Recent Results on CP Violation in Charm mesons at LHCb

Maurizio Martinelli (Università di Milano Bicocca and CERN) on behalf the LHCb Collaboration

Weak Interactions and Neutrino 2019
Bari, 04.06.2019
CP Violation in Charm
## CP Violation in The Standard Model

### CKM Matrix

- CPV is naturally introduced by the irreducible complex phase of the CKM matrix
- Relatively large effects in transitions involving the third generation of quarks

<table>
<thead>
<tr>
<th></th>
<th>d</th>
<th>s</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>$1-\lambda^2$</td>
<td>$\lambda$</td>
<td>$A\lambda^3(\rho-i\eta)$</td>
</tr>
<tr>
<td>c</td>
<td>$-\lambda$</td>
<td>$1-\lambda^2$</td>
<td>$A\lambda^2$ + $O(\lambda^4)$</td>
</tr>
<tr>
<td>t</td>
<td>$-A\lambda^2$</td>
<td>1</td>
<td>$A\lambda^3(1-\rho-i\eta)$</td>
</tr>
</tbody>
</table>

### B decays

Motivation
**CP Violation in The Standard Model**

### CKM Matrix
- CPV is naturally introduced by the irreducible complex phase of the CKM matrix
- Relatively large effects in transitions involving the third generation of quarks
- Highly suppressed in Charm

<table>
<thead>
<tr>
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</tr>
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<tr>
<td><strong>u</strong></td>
<td>1-(\lambda^2)</td>
<td>(\lambda)</td>
<td>(\Lambda \lambda^3 (\rho-i\eta))</td>
</tr>
<tr>
<td><strong>c</strong></td>
<td>-(\lambda)</td>
<td>1-(\lambda^2)</td>
<td>(\Lambda \lambda^2)</td>
</tr>
<tr>
<td><strong>t</strong></td>
<td>(\Lambda \lambda^3 (1-\rho-i\eta))</td>
<td>-(\Lambda \lambda^2)</td>
<td>1</td>
</tr>
</tbody>
</table>

#### B decays
- \(\alpha = \phi_s\)
- \(\beta = \phi_f\)
- \(\gamma = \phi_3\)

#### D decays
- \(\Lambda_B \sim \mathcal{O}(\lambda^5)\)
- \(\Lambda_s \sim \mathcal{O}(\lambda)\)
- \(\Lambda_d \sim \mathcal{O}(\lambda)\)
Why Studying CPV in Charm Decays?

**Charming**

- Only up-type quark decay in which CPV can be probed
- Indirect CPV in Charm decays could probe extremely high BSM scales
- Complementary to direct searches for BSM particles
- We have billions of decays ready to be studied at LHCb!

![NP scale vs Wilson Coefficients](chart.png)

**Limits**

arxiv:1710.09644
CP Violation in Charm

**Decay**

\[ D^0 \rightarrow f \quad \neq \quad \bar{D}^0 \rightarrow \bar{f} \]

**Mixing**

\[ D^0 \quad \bar{D}^0 \rightarrow f \quad \neq \quad \bar{D}^0 \rightarrow \bar{f} \]

**Interference Mixing and Decay**

\[ D^0 \quad \bar{D}^0 \rightarrow f + \bar{f} \quad \neq \quad \bar{D}^0 \rightarrow \bar{f} + D^0 \rightarrow f \]
Charm at LHCb
Charm quarks produced in low $\eta$ at LHC
$\sigma(pp\rightarrow cc) \sim 20\sigma(pp\rightarrow bb)$

$\varepsilon_{VELO} \approx 98\%$
$\delta t/t = 45\text{fs}$
$\sigma(\text{IP}) \approx 20\mu\text{m}$
$\delta p/p \approx 0.5\%$

$\varepsilon_{Track} \approx 95\%$
$\varepsilon_{PID(K)} \approx 95\%$
$\varepsilon_{PID(\mu)} \approx 97\%$
$\varepsilon_{PID(e)} \approx 90\%$

Tracking Reconstruction at LHCb

- VELO track
- Downstream track
- Long track
- Upstream track
- TT
- T track
- T1, T2, T3
- B

