Future prospects for charm physics at Belle II

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Belle II collaboration

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Topics

- $D^0 - \bar{D}^0$ mixing and t-dependent CPV
- t-integrated CPV ($A_{CP}$)
- Rare decays (FCNC, LFV, LV)
$D^0 - \overline{D}^0$ mixing

- Mass eigenstates differ from flavor eigenstates

\[ |D_{1,2}^0\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \]

- $D_{1,2}^0$ with masses $m_1, m_2$ and partial widths $\Gamma_1, \Gamma_2$
- CP violation if $q \neq p$

- Mixing parameters:

\[
x = \frac{\Delta m}{\Gamma} \quad \quad y = \frac{\Delta \Gamma}{2\Gamma}
\]

- Time dependent decay rates of $D^0 \rightarrow f$ (since mixing is small):

\[
\frac{dN_{D^0 \rightarrow f}}{dt} \propto e^{-\Gamma t}|\langle f|\mathcal{H}|D^0\rangle + \frac{q}{p}\left(\frac{y + ix}{2}\Gamma t\right)|\langle f|\mathcal{H}|\overline{D}^0\rangle|^2
\]
Measurement strategies

\[ \frac{dN_{D^0 \rightarrow f}}{dt} \propto e^{-\Gamma t} \left| \langle f|\mathcal{H}|D^0 \rangle + \frac{q}{p} (\frac{y+ix}{2\Gamma t}) \langle f|\mathcal{H}|\overline{D^0} \rangle \right|^2 \]

- Wrong-sign semileptonic decays \((D^0 \rightarrow K^+ \ell^- \nu)\)
  - WS only via mixing: \(\langle f|\mathcal{H}|D^0 \rangle = 0\)
  - measures time integrated mixing rate \(R_M = \frac{x^2+y^2}{2} = \frac{N_{WS}}{N_{RS}}\)

- Wrong-sign hadronic decays \((D^0 \rightarrow K^+ \pi^-)\)
  - WS via doubly Cabibbo suppressed (DCS) decays or mixing
  - interference between DCS and mixing (strong phase \(\delta\))
  - measures \(x' = x \cos \delta + y \sin \delta, \ y' = y \cos \delta - x \sin \delta\)

- Decays to CP eigenstates \((D^0 \rightarrow K^+ K^-, \pi^+ \pi^-)\)
  - if no direct CPV: \(\langle f|\mathcal{H}|\overline{D^0} \rangle = -\langle f|\mathcal{H}|D^0 \rangle\)
  - measures \(y\)

- Decays to self-conjugate states \((D^0 \rightarrow K_s^0 \pi^+ \pi^-)\)
  - time dependent Dalitz plot analysis
  - measures \(x\) and \(y\)
CP violation

\[ \frac{dN_{D^0 \to f}}{dt} \propto e^{-\Gamma t} \langle f | \mathcal{H} | D^0 \rangle + \frac{q}{p} \left( \frac{y+ix}{2} \Gamma t \right) \langle f | \mathcal{H} | \bar{D}^0 \rangle \]

Two kinds:
- \( q/p \neq 1 \) ⇒ indirect CP violation
- \( q/p = |q/p| \cdot e^{i\phi} \):
  - \( |q/p| \neq 1 \) ⇒ CP violation in mixing
  - \( \phi \neq 0(\pi) \) ⇒ CP violation in interference of decays w/ and w/o mixing
- \( |A(D^0 \to f)|^2 \neq |A(\bar{D}^0 \to \bar{f})|^2 \) ⇒ direct CP violation

Indirect CPV
- \( D^0 \) only, common to all decay modes

Direct CPV
- All three species \( (D^0, D^+, D_s^+) \), decay mode dependent
CP violation

Experimental techniques

- Time-dependent analysis:
  - difference in proper decay time distributions of $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow \bar{f}$
  - we measure indirect CPV

- Time-integrated analysis:
  - difference in time-integrated decay rates of $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow \bar{f}$
  - we measure direct+indirect CPV

Time-integrated analysis

- Asymmetry in time-integrated decay rates:
  \[ A_{CP}^f = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})} \]

