Measurement of $D^0 - \bar{D}^0$ mixing and CP violation in $D^0 \rightarrow K^+ \pi^-$ decays

LHC seminar - March 26th 2024

Roberto Ribatti (EPFL)

on behalf of the LHCb collaboration
What's charming in Charm physics?

- Charm is the **only up-type quark** that mixes and allows high precision CP violation (CPV) measurements.

\[ \begin{array}{c|ccc}
   & d & s & b \\
\hline
u & 1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3 (\rho - i\eta) \\
c & -\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\
t & A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1 \\
\end{array} \]

- A **single complex phase** in CKM matrix is the only measured source of CPV → can’t account for baryonic asymmetry observation.

- In Charm, CPV and flavour changing neutral currents are **extremely suppressed in SM** → powerful probe for new interactions at energy scales \( \gg \) colliders’ energy.

### Diagram

![Diagram](image-url)

\( Q = +\frac{2}{3} \) : \( u, c, t \)

\( Q = -\frac{1}{3} \) : \( d, s, b \)

\( B^0, B_s^0 \)
Flavour Changing Neutral Currents

- Weak interactions violate flavour conservation → flavoured neutral meson oscillate:

\[ i \frac{\partial}{\partial t} \left( \frac{M^0(t)}{\bar{M}^0(t)} \right) = \left[ \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix} \right] \left( \frac{M^0(t)}{\bar{M}^0(t)} \right) \]

\( x \sim 0.004 \quad y \sim 0.006 \)

- Oscillations are governed by two mixing parameters \( x_{12} = 2|M_{12}|/\Gamma \) and \( y_{12} = 2|\Gamma_{12}|/\Gamma \)

\( x \sim 0.95 \quad y \sim 0.99 \quad x \sim 0.77 \quad y \sim 0.001 \quad x \sim 27 \quad y \sim 0.08 \)

NP → off-shell transitions

on-shell transitions

Kagan & Sokoloff 2009
Kagan & Silvestrini 2021
$D^0 - \overline{D^0}$ mixing SM predictions

- Mixing amplitudes governed by two contributions
  - Short distance:
    - suppressed by CKM $b$ couplings
    - suppressed by GIM cancellation broken by $b$ quark
  - Long distance:
    - low-energy QCD through on-shell resonances
    - theoretical prediction of $x$ and $y$ very challenging

\[\lambda \approx 0.22\]

<table>
<thead>
<tr>
<th></th>
<th>$d$</th>
<th>$s$</th>
<th>$b$</th>
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<tbody>
<tr>
<td>$u$</td>
<td>$1 - \frac{1}{2} \lambda^2$</td>
<td>$\lambda$</td>
<td>$A\lambda^3(\rho - i\eta)$</td>
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<tr>
<td>$c$</td>
<td>$-\lambda$</td>
<td>$1 - \frac{1}{2} \lambda^2$</td>
<td>$A\lambda^2$</td>
</tr>
<tr>
<td>$t$</td>
<td>$A\lambda^3(1 - \rho - i\eta)$</td>
<td>$-A\lambda^2$</td>
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Experimental state of the art – Mixing

- First observation of mixing in charm dates back to 2009 in $D^0 \rightarrow K^+\pi^-$
- Today Charm global average largely dominated by LHCb results, which exploit the largest charm hadron dataset ever collected
- First observation of $x_{12} \neq 0$ in 2021 exploiting $D^0 \rightarrow K_S^0 \pi^+\pi^-$ decay
- Recent $D^0 \rightarrow h^+h^-$ measurement and charm+beauty combination leads to a 3% relative precision on $y_{12}$

LHCb-CONF-2022-003
**CP violation manifestations**

- **CPV in the decay**

\[ A(M \rightarrow f) = |a_1| e^{i(\delta_1 + \phi_1)} + |a_2| e^{i(\delta_2 + \phi_2)} \]
\[ A(\bar{M} \rightarrow \bar{f}) = |a_1| e^{i(\delta_1 - \phi_1)} + |a_2| e^{i(\delta_2 - \phi_2)} \]

\[ a_f^d = \frac{|A(M \rightarrow f)|^2 - |A(\bar{M} \rightarrow \bar{f})|^2}{|A(M \rightarrow f)|^2 + |A(\bar{M} \rightarrow \bar{f})|^2} \approx \sin(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1) \]

need for at least two interfering amplitudes with different weak \( \phi \) and strong \( \delta \) phases
**CP violation manifestations**