JINST 10 (2015) P02007
### LHCb Dataset

<table>
<thead>
<tr>
<th>Year</th>
<th>Luminosity (1/fb)</th>
<th>CM Energy (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>0.04</td>
<td>7</td>
</tr>
<tr>
<td>2011</td>
<td>1.11</td>
<td>7</td>
</tr>
<tr>
<td>2012</td>
<td>2.08</td>
<td>8</td>
</tr>
<tr>
<td>2015</td>
<td>0.33</td>
<td>13</td>
</tr>
<tr>
<td>2016</td>
<td>1.67</td>
<td>13</td>
</tr>
<tr>
<td>2017</td>
<td>1.71</td>
<td>13</td>
</tr>
<tr>
<td>2018</td>
<td>2.19</td>
<td>13</td>
</tr>
</tbody>
</table>

Run1

Run2

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018

- 2018 (6.5 TeV): 2.19 /fb
- 2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
- 2016 (6.5 TeV): 1.67 /fb
- 2015 (6.5 TeV): 0.33 /fb
- 2012 (4.0 TeV): 2.08 /fb
- 2011 (3.5 TeV): 1.11 /fb
- 2010 (3.5 TeV): 0.04 /fb

$\mathcal{L} = 4 \times 10^{32} / (\text{cm}^2 \cdot \text{s})$
An Experiment By Itself

- With the charm production cross-section at LHCb and our ability of triggering it we have a vast physics program in Charm

- **Pro**: huge yields ($10^9 D^0 \rightarrow K^{-}\pi^+ C F$ decays in LHCb with $9/\text{fb}$)
- **Cons**: poor neutrals reconstruction
  Focus on hadronic and semileptonic decays
Charm Production at LHCb

Prompt (π-tagged)

Secondary (μ-tagged)
Recent CPV Measurements by LHCb
LHCb discovers matter-antimatter asymmetry in charm quarks

A new observation by the LHCb experiment finds that charm quarks behave differently than their antiparticle counterparts.

LHCb sees a new flavour of matter-antimatter asymmetry

The LHCb collaboration has observed a phenomenon known as CP violation in the decays of a particle known as a D0 meson for the first time

21 MARCH, 2019
Why $\Delta A_{CP}$ and How to Measure it

Correcting for Instrumental Asymmetries

$$A_{h^+h^-} = \frac{N(D^0 \to h^+h^-) - N(\bar{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\bar{D}^0 \to h^+h^-)}$$
Why $\Delta A_{CP}$ and How to Measure it

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$$A_{h^+h^-} = A_{CP}(h^+h^-) + A_D + A_P$$

The asymmetry we want to measure

Detection Asymmetry of tagging track ($\mu^\pm$ or $\pi^\pm$)

Production Asymmetry ($D^*$ or $B$)

(*) Valid only if $A_{hh}$ small
Why $\Delta A_{CP}$ and How to Measure it

Correcting for Instrumental Asymmetries

$$A_{h^+h^-} = \frac{N(D^0 \rightarrow h^+h^-) - N(\bar{D}^0 \rightarrow h^+h^-)}{N(D^0 \rightarrow h^+h^-) + N(\bar{D}^0 \rightarrow h^+h^-)}$$

$$A_{h^+h^-} = A_{CP}(h^+h^-) + A_D + A_P \quad (*)$$

The asymmetry we want to measure
Detection Asymmetry of tagging track ($\mu^\pm$ or $\pi^\pm$)
Production Asymmetry (D* or B)

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

(*) Valid only if $A_{hh}$ small
Why is $\Delta A_{\text{CP}} \neq 0$?

CPV Arising from Interference

- In this limit, $A_{\text{CP}}(K^+K^-)$ and $A_{\text{CP}}(\pi^+\pi^-)$ are equal and opposite in sign, resulting in $\Delta A_{\text{CP}} \sim 10^{-3}$

SU(3) Symmetry

- $\Delta A_{\text{CP}} \neq 0$

References:
- Phys. Rev. D75 (2007) 036008
Observation of CPV

A\_CP Dataset (π-tagged)

\[ m(D^0 \pi^+) \text{ [MeV/c}^2\text{]} \]

LHCb

\[ \times 10^3 \]

Candidates / (0.1 MeV/c^2)

Run2 (6/fb)

LHCb

\[ \times 10^3 \]

Candidates / (0.1 MeV/c^2)

Data

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

Comb. bkg.

\[ D^0 \to \pi^-\pi^+ \]

Comb. bkg.