- Charged D mesons: $A_{CP}^f = a_{dir}^f$

- Neutral D mesons: $A_{CP}^f = a_{dir}^f + a_{ind}^f$
  - indirect CPV is universal: $a_{ind}^f \equiv -A_{\Gamma}$ (neglecting terms with $y_{CP}$)
  - world average: $A_{\Gamma} = (-0.014 \pm 0.052)\%$ (HFAG, June-2014)
**D^0 flavor tag**

- Usually using \( D^{*+} \rightarrow D^0 \pi^+ \)
  - flavor tagging by \( \pi_{\text{slow}} \) charge
  - provides also considerable background suppression

**Observables:**
- \( D^0 \) invariant mass: \( M \equiv m(K\pi) \)
- \( D^{*+} \) mass difference: \( \Delta M \equiv m(K\pi\pi_{\text{slow}}) - m(K\pi) \) or \( Q \equiv \Delta M - m_\pi \)

**Measurements performed mainly at \( \Upsilon(4S) \)**
- \( D^{*+} \) from \( B \) decays can be completely rejected with
  
  \[ p^{CMS}_{D^{*+}} > 2.5 \text{ GeV}/c \]

- similar requirement used also when reconstructing charged \( D \) mesons

- IP constrained refit of \( \pi_{\text{slow}} \) to improve \( \Delta M \) resolution

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\[ t = \frac{l_{\text{dec}}}{c\beta\gamma}, \quad \beta\gamma = \frac{p_{D^0}}{M_{D^0}} \]
Time-integrated measurements ($A_{CP}$)

- Asymmetry in time-integrated decay rates of $D^0 \to f$ and $\bar{D}^0 \to \bar{f}$

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

- Raw asymmetry

\[
A_{raw} = \frac{N - \bar{N}}{N + \bar{N}} = A_{prod} + A_{\epsilon}^f + A_{CP}^f
\]

- $A_{prod}$ production asymmetry
- $A_{\epsilon}^f$ asymmetry in efficiency

- Production asymmetry at B-factory
  - odd function of CMS polar angle
  - $A_{prod} \equiv A_{FB}(\cos \theta^*)$
  - can easily be disentangled

\[
A_{CP} = \frac{A_{cor}^{\text{raw}}(\cos \theta^*) + A_{cor}^{\text{raw}}(-\cos \theta^*)}{2}
\]

\[
A_{FB} = \frac{A_{cor}^{\text{raw}}(\cos \theta^*) - A_{cor}^{\text{raw}}(-\cos \theta^*)}{2}
\]
Detection asymmetries $A^f_{\epsilon}$

- Asymmetries in detection efficiency can be measured with sufficient precision using CF decays (direct CPV is very unlikely)
  - must be performed in bins of relevant phase-spaces
  - requires production asymmetries to be known
  - at B-factory: $A_{\text{prod}} \equiv A_{FB}(\cos \theta^*)$

- Slow pions: from tagged and untagged $D^0 \rightarrow K^- \pi^+$ decays
- Kaons: from decays $D^0 \rightarrow K^- \pi^+$ and $D^+_s \rightarrow \phi \pi^+$
- Pions: from decays $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^0$
Belle II experiment

- Successor of Belle experiment (KEK, Tsukuba, Japan)

SuperKEKB accelerator
- upgraded KEKB
- luminosity $40 \times KEKB$ \((8 \times 10^{35}\text{ cm}^{-2}\text{s}^{-1})\)
- nano-beam optics

Belle II detector
- upgraded Belle detector
- majority of components replaced
Critical issues at $\mathcal{L} = 8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$

- Higher background ($\times 10 - 20$)
  - radiation damage and occupancy
  - fake hits and pile-up noise in EM calorimeter
- Higher event rate ($\times 40$)
  - affects trigger, DAQ and computing

Have to employ and develop new technologies to make such an apparatus work efficiently.
Belle II detector upgrade

- **Vertex detector**
  - 4-layer DSSD replaced with 2 DEPFET layers + 4 DSSD layers
  - smaller inner radius, larger outer radius
    → better vertex resolution
    → improved efficiency for slow pions and $K_S$