- **CPV in the decay**
  \[
  a_f^d = \frac{|A(M \to f)|^2 - |A(\bar{M} \to \bar{f})|^2}{|A(M \to f)|^2 + |A(\bar{M} \to \bar{f})|^2} \neq 0
  \]

- **CPV in the mixing**
  \[
  \arg \left( \frac{M_{12}}{\Gamma_{12}} \right) = \phi_2^M - \phi_2^\Gamma \neq 0
  \]

- **CPV in the interference**
  (of decay and mixing)
Experimental state of the art − $CPV$ in the decay

- In 2019 LHCb report first observation of $CPV$ in charm decay

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4} \ (5.3 \sigma)$$

- Followed in 2023 by evidence of $CPV$ in $D^0 \rightarrow \pi^+\pi^-$ decay

$$\alpha_{\pi\pi}^d = (23.2 \pm 6.1) \times 10^{-4} \ (3.8 \sigma)$$

- Theoretical interpretation is debated, is this NP or SM effect?
Experimental state of the art – Other CPV sources

- Crucial to search for other CPV manifestation in charm sector
- Still no evidence of CPV in mixing and interference
- $D^0 \rightarrow K^+\pi^-$ decay channel allows to simultaneously measure mixing and all types of CPV, with excellent sensitivity to $\phi^M_2$ and $y$

New world-best LHCb measurement of mixing and CPV in $D^0 \rightarrow K^+\pi^-$ is presented here for the first time
$D^0 \rightarrow K\pi$  WS/RS

- Neutral $D$ meson flavour tagged exploiting strong decay $D^+ \rightarrow D^0 \pi_s^+$ and $D^- \rightarrow \bar{D}^0 \pi_s^-$
- Distinguish two processes: **wrong sign (WS)** and **right sign (RS)**

- Accounting for CPV we measure time dependence of WS/RS yield ratio $R_{K\pi}^\pm(t)$

\[
R_{K\pi}^+(t) = \frac{\Gamma(D^0(t) \rightarrow K^+\pi^-)}{\Gamma(D^0(t) \rightarrow K^+\pi^-)} \quad \text{and} \quad R_{K\pi}^-(t) = \frac{\Gamma(\bar{D}^0(t) \rightarrow K^-\pi^+)}{\Gamma(D^0(t) \rightarrow K^-\pi^+)}
\]

- Since $x_{12}, y_{12} \ll 1$ the ratio can be expanded as:

\[
R_{K\pi}^\pm(t) = R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})} (c_{K\pi} + \Delta c_{K\pi}) t/\tau_{D^0} + (c'_{K\pi} + \Delta c'_{K\pi}) (t/\tau_{D^0})^2
\]
\( D^0 \rightarrow K\pi \)  WS/RS

\[
R_{K\pi}^\pm(t) = R_{K\pi} (1 \pm A_{K\pi}) + \sqrt{R_{K\pi} (1 \pm A_{K\pi})} (c_{K\pi} \pm \Delta c_{K\pi}) t/\tau_{D^0} + (c'_{K\pi} \pm \Delta c'_{K\pi}) (t/\tau_{D^0})^2
\]

- \( R_{K\pi} \) is the DCS/CF ratio \( \sim 3.4 \times 10^{-3} \)
- Mixing observables:
  - \( c_{K\pi} \approx y_{12} \cos \phi_2^R \cos \Delta_{K\pi} + x_{12} \cos \phi_2^M \sin \Delta_{K\pi} \)
  - \( c'_{K\pi} \approx \frac{1}{4} (x_{12}^2 + y_{12}^2) \)
- CPV observables:
  - \( \Delta c_{K\pi} = -10^\circ \pm 3^\circ \) measured by LHCb, CLEO, BESIII
  - \( A_K\pi \) is the CP asymmetry in DCS
  - \( \Delta c'_{K\pi} = \frac{1}{2} x_{12} y_{12} \sin (\phi_2^M - \phi_2^R) \)