44M

14M

\text{PRL122 (2019) 211803}
**∆A_{CP} Dataset (μ-tagged)**

![Graphs](image)

**LHCb**

- Data

- $D^{0} \rightarrow K^{-}K^{+}$
- $D^{0} \rightarrow K^{-}\pi^{+}$
- Comb. bkg.

**Candidates / (1 MeV/c^2)**

- 9M
- 3M

**Run2 (6/fb)**

- Data

- $D^{0} \rightarrow \pi^{-}\pi^{+}$
- $D^{0} \rightarrow K^{-}\pi^{+}$
- Comb. bkg.

**Candidates / (1 MeV/c^2)**

- 1800
- 1850
- 1900

**$m(D^{0})$ [MeV/c^2]**

**PRL122 (2019) 211803**
Tracking Asymmetries

Sources of Inefficiency

- **Material Interactions**
  15% nuclear interaction length before end of tracker
- **Geometry**
  Trajectories through dead-channels, beam-pipe or out of the detector
- **Tracking**
  High occupancy, low $p_T$

Uncertainty

- 10% on material budget, detector conditions over time, beam positions, detector simulation

Strategies

- **Avoidance**
  Use observables non-sensitive to detection asymmetries (e.g. $\Delta A_{CP}$)
- **Calibration**
  Measure and correct the asymmetries
- **Ignore it**
  When statistical uncertainty much larger than residual asymmetry after averaging the two polarities

Depend on charge (+kinematics, detector/machine conditions)

Observation of CPV
depend on charge (+kinematics, detector/machine conditions)

Courtesy of M. Vesterinen

Maurizio Martinelli - Recent Results in CPV in Charm at LHCb | 04.06.2019
Remove Areas with Large Asymmetry

- Regions in which only $D^*$ or $D^-$ are possible since low momentum pion escapes detection
- Break the assumption that $A_{hh}$ is small
Correcting Tracking Asymmetries

Reweight By Momenta Distributions

- Detection and production asymmetry dependent on the kinematics of the reconstructed particles
- Variables ($p$, $p_T$, $\phi$) for $D^{*+}$ and $D^0$

LHCb

$D^0 \to \pi^- \pi^+$

$D^0 \to K^- K^+$

Normalized candidates

$p(D^{*+})$ [GeV/c]

Normalized candidates

$p(D^{*+})$ [GeV/c]
Systematic Uncertainties

**π-tagged**

- **Fit Model**  
  Evaluated by fitting pseudo experiments with alternative models

- **Peaking Background:**  
  \( D^0 \rightarrow K^- \pi^+ \pi^0 \) and \( D^0 \rightarrow \pi^- \pi^+ \nu \) peak in the \( m(D^0\pi) \) signal region  
  Estimated by measuring the yields and asymmetries of backgrounds in the \( m(D^0\pi) \) distributions

**μ-tagged**

- **Mistag (wrong muon assignment)**  
  Estimated from a control sample of \( B \rightarrow D^0(\rightarrow K^- \pi^+)\mu X \)

<table>
<thead>
<tr>
<th>Source</th>
<th>( \pi )-tagged</th>
<th>( \mu )-tagged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit model</td>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>Mistag</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>Weighting</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Secondary decays</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>( B ) fractions</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>( B ) reco. efficiency</td>
<td>–</td>
<td>2</td>
</tr>
<tr>
<td>Peaking background</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>0.9</td>
<td>5</td>
</tr>
</tbody>
</table>
**ΔA_{CP} Results**

π-tagged (6/fb)

\[ \Delta A_{CP}^{π-tagged} = [-18.2 \pm 3.2\,\text{(stat.)} \pm 0.9\,\text{(syst.)}] \times 10^{-4} \]

μ-tagged (6/fb)

\[ \Delta A_{CP}^{μ-tagged} = [-9 \pm 8\,\text{(stat.)} \pm 5\,\text{(syst.)}] \times 10^{-4} \]

**Combination with Run1 data**

\[ \Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4} \]

5.3 std dev significance
CPV in Charm World Average

Observation of CPV

Maurizio Martinelli - Recent Results in CPV in Charm at LHCb | 04.06.2019
What Does It Tell Us?

