int_{TP_1}^{TP_1+TP_{\text{diff}}} f(t|\text{class}) \, dt}
\]

where \(\Theta(t)\) is the heavy-side function.

\(f(t|\text{class})\) is the “unbiased” PDF, for prompt signal:

\[
f(t|\text{sig.}, \text{prompt}) = \frac{1}{\tau} e^{-t'\tau} \otimes R(t', t)
\]

Where \(R(t', t)\) is the detector decay-time resolution.
\( \pi^+ \pi^- \) unbinned likelihood fits
$\pi^+\pi^- \text{ binned } A_\Gamma \text{ fits}$

$A^{\pi\pi}_{\text{raw}}(t)$

$A^{\pi\pi}_{\text{corr}}(t)$

$\chi^2/\text{ndf}$:

- 2011 Up: $+4.94 \pm 1.62$, $\chi^2/\text{ndf}: 23.92/27$
- 2011 Down: $-0.71 \pm 1.35$, $\chi^2/\text{ndf}: 14.04/27$
- 2012 Up: $+3.54 \pm 0.98$, $\chi^2/\text{ndf}: 17.20/27$
- 2012 Down: $+0.23 \pm 0.95$, $\chi^2/\text{ndf}: 37.63/27$
- Avg.: $+1.77 \pm 0.57$, $\chi^2/\text{ndf}: 13.09/3$

- 2011 Up: $+0.46 \pm 0.58$, $\chi^2/\text{ndf}: 20.99/27$
- 2011 Down: $-1.76 \pm 1.37$, $\chi^2/\text{ndf}: 16.34/27$
- 2012 Up: $+1.42 \pm 0.99$, $\chi^2/\text{ndf}: 19.54/27$
- 2012 Down: $-0.50 \pm 0.96$, $\chi^2/\text{ndf}: 35.43/27$
- Avg.: $+0.46 \pm 0.58$, $\chi^2/\text{ndf}: 8.67/3$
Define mixing parameters:

\[ |D_{1,2}⟩ = p|D^0⟩ ± q|\bar{D}^0⟩ \]

\[ x := \frac{δm}{Γ} := \frac{2(m_1 - m_2)}{Γ_1 + Γ_2}, \quad y := \frac{Γ_2 - Γ_1}{Γ_2 + Γ_1}, \quad \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos δ & \sin δ \\ -\sin δ & \cos δ \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \]
Counting experiment for $N$ observed WS and RS decays for two flavours ($\pm$).

\[
R(t)_{\text{obs}}^\pm = R(t)^\pm (1 - \Delta_p^\pm) \left( \frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)} \right)^{\pm1} + p_{\text{other}}^\pm
\]
Counting experiment for N observed WS and RS decays for two flavours ($\pm$).

$$R(t)^{\pm}_{\text{obs}} = R(t)^{\pm}(1 - \Delta^{\pm}_p) \left( \frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)} \right)^{\pm 1} + p^{\pm}_{\text{other}}$$

Time-dependent ratio.
Counting experiment for $N$ observed WS and RS decays for two flavours ($\pm$).

$$R(t)^{\pm}_{\text{obs}} = R(t)^{\pm}(1 - \Delta_p^{\pm}) \left( \frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)} \right)^{\pm1} + p^{\pm}_{\text{other}}$$

- Time-dependent ratio.
- $\propto$ fraction of prompt in DT sample.
Counting experiment for $N$ observed WS and RS decays for two flavours ($\pm$).

$$R(t)^\pm_{\text{obs}} = R(t)^\pm (1 - \Delta_p^\pm) \left(\frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)}\right)^{\pm1} + p_{\text{other}}^\pm$$

- Time-dependent ratio.
- $\propto$ fraction of prompt in DT sample.
- Detection efficiency asymmetry.
Counting experiment for $N$ observed WS and RS decays for two flavours ($\pm$).

$$R(t)_{\text{obs}}^{\pm} = R(t)^{\pm}(1 - \Delta_{p}^{\pm}) \left( \frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)} \right)^{\pm1} + p_{\text{other}}^{\pm}$$

Time-dependent ratio.

$\propto$ fraction of prompt in DT sample.

Detection efficiency asymmetry.