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Roberto Ribatti | Mixing and CPV in \( D^0 \rightarrow K\pi \)

low sensitivity to quadratic term

small angle, large uncertainty

strong phase difference of DCS/CF

LHCb-CONF-2022-003, PRD86.112001, EPJC82.1009

only one amplitude in \( D^0 \rightarrow K\pi \)
\( \Rightarrow A_{K\pi} = 0 \) null test of SM

mostly sensitive to \( y_{12} \)

mostly sensitive to \( x_{12} \phi_2^M \approx \Delta y \approx -\Delta Y \)
This measurement is dominated by previous LHCb result
→ Run 1 + 2015/16: 0.7 M WS + 180 M RS

In 2017-2018 collected additional 1.1 M WS + 280 M RS
→ total yield more than doubled

The measurement presented here uses the full Run 2 sample
→ 2015-2016 re-analysed with improved strategy

Average with Run 1 results performed to return the LHCb Run 1+2 legacy results
LHCb experiment – Run 1+2

**Vertex tracker**

\[ \sigma(\text{IP}) = 15+29/p_T (\text{GeV/c}) \mu m \]

\[ \sigma(t) = 45 \text{ fs} \approx 0.1 \tau(D^0) \]

**Cherenkov detectors**

\( K \) 95% eff. for 5% \( \pi \rightarrow K \) misID

**Hadron calorimeter**

**Muon chambers**

**Vertex tracker**

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**Muon chambers**
Online selection

- LHCb’s excellent trigger capabilities reduce rate from 40 MHz bunch crossing to 12.5 kHz on tape

- Charm analysis pioneered “Turbo” data-taking paradigm
  → only signal candidates recorded → yield/ fb$^{-1}$ x 2 wrt Run 1

- Online selection designed to select signal with high purity while limited by a maximum bandwidth

Analysis workflow

- General philosophy of offline selection design is targeting robustness
- Sample is divided between $D^0$ final state ($K^+\pi^-$, $K^-\pi^+$), 18 $D^0$ decay-time intervals and 3 data-taking period (2015-16, 2017 and 2018).

In each subsample we determine:
  - average $D^0$ decay time, $t$
  - WS-to-RS ratio, $R$, fitting $D^*$ mass to disentangle signal from combinatorial and ghost backgrounds

- And we correct them from the known systematic effects
  - bias to the ratio
  - bias to asymmetry
  - bias to $D^0$ decay-time

- Time dependence is fitted $\rightarrow$ extract mixing and CPV parameters
Systematic sources of biases
Ratio biases – Ghost background

- Our normalization channel, $D^0 \rightarrow K^- \pi^+$, is also one of the main source of background → much more abundant, if misidentified it can leak in our WS signal

- Ghost bkg result from misassociation of correctly-identified hits in VELO with hits in T-Stations from different particles

- Soft pion from RS decays seed the production of both RS and WS ghosts → peak in $D^*$ mass because even if $\pi_s$ momentum is random, direction is correct

- Percent level contamination but we aim at sub-percent precision
Ratio biases – Ghost background proxy

- A fraction of $D^0$ candidates is used to reconstruct both WS $D^{*+}$ and RS $D^{*-}$
- $RS D^*$ within 3$\sigma$ from $D^*$ peak, are most likely genuine → common WS are are either ghost or combinatorial bkg and discarded to improve signal-to-noise ratio
- In this sample, ghost and combinatorial component can be disentangled looking at angle between $\pi^+_S$ and $\pi^-_S$
- This pure subsample of common ghost (CG) is used as a proxy for residual ghost bkg
Ratio biases – common WS removal

- Removing these WS-RS multiple candidates, a small fraction of proper WS decays are removed, biasing the ratio.