Compatible with SM \( \text{arXiv:1812.07638} \)

- Predictions range between \(10^{-4}\) and \(10^{-2}\)
  Most of them in the \(10^{-3}\) ball park

Other Channels?

- Observation in other channels would provide a nice confirmation of the effect
  And help its interpretation

Indirect CPV

- Still missing
  Expected \(~10^{-5}\)
- Could still be sensitive to BSM effects
Where to look for Direct CPV?
**ACP in D⁰ → hh**

### Measurement of individual CPV

- With $\Delta A_{CP}$ we know that there is CPV up to a certain level
- But what is its exact value?
- Individual measurement is needed
- But adds layers of complication

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

#### Run1 Result  
**PLB 767 (2017) 177**

- $A_{CP}(KK) = (0.04\pm0.12\pm0.10)\%$
- $A_{CP}(\pi\pi\pi) = (0.07\pm0.14\pm0.11)\%$

#### Prospects

- Run2 analysis ongoing
- Main challenge is keeping the systematic uncertainties low
  Largest uncertainties due to weighting technique
**K⁰ Asymmetries**

### The Effect
- \( K^0 \) violate CP and interacting with the detector may show \( K^0_S \) from \( K^0_L \) regeneration
- Result is a detection asymmetry
  \[ A(K^0_S \text{ LL}) = (-0.73 \pm 0.05) \times 10^{-3} \]
  \[ A(K^0_S \text{ DD}) = (-6.2 \pm 0.3) \times 10^{-3} \]

### Uncertainty
- From knowledge of detector material
- Currently using only LL \( K^0_S \) for asymmetry measurements
  1/3 total \( K^0_S \) in LHCb detector
Quasi-Two-Body Decays - $D_{(s)}^+ \rightarrow K^0_S(\phi)h^+$

$D_{(s)}^+ \rightarrow K^0_S K(\pi)^+$ and $D^+ \rightarrow \phi \pi^+$

- The measured asymmetry can be factorised in the limit of small asymmetries
  \[
  A(D_{(s)}^+ \rightarrow f^+) \approx A_{CP}(D_{(s)}^+ \rightarrow f^+) + A_P(D_{(s)}^+) + A_D(f^+)
  \]

- Use control samples to correct for production and detection asymmetries
  \[
  A_{CP}(D_s^+ \rightarrow K_S^0 \pi^+) \approx A(D_s^+ \rightarrow K_S^0 \pi^+) - A(D_s^+ \rightarrow \phi \pi^+)
  \]
  \[
  A_{CP}(D^+ \rightarrow K_S^0 K^+) \approx A(D^+ \rightarrow K_S^0 K^+) - A(D^+ \rightarrow K_S^0 \pi^+) - A(D_s^+ \rightarrow K_S^0 K^+) + A(D_s^+ \rightarrow \phi \pi^+)
  \]
  \[
  A_{CP}(D^+ \rightarrow \phi \pi^+) \approx A(D^+ \rightarrow \phi \pi^+) - A(D^+ \rightarrow K_S^0 \pi^+)
  \]

- Crucial to measure very well $K^0_S$ and $K/\pi$ reconstruction asymmetries, and $D_{(s)}^+$ production asymmetries
Quasi-Two-Body Decays - $D_{[s]}^+ \rightarrow K^0_S(\phi)h^+$

Results

- High yields, sensitivity already lower than $10^{-3}$ for $D^+ \rightarrow K^0_S K^+$ and $D^+ \rightarrow \phi \pi^+$
  
  \[
  a_{CP}(D_s^+ \rightarrow K_S^0 \pi^+) = (1.6 \pm 1.7 \pm 0.5) \times 10^{-3}
  \]
  
  \[
  a_{CP}(D^+ \rightarrow K_S^0 K^+) = (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3}
  \]
  
  \[
  a_{CP}(D^+ \rightarrow \phi \pi^+) = (0.03 \pm 0.40 \pm 0.29) \times 10^{-3}
  \]

- Major systematics from fit model
Search for Indirect CPV
CPV in the $D^0 \rightarrow K\pi$ WS Mixing

Previous result (Run1+2015/6)