MisID and peaking backgrounds.
### $R(t)^{\pm}$ Fit Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DT + Prompt</th>
<th>Prompt-only</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No CPV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_D[10^{-3}]$</td>
<td>$3.533 \pm 0.054$</td>
<td>$3.568 \pm 0.067$</td>
</tr>
<tr>
<td>$x'[10^{-4}]$</td>
<td>$0.36 \pm 0.43$</td>
<td>$0.55 \pm 0.49$</td>
</tr>
<tr>
<td>$y'[10^{-3}]$</td>
<td>$5.23 \pm 0.84$</td>
<td>$4.8 \pm 0.9$</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>$96.6/111$</td>
<td>$86.4/101$</td>
</tr>
<tr>
<td><strong>No direct CPV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_D[10^{-3}]$</td>
<td>$3.533 \pm 0.054$</td>
<td>$3.568 \pm 0.067$</td>
</tr>
<tr>
<td>$(x'^+)^2 [10^{-4}]$</td>
<td>$0.49 \pm 0.50$</td>
<td>$0.64 \pm 0.56$</td>
</tr>
<tr>
<td>$y'^+ [10^{-3}]$</td>
<td>$5.14 \pm 0.91$</td>
<td>$4.8 \pm 1.1$</td>
</tr>
<tr>
<td>$(x'^-)^2 [10^{-4}]$</td>
<td>$0.24 \pm 0.50$</td>
<td>$0.46 \pm 0.55$</td>
</tr>
<tr>
<td>$y'^- [10^{-3}]$</td>
<td>$5.32 \pm 0.91$</td>
<td>$4.8 \pm 1.1$</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>$96.1/109$</td>
<td>$86.0/99$</td>
</tr>
<tr>
<td><strong>All CPV allowed</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_D^+ [10^{-3}]$</td>
<td>$3.474 \pm 0.081$</td>
<td>$3.545 \pm 0.095$</td>
</tr>
<tr>
<td>$(x'^+)^2 [10^{-4}]$</td>
<td>$0.11 \pm 0.65$</td>
<td>$0.49 \pm 0.70$</td>
</tr>
<tr>
<td>$y'^+ [10^{-3}]$</td>
<td>$5.97 \pm 1.25$</td>
<td>$5.1 \pm 1.4$</td>
</tr>
<tr>
<td>$R_D^- [10^{-3}]$</td>
<td>$3.591 \pm 0.081$</td>
<td>$3.591 \pm 0.090$</td>
</tr>
<tr>
<td>$(x'^-)^2 [10^{-4}]$</td>
<td>$0.61 \pm 0.61$</td>
<td>$0.60 \pm 0.68$</td>
</tr>
<tr>
<td>$y'^- [10^{-3}]$</td>
<td>$4.50 \pm 1.21$</td>
<td>$4.5 \pm 1.4$</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>$95.0/108$</td>
<td>$85.9/98$</td>
</tr>
</tbody>
</table>
$R(t) \pm$ DT only fits.
### DT only fit results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D[10^{-3}]$</td>
<td>$3.48 \pm 0.10 \pm 0.01$</td>
</tr>
<tr>
<td>$x'[{10}^{-4}]$</td>
<td>$0.28 \pm 3.10 \pm 0.11$</td>
</tr>
<tr>
<td>$y'[10^{-3}]$</td>
<td>$4.60 \pm 3.70 \pm 0.18$</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>$6.3/7$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D[10^{-3}]$</td>
<td>$3.48 \pm 0.10 \pm 0.01$</td>
</tr>
<tr>
<td>$(x')^2[10^{-4}]$</td>
<td>$1.94 \pm 3.67 \pm 1.17$</td>
</tr>
<tr>
<td>$y'^+ [10^{-3}]$</td>
<td>$2.79 \pm 4.27 \pm 0.98$</td>
</tr>
<tr>
<td>$(x'-)^2 [10^{-4}]$</td>
<td>$-1.53 \pm 4.04 \pm 1.68$</td>
</tr>
<tr>
<td>$y'^- [10^{-3}]$</td>
<td>$6.51 \pm 4.38 \pm 1.66$</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>$5.6/5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D^+[10^{-3}]$</td>
<td>$3.38 \pm 0.15 \pm 0.06$</td>
</tr>
<tr>
<td>$(x'^+)^2 [10^{-4}]$</td>
<td>$-0.19 \pm 4.46 \pm 0.32$</td>
</tr>
<tr>
<td>$y'^+ [10^{-3}]$</td>
<td>$5.81 \pm 5.25 \pm 0.31$</td>
</tr>
<tr>
<td>$R_D^- [10^{-3}]$</td>
<td>$3.60 \pm 0.15 \pm 0.07$</td>
</tr>
<tr>
<td>$(x'^-)^2 [10^{-4}]$</td>
<td>$0.79 \pm 4.31 \pm 0.38$</td>
</tr>
<tr>
<td>$y'^- [10^{-3}]$</td>
<td>$3.32 \pm 5.21 \pm 0.40$</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>$4.5/4$</td>
</tr>
</tbody>
</table>