- Estimated and subtracted bias $\sim \sigma(R_{K\pi})/5$.
**Ratio biases – Test of ghost bkg. subtraction**

- Test capability to correctly remove ghost bkg.
- Fit WS-to-RS ratio in 6 bin of $P_{\text{ghost}}(\pi^+_s)$ with and without ghost component
- When ghosts are neglected clear bias appears
- Adding ghost component removes any dependence
- The subtracted bias on $R_{K\pi}$ from ghost bkg. is $\sim$1%
**Ratio biases – Particles misidentification**

- Remove background from single mis-ID $D^0 \rightarrow K^+(\rightarrow \pi^+) K^-$ and $D^0 \rightarrow \pi^+(\rightarrow K^+) \pi^-$
  
  \[ |m(K\pi) - m(D^0)_{PDG}| < 24 \text{ MeV} \ (3\sigma) \]

- Misreconstructed multibody charm decays found to be negligible in previous studies

- Reduce by factor of 5 background from double mis-ID $D^0 \rightarrow K^- (\rightarrow \pi^-) \pi^+ (\rightarrow K^+) (RS\rightarrow WS)$

  \[ |m(K\pi)_{\text{swap}} - m(D^0)_{PDG}| > 16 \text{ MeV} \ (1.5\sigma) \]

  Subtracted residual bias $\sim \sigma(R_{K\pi})/10$
Asymmetry bias – Nuisance asymmetry

- Differences in reconstruction efficiency between WS and RS may mimic CPV

\[ \tilde{R}'^\pm = R'^\pm \frac{\int [1 \pm A_P(D^*)] \epsilon(\pi^\pm_s) \epsilon(K^\pm_{\pi^\mp}) d\bar{p}_{D^0} d\bar{p}_{\pi_s}}{\int [1 \mp A_P(D^*)] \epsilon(\pi^\mp_s) \epsilon(K_{\pi^\pm}) d\bar{p}_{D^0} d\bar{p}_{\pi_s}} \sim R'^\pm \frac{1 \pm [A_D(\pi_s) + A_P(D^*)]}{1 \mp [A_D(\pi_s) + A_P(D^*)]} \]

- \( A_D(\pi_s) + A_P(D^*) \) measured exploiting \( a_{KK}^d \) LHCb analysis in \( D^0 \rightarrow K^+K^- \) CS decays \[ \text{PRL131.091802} \]

\[ A_D(\pi_s) + A_P(D^*) = A^{\text{raw}}(KK) - a_{KK}^d - \Delta Y \langle t \rangle \]

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Roberto Ribatti | Mixing and CPV in \( D^0 \rightarrow K^+\pi^- \)
Asymmetry bias – Nuisance asymmetry correction

- When $A_D(\pi_s)$ is not small, correction terms appear in equations in previous slide
- Very high asymmetry regions are conservatively removed (15% signal loss) → collateral benefit: remove 40% of residual ghost contamination
Asymmetry bias – $A^{\text{raw}}(KK)$ measurement

- $A_D(\pi_s)$ depends on kinematics → $D^0 \rightarrow K^+K^-$ kinematics is equalized to $D^0 \rightarrow K^-\pi^+$
- Then $D^{*+}$ and $D^{*-}$ samples are fitted simultaneously to extract the raw asymmetry
Decay-time biases – Sources

- Poor $D^*$ vertex resolution ($\sim 1\,\text{cm}) \rightarrow D^*$ is constrained in the PV
- Due to this constraint, contamination from secondary $D^*$ from $b$-hadrons decays
  - bias decay time towards higher values
  - feature a deformed $D^*$ mass line-shape
- Reject this background as much as possible requiring $\text{IP}(D^0) < 60\,\mu\text{m}$
- Total bias, in each decay-time bin $i$, is computed as the weighted sum

$$
\delta t_i \equiv \langle \delta t \rangle^P_i (1 - f^S_i) + \langle \delta t \rangle^S_i f^S_i
$$

- bias in prompt $D^*$
- bias in secondary $D^*$
Decay-time bias – Simulation tunings

- Time biases and $f_i^S$ in each decay-time bin determined by a 2D template fit to $t(D^0)$ vs. IP($D^0$)
- Templates generated with LHCb simulation
  - Kinematics of simulated samples weighted to data
  - $\sim$10 $\mu$m VELO misalignment, which degrades IP resolutions in data, identified and injected in simulation
  - PV and $D^0$ decay vertex (DV) resolutions tuned to reproduce the features observed in data → scale factors to PV and DV resolutions are applied and treated as nuisance parameters
  - The knowledge of the cocktail of b-hadron to $D^*$ decay is partial. As an effective correction a small fraction of $B^0\rightarrow D^* X$ decays are added → $m(X)$ and relative fraction treated as nuisance parameters
Decay-time bias – Results