- Established technique with small systematic uncertainties based on control samples
- Technique originally developed to measure mixing, extended to extract CP asymmetry parameters
  By comparing the mixing parameters for $D^0$ and $\bar{D}^0$

Run1+Run2 Expectations

- Direct CPV will be probed up to 0.5% from ratio of WS/RS decays at $t=0$
- CPV in mixing from $x'$, $y' \rightarrow \sigma(|q/p|) \approx 0.1$, $\sigma(\phi) \approx 10^\circ$

$$R_{K\pi} \approx R_{K\pi} + \sqrt{R_{K\pi}} y'(\Gamma t) + \frac{x'^2 + y'^2}{4} (\Gamma t)^2$$

$$R_D = (3.454 \pm 0.031) \times 10^{-3}$$
$$x'^2 = (3.9 \pm 2.7) \times 10^{-5}$$
$$y' = (5.28 \pm 0.52) \times 10^{-3}$$

$$A_D = (-0.1 \pm 9.1) \times 10^{-3}$$
$$1.00 < |q/p| < 1.35 \text{ @68.3\% CL}$$

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### Indirect CPV Measurement

- \( A_\Gamma \sim -a^{\text{CP}}_{\text{ind}} \)

\[
A_\Gamma = \frac{\hat{\Gamma}(D^0 \to h^+h^-) - \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}{\hat{\Gamma}(D^0 \to h^+h^-) + \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}
\]

- Important input to the interpretation of \( \Delta A_{\text{CP}} \)

\[
\Delta A_{\text{CP}} \simeq \Delta A^{\text{dir}}_{\text{CP}} \left( 1 + \frac{\langle x \rangle}{\tau_{D^0}} y_{\text{CP}} \right) + \frac{\Delta \langle x \rangle}{\tau_{D^0}} a^{\text{ind}}_{\text{CP}}
\]

### Challenging Systematics

- Need to control any potential source of asymmetry in decay time
  Luckily CF \( D^0 \to K\pi^+ \) comes at help
- Secondary \( D^0 \) decays need precise estimate

### 2015-2016 result and Prospects

- \( A_\Gamma(KK) = (1.3\pm3.5\pm0.7) \times 10^{-4} \)
  \( A_\Gamma(\pi\pi) = (11.3\pm6.9\pm0.8) \times 10^{-4} \)
- Averaged and combined with Run1: \( A_\Gamma(KK+\pi\pi) = (0.9\pm2.1\pm0.7) \times 10^{-4} \)
- With full LHCb dataset (adding 4/fb) a precision of \( 1.6 \times 10^{-4} \) is achievable
The Golden Channel: $D^0 \rightarrow K^0_S\pi^+\pi^-$

Mixing and indirect CPV

- Allows to measure directly $x$
- Indirect CPV from measurement of $q/p$

Analysis Approaches

- Time-dependent amplitude analysis
- Bin-flip

Bin-flip  \hspace{1cm} PRD 99, 012007 (2019)

- An extension of the WS mixing measurement concept to multi body decays
  \[ R_b \approx r_b - \sqrt{r_b} \left[ (1 - r_b) c_b y - (1 + r_b) s_b x \right] \Gamma t \]

- Hadronic parameters constrained by external input
  From measurement of quantum-correlated $D^0-\bar{D}^0$ pairs (e.g. CLEO, BESIII)
- Slightly degraded precision with respect to amplitude analysis approach
  At the advantage of significantly simplified analysis
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    - At the advantage of significantly simplified analysis
Run 1 Data (3/fb)

- Two categories of $K^0_S$ candidates (LL and DD)

\[ D^+ \rightarrow D^0 (\rightarrow K^0_S \pi^+ \pi^-) \pi^+ \]

\[ B^+ \rightarrow D^0 (\rightarrow K^0_S \pi^+ \pi^-) \mu^- X \]

LHCb

\[ N_S = 1.3 \text{M} \]

\[ N_S = 1 \text{M} \]

Candidates per 0.1 MeV/c^2

Candidates per 1.5 MeV/c^2
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Mixing: $D^0 + \bar{D}^0$

CPV: $D^0 - \bar{D}^0$
Mixing: $D^0 + \bar{D}^0$

CPV: $D^0 - \bar{D}^0$

World’s most precise measurement of $x$, $|q/p|$, and $\phi$
Impact on World Average