- **Central drift chamber**
  - smaller cells, larger outer radius
    → improved momentum resolution and dEdx

- **Hadron ID**
  - ACC + TOF replaced with TOP (barrel) and aerogel RICH (forward)
    → less material in front of calorimeter
    → improved hadron ID

- **Electromagnetic calorimeter**
  - waveform sampling technique to cope with increased background

- **K-long and muon detector**
  - RPC’s in endcaps and first two layers of barrel replaced with scintillator counters to cope with increased neutron background
Belle II schedule

- 2018: start to increase luminosity
- collect $\sim 10 \text{ ab}^{-1}$ by mid 2020
- collect 50 $\text{ ab}^{-1}$ by 2024
Belle measurements extrapolated to 50 ab$^{-1}$

Systematic uncertainties primarily scale with integrated luminosity, with two exceptions:

- $t$-dependent Dalitz: model related systematics (resonance parameters - masses, widths, form factors, angular dependence etc.)

- $A_{CP}$ of modes with $K_s^0$: asymmetry of $K^0/\bar{K}^0$ interactions in material (PRD 84, 111501 (2011)), $\sigma_{ired} \approx 0.02\%$

Extrapolation:

$$\sigma_{BelleII} = \sqrt{(\sigma^2_{stat} + \sigma^2_{sys}) \frac{L_{Belle}}{50 \text{ ab}^{-1}} + \sigma^2_{ired}}$$

Detector performance improvements are not included in the extrapolation (detailed MC studies are on the way)
Mixing and indirect CPV

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate, fb$^{-1}$</th>
<th>Branching, ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to K^{(*)-} \ell^+ \nu$</td>
<td>492</td>
<td>50</td>
</tr>
<tr>
<td>$R_M$</td>
<td>$(1.3 \pm 2.2 \pm 2.0) \times 10^{-4}$</td>
<td>$\pm 0.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$D^0 \to K^+ K^-, \pi^+ \pi^-$</td>
<td>976</td>
<td>50</td>
</tr>
<tr>
<td>$\gamma_{CP}$</td>
<td>$(1.11 \pm 0.22 \pm 0.11)$%</td>
<td>$\pm 0.04$%</td>
</tr>
<tr>
<td>$A_\Gamma$</td>
<td>$(-0.03 \pm 0.20 \pm 0.08)$%</td>
<td>$\pm 0.03$%</td>
</tr>
<tr>
<td>$D^0 \to K^+ \pi^-$</td>
<td>400</td>
<td>50</td>
</tr>
<tr>
<td>$x'^2$</td>
<td>$(1.8 \pm 2.2 \pm 1.1) \times 10^{-4}$</td>
<td>$\pm 0.22 \times 10^{-4}$</td>
</tr>
<tr>
<td>$y'$</td>
<td>$(0.06 \pm 0.40 \pm 0.20)$%</td>
<td>$\pm 0.04$%</td>
</tr>
<tr>
<td>$A_M$</td>
<td>$0.67 \pm 1.20$</td>
<td>$\pm 0.11$</td>
</tr>
<tr>
<td>$</td>
<td>\phi</td>
<td>$</td>
</tr>
<tr>
<td>$D^0 \to K^0_s \pi^+ \pi^-$</td>
<td>921</td>
<td>50</td>
</tr>
<tr>
<td>$x$</td>
<td>$(0.56 \pm 0.19 \pm 0.06 \pm 0.08)$%</td>
<td>$\pm 0.08$%</td>
</tr>
<tr>
<td>$y$</td>
<td>$(0.30 \pm 0.15 \pm 0.06 \pm 0.04)$%</td>
<td>$\pm 0.05$%</td>
</tr>
<tr>
<td>$</td>
<td>q/p</td>
<td>$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$-0.10 \pm 0.19 \pm 0.04 \pm 0.07$</td>
<td>$\pm 0.07$</td>
</tr>
</tbody>
</table>

\[ |q/p| = 1 + \frac{1}{2} A_M \Rightarrow \delta |q/p| = \frac{1}{2} \delta A_M \]
**Time-integrated measurements ($A_{CP}$)**