- Final results in 2018 data-taking period
WS/RS measurements & results
WS/RS Ratio determination – $D^*$ mass fit

- Constraining $D^*$ in the PV improve mass resolution by a factor of 2
- A $\chi^2$ binned fit is performed simultaneously to $D^*$ mass distributions of WS, RS and CG
- Each subsample independently fitted (decay-time interval, data-taking period, and $D^0$ final state)
- Signal and Ghost bkg pdf are shared
Mixing + CPV fit - Model

- Minimize a $\chi^2$ that incorporates all systematic biases:

$$\chi^2 = \sum_{t,y,f} \left( \frac{r_{ty}^f - R_{ty}^f}{\epsilon \cdot \sigma(r_{ty}^f)} \right)^2 + \chi^2_{\text{nuis}}$$

6 parameters of interest: $R_{K\pi}^\pm$, mixing & CPV parameters.

$$R_{ty}^\pm \equiv \left[ R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})} \right] \left( c_{K\pi} \pm \Delta c_{K\pi} \right) \langle T \rangle_{ty}^\pm + \left( c'_{K\pi} \pm \Delta c'_{K\pi} \right) \langle T^2 \rangle_{ty}^\pm \times (1 \pm 2A_{ty}) \cdot C + D$$

- removed common WS
- mass model
- doubly mis-ID

$$(T)_{ty}^\pm \equiv \langle (t)_{ty}^\pm - \langle \delta T \rangle_{ty} \rangle \cdot S$$

- decay-time bias

$$(A_{ty}) \equiv A_{ty}^{\text{raw}} (K K) - a_{KK}^d - \Delta Y \cdot (T)_{ty}$$

- raw KK asymmetry
- direct KK CP asymmetry
- time dep. KK CP asymmetry ext.

$m(D^0)/\tau(D^0)$ ext. input
Mixing + CPV fit – Results

Mixing observables

\[ c'_{K\pi} \neq 0 \text{ (3.5}\sigma) \] evidence for a significant quadratic term

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( R_{K\pi} )</th>
<th>( c_{K\pi} )</th>
<th>( c'_{K\pi} )</th>
<th>( A_{K\pi} )</th>
<th>( \Delta c_{K\pi} )</th>
<th>( \Delta c'_{K\pi} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{K\pi} )</td>
<td>(343.1 ± 2.0) \times 10^{-5}</td>
<td>100.0</td>
<td>-92.4</td>
<td>80.0</td>
<td>0.9</td>
<td>-0.8</td>
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<td>( c_{K\pi} )</td>
<td>(51.4 ± 3.5) \times 10^{-4}</td>
<td>100.0</td>
<td>-94.1</td>
<td>-1.4</td>
<td>1.4</td>
<td>-0.7</td>
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<tr>
<td>( c'_{K\pi} )</td>
<td>(13.1 ± 3.7) \times 10^{-6}</td>
<td>100.0</td>
<td>0.7</td>
<td>-0.7</td>
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<td>( A_{K\pi} )</td>
<td>(-7.1 ± 6.0) \times 10^{-3}</td>
<td>100.0</td>
<td>-91.5</td>
<td>79.4</td>
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<td>( \Delta c_{K\pi} )</td>
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<td>100.0</td>
<td>-94.1</td>
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<tr>
<td>( \Delta c'_{K\pi} )</td>
<td>(-1.9 ± 3.8) \times 10^{-6}</td>
<td>100.0</td>
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</tbody>
</table>

CPV observables

No evidence of CPV neither in decay, mixing nor interference

LHCb preliminary

Data

Baseline

No CP violation

\( D^0 \) decay time / \( \tau_{D^0} \)

\( (R^+ - R^-) / 2 \times 10^5 \)

550

500

450

400

350

300

250

200

150

100

50

0

-50

-100

-150

-200

-250

-300

-350

LHCb-PAPER-2024-008
Mixing + $CPV$ fit – Systematic uncertainties

- Main systematic sources are $D^+$ mass fit model and ghost bkg pdf
- Instrumental asymmetry and $a_{KK}^d$ external input are relevant only for $CPV$ observables → statistically dominated
- Dominant systematic in previous iteration (decay-time bias) reduced by one order of magnitude  PRD97,031101
- Total systematic uncertainty improved by a factor of 2