HFLAV CHARM 2018

CPV allowed

HFLAV CHARM 2018

NO CPV

NO MIXING
Impact on World Average

\[ x = \left( 0.39^{+0.11}_{-0.12} \right) \% \]
\[ y = \left( 0.651^{+0.063}_{-0.069} \right) \% \]
\[ |q/p| = \left( 0.969^{+0.050}_{-0.045} \right) \]
\[ \phi = \left( -3.9^{+4.5}_{-4.6} \right)^\circ \]
Off the Beaten Path
Multibody Decays

Pro and Cons

- Rich resonant structure may favour interference giving rise to CPV effects
- Difficult to perform $\Delta A_{CP}$-like measurements

Techniques

- **Triple Products**  
  $\sigma_{CP^{Tod}}(D^0 \to K^+ K^- \pi^+ \pi^-) = 2.9 \times 10^{-3}$
  Analysis ongoing on Run2 LHCb dataset
  $\sigma(D^0 \to K^+ K^- \pi^+ \pi^-) \sim 5.4 \times 10^{-4}$
  $\sigma(D^0 \to \pi^+ \pi^- \pi^+ \pi^-) \sim 2.4 \times 10^{-4}$

- **Energy Test**  
  PLB 769 (2017) 345-356
  Compares distribution in the phase-space
  Discovery tool, does not identify source of CPV

\[
A_T = \frac{N(D^0, \Phi > 0) - N(D^0, \Phi < 0)}{N(D^0, \Phi > 0) - N(D^0, \Phi < 0)}
\]
\[
\overline{A}_T = \frac{N(\overline{D}^0, -\Phi > 0) - N(\overline{D}^0, -\Phi < 0)}{N(\overline{D}^0, -\Phi > 0) - N(\overline{D}^0, -\Phi < 0)}
\]
\[
a_{CP}^{T-\text{odd}} = \frac{1}{2} (A_T - \overline{A}_T)
\]

\[
\Phi = \Phi_{lmn} = P_l(\cos \theta_a) P_m(\cos \theta_b) \sin n\phi
\]

PRD 92, 076013 (2015)
Advantages

• Clear identification of responsible processes
• Possibility to probe regions of phase space with different strong phase difference

Challenges

• Model building complexity
• Model-dependent results

Results

• Most precise amplitude modelling of $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$
• Compatible with CP symmetry
  Sensitivity ranging from 1% ($\phi_\rho$, $K_1^+ K^-$) to 15%
### CPV Searches with Amplitude Analyses - $D^0 \rightarrow K^+K^-\pi^+\pi^-$