<table>
<thead>
<tr>
<th>Source</th>
<th>$R_{K\pi}$</th>
<th>$c_{K\pi}$</th>
<th>$c_{K\pi}'$</th>
<th>$A_{K\pi}$</th>
<th>$\Delta c_{K\pi}$</th>
<th>$\Delta c_{K\pi}'$</th>
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<tbody>
<tr>
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<td>0.9</td>
<td>1.4</td>
<td>0.8</td>
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<td>Ghost soft pions</td>
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<td>$a_{KK}^d$ ext. input</td>
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<td></td>
<td></td>
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<td>$\Delta Y$ ext. input</td>
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<td>Doubly Mis-ID bkg.</td>
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<td>Decay-time bias</td>
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<td>0.1</td>
<td>0.1</td>
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<tr>
<td>$m_{D^0}/\tau_{D^0}$ ext. input</td>
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<td>0.1</td>
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<td>Total syst. uncertainty</td>
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<td>1.1</td>
<td>1.2</td>
<td>2.4</td>
<td>1.3</td>
<td>1.4</td>
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<td>Statistical uncertainty</td>
<td>1.9</td>
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<td>3.5</td>
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<td>3.3</td>
<td>3.5</td>
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<td>Total uncertainty</td>
<td>2.0</td>
<td>3.5</td>
<td>3.7</td>
<td>6.0</td>
<td>3.6</td>
<td>3.8</td>
</tr>
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Mixing + CPV fit – LHCb Run 1+2 Legacy result

- Simultaneous minimization of Run 2 $\chi^2$ and Run 1 $\chi^2$ from PRD97,031101 [LHCb internal note]

<table>
<thead>
<tr>
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<th>This result Run 1 + 2</th>
<th>PRD97,031101 Run 1 + 2015/16</th>
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<tr>
<td>$R_{K\pi}$</td>
<td>$(342.7 \pm 1.9) \times 10^{-5}$</td>
<td>$(345.2 \pm 3.1) \times 10^{-5}$</td>
</tr>
<tr>
<td>$c_{K\pi}$</td>
<td>$(52.8 \pm 3.3) \times 10^{-4}$</td>
<td>$(53.3 \pm 5.1) \times 10^{-4}$</td>
</tr>
<tr>
<td>$c'_{K\pi}$</td>
<td>$(12.0 \pm 3.5) \times 10^{-6}$</td>
<td>$(15.8 \pm 5.2) \times 10^{-6}$</td>
</tr>
<tr>
<td>$A_{K\pi}$</td>
<td>$(-6.6 \pm 5.7) \times 10^{-3}$</td>
<td>$(-0.9 \pm 8.9) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Delta c_{K\pi}$</td>
<td>$(2.0 \pm 3.4) \times 10^{-4}$</td>
<td>$(-2.0 \pm 5.1) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta c'_{K\pi}$</td>
<td>$(-0.7 \pm 3.6) \times 10^{-6}$</td>
<td>$(4.4 \pm 5.2) \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Results are compatible
Total uncertainty improved by 1.6x
Impact on World average – $CP$ violation

- Global fit performed à la HFLAV
  \[ JHEP2022.162 \]

20% improvement on $\phi_2^M$

$\Delta c_{K\pi} \approx x_{12} \sin \phi_2^M \cos \Delta_{K\pi} - y_{12} \sin \phi_2^\Gamma \sin \Delta_{K\pi}$

$\Delta_{K\pi}$ small, mostly sensitive to dispersive $CPV$

No $CP$ violation

LHCb preliminary

contours hold 68%, 95% CL
Impact on World average – Mixing

- \( c_{K\pi} \approx y_{12} \cos \Delta_{K\pi} + x_{12} \sin \Delta_{K\pi} \)

  → sensitivity to \( y_{12} \) is limited by independent \( \Delta_{K\pi} \) measurements

- Conversely, combining \( c_{K\pi} \) with LHCb measurements

  \[ y_{CP} \approx y_{12} \quad \text{and} \quad x_{CP} \approx x_{12} \]

  allows for a precise determination of \( \Delta_{K\pi} \)