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>$A_{kL}$ [%]</th>
<th>$\Delta \arg(c_k)$ [%]</th>
<th>$A_{Fk}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow [\phi(1020)(\rho - \omega)^0]_{L=0}$</td>
<td>0 (fixed)</td>
<td>0 (fixed)</td>
<td>$-1.8 \pm 1.5 \pm 0.2$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_1(1400)^+K^-$</td>
<td>$-1.4 \pm 1.1 \pm 0.2$</td>
<td>$1.3 \pm 1.5 \pm 0.3$</td>
<td>$-4.5 \pm 2.1 \pm 0.3$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [K^-\pi^+]<em>{L=0}[K^+\pi^-]</em>{L=0}$</td>
<td>$1.9 \pm 1.1 \pm 0.3$</td>
<td>$-1.2 \pm 1.3 \pm 0.3$</td>
<td>$2.0 \pm 1.8 \pm 0.7$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_1(1270)^+K^-$</td>
<td>$-0.4 \pm 1.0 \pm 0.2$</td>
<td>$-1.1 \pm 1.4 \pm 0.2$</td>
<td>$-2.6 \pm 1.7 \pm 0.2$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [K^<em>(892)^0\bar{K}^</em>(892)^0]_{L=0}$</td>
<td>$-1.3 \pm 1.3 \pm 0.3$</td>
<td>$-1.7 \pm 1.5 \pm 0.2$</td>
<td>$-4.3 \pm 2.2 \pm 0.5$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^*(1680)^0K^-\pi^+_{L=0}$</td>
<td>$2.2 \pm 1.3 \pm 0.3$</td>
<td>$1.4 \pm 1.5 \pm 0.2$</td>
<td>$2.6 \pm 2.2 \pm 0.4$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^<em>(892)^0\bar{K}^</em>(892)^0_{L=1}$</td>
<td>$-0.4 \pm 1.7 \pm 0.2$</td>
<td>$3.7 \pm 2.0 \pm 0.2$</td>
<td>$-2.6 \pm 3.2 \pm 0.3$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_1(1270)^0K^+$</td>
<td>$2.6 \pm 1.7 \pm 0.4$</td>
<td>$-0.1 \pm 2.1 \pm 0.3$</td>
<td>$3.3 \pm 3.5 \pm 0.5$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [K^+K^-]<em>{L=0}[\pi^+\pi^-]</em>{L=0}$</td>
<td>$3.5 \pm 2.5 \pm 1.5$</td>
<td>$-5.5 \pm 2.6 \pm 1.6$</td>
<td>$5.1 \pm 5.1 \pm 3.1$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_1(1400)^-K^+$</td>
<td>$0.2 \pm 2.9 \pm 0.7$</td>
<td>$2.5 \pm 3.5 \pm 1.0$</td>
<td>$-1.3 \pm 6.0 \pm 1.0$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [K^<em>(1680)^0\bar{K}^</em>(892)^0]_{L=0}$</td>
<td>$4.0 \pm 2.7 \pm 0.8$</td>
<td>$-5.4 \pm 2.8 \pm 0.8$</td>
<td>$6.2 \pm 5.2 \pm 1.5$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [\bar{K}^<em>(1680)^0\bar{K}^</em>(892)^0]_{L=1}$</td>
<td>$-0.4 \pm 2.1 \pm 0.3$</td>
<td>$0.4 \pm 2.1 \pm 0.3$</td>
<td>$-2.5 \pm 3.9 \pm 0.4$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^*(1680)^0K^-\pi^-_{L=1}$</td>
<td>$2.1 \pm 2.0 \pm 0.6$</td>
<td>$-1.8 \pm 2.2 \pm 0.3$</td>
<td>$2.4 \pm 3.7 \pm 1.1$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [\phi(1020)(\rho - \omega)^0]_{L=2}$</td>
<td>$0.8 \pm 1.9 \pm 0.3$</td>
<td>$-1.2 \pm 2.0 \pm 0.5$</td>
<td>$-0.1 \pm 3.3 \pm 0.5$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [K^<em>(892)^0\bar{K}^</em>(892)^0]_{L=2}$</td>
<td>$-0.6 \pm 2.5 \pm 0.4$</td>
<td>$0.6 \pm 2.6 \pm 0.4$</td>
<td>$-3.0 \pm 5.0 \pm 0.7$</td>
</tr>
<tr>
<td>$D^0 \rightarrow \phi(1020)[\pi^+\pi^-]_{L=0}$</td>
<td>$3.8 \pm 3.1 \pm 0.7$</td>
<td>$-0.5 \pm 3.9 \pm 0.7$</td>
<td>$5.8 \pm 6.1 \pm 0.8$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^<em>(1680)^0\bar{K}^</em>(892)^0_{L=1}$</td>
<td>$1.6 \pm 2.8 \pm 0.5$</td>
<td>$0.7 \pm 3.0 \pm 0.4$</td>
<td>$1.3 \pm 5.3 \pm 0.6$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [\phi(1020)\rho(1450)^0]_{L=1}$</td>
<td>$4.6 \pm 4.1 \pm 0.6$</td>
<td>$9.3 \pm 3.3 \pm 0.6$</td>
<td>$7.5 \pm 8.5 \pm 1.1$</td>
</tr>
<tr>
<td>$D^0 \rightarrow a_0(980)^0f_2(1270)^0$</td>
<td>$1.6 \pm 3.6 \pm 0.7$</td>
<td>$-7.3 \pm 3.3 \pm 0.8$</td>
<td>$1.5 \pm 7.2 \pm 1.3$</td>
</tr>
<tr>
<td>$D^0 \rightarrow a_1(1260)^+\pi^-$</td>
<td>$-4.4 \pm 5.6 \pm 3.7$</td>
<td>$9.3 \pm 6.1 \pm 1.3$</td>
<td>$-10.6 \pm 11.7 \pm 7.0$</td>
</tr>
<tr>
<td>$D^0 \rightarrow a_1(1260)^-\pi^+$</td>
<td>$-3.4 \pm 7.0 \pm 1.9$</td>
<td>$-5.8 \pm 5.6 \pm 4.3$</td>
<td>$-8.7 \pm 13.7 \pm 2.9$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [\phi(1020)(\rho - \omega)^0]_{L=1}$</td>
<td>$2.1 \pm 5.2 \pm 0.8$</td>
<td>$-12.2 \pm 5.5 \pm 0.6$</td>
<td>$2.4 \pm 11.0 \pm 1.4$</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^<em>(1680)^0\bar{K}^</em>(892)^0_{L=2}$</td>
<td>$5.2 \pm 7.1 \pm 1.9$</td>
<td>$-5.6 \pm 8.1 \pm 1.3$</td>
<td>$8.5 \pm 14.3 \pm 3.5$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [K^+K^-]_{L=0}(\rho - \omega)^0$</td>
<td>$11.7 \pm 6.0 \pm 1.9$</td>
<td>$4.8 \pm 6.2 \pm 1.1$</td>
<td>$21.3 \pm 12.5 \pm 2.8$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [\phi(1020)f_2(1270)^0]_{L=1}$</td>
<td>$2.7 \pm 6.7 \pm 1.7$</td>
<td>$0.9 \pm 6.0 \pm 1.7$</td>
<td>$3.6 \pm 13.3 \pm 3.0$</td>
</tr>
<tr>
<td>$D^0 \rightarrow [K^<em>(892)^0\bar{K}^</em><em>2(1430)^0]</em>{L=1}$</td>
<td>$3.9 \pm 5.2 \pm 1.0$</td>
<td>$6.8 \pm 6.4 \pm 1.4$</td>
<td>$6.1 \pm 10.8 \pm 1.8$</td>
</tr>
</tbody>
</table>
CPV in Rare Decays

Rarest Charm Decay Observed So Far

- $\text{BF}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$
- $\text{BF}(D^0 \rightarrow K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$
- Studied triple product and Forward-Backward asymmetries
  Null with 4(11)% sensitivity for $D^0 \rightarrow \pi^+\pi^-(K^+K^-)\mu^+\mu^-$
- With full LHCb dataset expected factor 2 better sensitivity
- Further null tests of the SM are suggested
  An amplitude analysis may be needed to control hadronic uncertainties
- Suggested to test Lepton Universality with $D^0 \rightarrow h^+h^-e^+e^-$

![Graphs showing data and fit for different decay channels and sensitivity levels.](PRL 121, 091801 (2018))

![Graphs showing data and fit for different decay channels and sensitivity levels.](PRD 98, 035041 (2018))

Other Channels
(Long-Term) Future
Upcoming Competition - Belle II

25.03.2019
LHCb (Upgrade)  Belle II

HADRONIC CHANNELS

CHANNELS WITH $K^0_s$

CHANNELS WITH NEUTRALS

LHCb Upgrade II Physics Case

Belle II Physics Book
Towards Ultimate Precision

LHC

2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 ...
---
Run 3 LS3
---

HFLAV World Average 2017

contours hold 68%, 95% CL

LHCb Upgrade II Physics Case

HL-LHC

Upgrade Ia

Run 4 LS4 Run 5
---
LS3
---

LHCb

Upgrade Ib

Upgrade II
---

$L^\geq2\times10^{33}/(\text{cm}^2\text{s})$

$L\geq1.5\times10^{34}/(\text{cm}^2\text{s})$

$\phi$

0.2

0.1

0.0

-0.1

-0.2

0.85 0.9 0.95 1 1.05 1.1

$|q/p|$
Conclusions

CP Violation in Charm Finally Discovered

- Much effort is needed to fully understand the impact on our knowledge of the Standard Model
- Observing it in other decay channels will surely help and should be LHCb aim with its full dataset

Indirect CP Violation Still Escaping Detection

- We have many ways to find it and we can still explore them all with full LHCb dataset (9/fb)

Further Challenges Ahead

- The LHCb Upgrade will collect 50/fb by 2030
- Belle-II will join the competition in the same period
- LHCb Upgrade-II (300/fb) will provide the ultimate precision in flavour physics

Exciting Times Ahead!