- Further improvements expected from future charm + beauty LHCb combination

  expected 4\( \sigma \) evidence of U-spin symmetry breaking
Conclusions

- Presented for the first time the LHCb full Run 2 measurement of mixing and CPV parameters in prompt $D^0 \rightarrow K^+\pi^-$ and legacy Run 1+2 LHCb combination → total uncertainties improved by 1.6x → strong systematics reduction makes the measurement statistically dominated → it was one of the last missing Run 1+2 measurement in Charm mixing & CPV

- Future charm+beauty LHCb fit will be significatively impacted

- The way is paved for Run 3 and beyond
  LHCb plans to collect $D^0 \rightarrow hh'$ decays with doubled efficiency/fb$^{-1}$ wrt Run 2
  Uncertainties expected to halve by the end of Run 3

- Still more to come from Run 1+2, stay tuned!
Thank you for your attention!
Backup
Phenomenological vs Theoretical parametrization

\[ |D_{1,2}⟩ = p|D^0⟩ ± q|D^0⟩ \]

Phenomenological

\[ x = \Delta m / \Gamma \]

\[ y = \Delta \Gamma / 2\Gamma \]

Theoretical

\[ x_{12} = 2|M_{12}| / \Gamma \]

\[ y_{12} = 2|\Gamma_{12}| / \Gamma \]

\[ \phi_{2}^Γ \equiv \arg \left[ \frac{1}{4}(\lambda_s - \lambda_d)^2 \Gamma_2 \right] \]

\[ \phi_{2}^M \equiv \arg \left[ \frac{M_{12}}{4\Gamma_2} \right] \]

\[ \phi_{2} \approx - \frac{x_{12}^2}{x_{12}^2 + y_{12}^2} \phi_{2}^M - \frac{y_{12}^2}{x_{12}^2 + y_{12}^2} \phi_{2}^Γ \]

intrinsic CPV mixing phases, defined with respect to the dominant $\Delta U = 2$ dispersive and absorptive mixing amplitudes

Kagan & Silvestrini 2021
Bias on $A^{\text{raw}}(KK)$ determination

- Both Eq. (1) and (2) (slide 21) assume that $A_D(\pi_s)$ is small, however if fiducial cuts are not applied, regions with high detection asymmetry are present.

- Removing this assumption, Eq. (1) becomes:

$$\tilde{R}^{\pm}_i \simeq R^{\pm}_i \cdot \left(1 \pm 2 \int_{t_i} A(D^{*}\pi_s) \omega \, dt \, d\vec{p} + 2 \int_{t_i} A(K\pi) A(D^{*}\pi_s) \omega \, dt \, d\vec{p} \right)$$

- While Eq. (2) becomes:

$$A^{\text{raw}}_{\text{wgt},i}(KK) - A^{KK}_{CP,i} \simeq \int_{t_i} A(D^{*}\pi_s) \omega'(t) \, dt \, d\vec{p} - \int_{t_i} A^2(D^{*}\pi_s) \left[A(K\pi) + A^{KK}_{CP} \right] \omega'(t) \, dt \, d\vec{p}$$

- Correcting $R_{CP}$ and $A_D$, neglecting these two additional terms, could produce a bias $O(\text{stat. unc.})$.

$$\bar{R}_{CP} \simeq R_{CP} \left(1 + 2 \int A(K\pi) A(D^{*}\pi_s) \omega \, dt \, d\vec{p} \right)$$

$$\bar{A}_D \simeq A_D + 2 \int A^2(D^{*}\pi_s) \left[A(K\pi) + A^{KK}_{CP} \right] \omega \, dt \, d\vec{p}$$
## Inclusive secondary $D^*$ cocktail

<table>
<thead>
<tr>
<th>Secondary Decay</th>
<th>BR ($\times 10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^*\to e^+\nu_e$</td>
<td>50.5</td>
</tr>
<tr>
<td>$D^*\to \mu^+\nu_\mu$</td>
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</tr>
<tr>
<td>$D^<em>\to D_s^{</em>+}$</td>
<td>17.7</td>
</tr>
<tr>
<td>$D^*\to 2\pi^+\pi^-\pi^0$</td>
<td>17.6</td>
</tr>
<tr>
<td>$D^*\to \tau^+\nu_\tau$</td>
<td>15.7</td>
</tr>
<tr>
<td>$D^*\to \pi^+\pi^0$</td>
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</tr>
<tr>
<td>$D^*\to a_1^+(1260)$</td>
<td>13.</td>
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<tr>
<td>$D^*\to D_s^{*0}(2007)K^+$</td>
<td>10.6</td>
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<tr>
<td>$D^<em>\to D_s^{</em>+}(2460)$</td>
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</tr>
<tr>
<td>$D^<em>\to D^{</em>+}K^0$</td>
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<tr>
<td>$D^*\to D_s^+$</td>
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<tr>
<td>$D^*\to 2\pi^+\pi^-$</td>
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<tr>
<td>$D^*\to \rho^+$</td>
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<tr>
<td>$D^*\to \rho^{0}\pi^+$</td>
<td>5.7</td>
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<tr>
<td>$D^*\to D^-K^0$</td>
<td>4.7</td>
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<tr>
<td>$D^*\to 3\pi^+2\pi^-$</td>
<td>4.7</td>
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<td>$D^*\to \pi^+$</td>
<td>2.74</td>
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<tr>
<td>$D^*\to D^0K^+$</td>
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<tr>
<td>$D^*\to \omega(782)\pi^+$</td>
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<tr>
<td>$D^*\to D^0K^0$</td>
<td>1.8</td>
</tr>
<tr>
<td>$D^*\to D_s^{*0}(2317)$</td>
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</table>

<table>
<thead>
<tr>
<th>Secondary Decay</th>
<th>BR ($\times 10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^*\to p^+\bar{\theta}^0$</td>
<td>1.4</td>
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<td>$D^*\to \bar{K}^0$</td>
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<tr>
<td>$D^<em>\to D_s^{</em>+}(2700)$</td>
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<tr>
<td>$D^<em>\to D^{</em>+}$</td>
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<tr>
<td>$D^*\to D^-$</td>
<td>0.61</td>
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<tr>
<td>$D^*\to K^+\pi^-\pi^+$</td>
<td>0.47</td>
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<tr>
<td>$D^*\to p^+\bar{\theta}^-\pi^+$</td>
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<tr>
<td>$D^<em>\to K^{</em>+}(892)$</td>
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<tr>
<td>$D^*\to K^{0}\pi^+$</td>
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<tr>
<td>$D^*\to K^+$</td>
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<td>$D^*\to D_s^{*0}K^0$</td>
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<td>$D^*\to D^{0}K^0$</td>
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<td>$D^*\to 3\pi^+\pi^-$</td>
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<tr>
<td>$D^*\to 2\pi^+$</td>
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<tr>
<td>$D^<em>\to D^{</em>+}K^+$</td>
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<td>$D^*\to D^{0}(2007)$</td>
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<tr>
<td>$D^*\to D^-K^+$</td>
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<tr>
<td>$D^*\to D^+K^+$</td>
<td>0.6</td>
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<tr>
<td>$D^*\to D^{0}$</td>
<td>0.39</td>
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Decay-time bias – Template fit

- Systematic uncertainties on PV and DV res. scale, $m(X)$ and $f_X$ are treated with the template profile likelihood approach:
  - templates produced with PV and DV resolution independently scaled by a factor of -10%, 1, +10%, $m(X)$ is chosen between 0.5, 1.5, 2.5 GeV/$c^2$ and $f_X$ between 0%, 3%, 6%
  - templates corresponding to intermediate values obtained through linear interpolation
- Uncertainties on simulation statistics treated with Beeston-Barlow prescription:
  - each template bin became a nuisance parameter constrained (in the likelihood) with its statistical uncertainty
- The parameters of interest are the normalizations of prompt and secondary templates
Impact on World average – Superweak approximation

- Superweak approximation \textit{PRL13.562} assumes that the only CPV source is interaction with BSM particles with mass much higher than $D^0$
  
  $\rightarrow$ only parameter responsible for CPV would be $\phi^M_2$

- In the fit, this limit is implemented by fixing $A_{K\pi} = 0$ and $\phi^\Gamma_2 = 0$
  
  $\rightarrow$ under this assumption, precision on $\phi^M_2$ improves by 20% reaching 13 mrad precision