<table>
<thead>
<tr>
<th>mode</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>$A_{CP}$ (%)</th>
<th>Belle II at 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to K^+K^-$</td>
<td>976</td>
<td>$-0.32 \pm 0.21 \pm 0.09$</td>
<td>$\pm 0.03$</td>
</tr>
<tr>
<td>$D^0 \to \pi^+\pi^-$</td>
<td>976</td>
<td>$+0.55 \pm 0.36 \pm 0.09$</td>
<td>$\pm 0.05$</td>
</tr>
<tr>
<td>$D^0 \to \pi^0\pi^0$</td>
<td>966</td>
<td>$-0.03 \pm 0.64 \pm 0.10$</td>
<td>$\pm 0.09$</td>
</tr>
<tr>
<td>$D^0 \to K_s^0\pi^0$</td>
<td>966</td>
<td>$-0.21 \pm 0.16 \pm 0.07$</td>
<td>$\pm 0.03$</td>
</tr>
<tr>
<td>$D^0 \to K_s^0\eta$</td>
<td>791</td>
<td>$+0.54 \pm 0.51 \pm 0.16$</td>
<td>$\pm 0.07$</td>
</tr>
<tr>
<td>$D^0 \to K_s^0\eta'$</td>
<td>791</td>
<td>$+0.98 \pm 0.67 \pm 0.14$</td>
<td>$\pm 0.09$</td>
</tr>
<tr>
<td>$D^0 \to \pi^+\pi^-$</td>
<td>532</td>
<td>$+0.43 \pm 1.30$</td>
<td>$\pm 0.13$</td>
</tr>
<tr>
<td>$D^0 \to K^+\pi^-\pi^0$</td>
<td>281</td>
<td>$-0.60 \pm 5.30$</td>
<td>$\pm 0.40$</td>
</tr>
<tr>
<td>$D^0 \to K^+\pi^-\pi^-\pi^-$</td>
<td>281</td>
<td>$-1.80 \pm 4.40$</td>
<td>$\pm 0.33$</td>
</tr>
<tr>
<td>$D^+ \to \phi\pi^+$</td>
<td>955</td>
<td>$+0.51 \pm 0.28 \pm 0.05$</td>
<td>$\pm 0.04$</td>
</tr>
<tr>
<td>$D^+ \to \eta\pi^+$</td>
<td>791</td>
<td>$+1.74 \pm 1.13 \pm 0.19$</td>
<td>$\pm 0.14$</td>
</tr>
<tr>
<td>$D^+ \to \eta'\pi^+$</td>
<td>791</td>
<td>$-0.12 \pm 1.12 \pm 0.17$</td>
<td>$\pm 0.14$</td>
</tr>
<tr>
<td>$D^+ \to K_s^0\pi^+$</td>
<td>977</td>
<td>$-0.36 \pm 0.09 \pm 0.07$</td>
<td>$\pm 0.03$</td>
</tr>
<tr>
<td>$D^+ \to K_s^0K^+$</td>
<td>977</td>
<td>$-0.25 \pm 0.28 \pm 0.14$</td>
<td>$\pm 0.05$</td>
</tr>
<tr>
<td>$D_s^+ \to K_s^0\pi^+$</td>
<td>673</td>
<td>$+5.45 \pm 2.50 \pm 0.33$</td>
<td>$\pm 0.29$</td>
</tr>
<tr>
<td>$D_s^+ \to K_s^0K^+$</td>
<td>673</td>
<td>$+0.12 \pm 0.36 \pm 0.22$</td>
<td>$\pm 0.05$</td>
</tr>
</tbody>
</table>
Direct CPV in $D^0 \rightarrow \phi\gamma, \rho^0\gamma$

- Direct CPV in radiative decays can be enhanced to exceed 1% (G. Isidori and J. F. Kamenik, PRL 109, 171801 (2012))
  - $D^0 \rightarrow \phi\gamma$: $A_{CP}$ up to 2%
  - $D^0 \rightarrow \rho^0\gamma$: $A_{CP}$ up to 10%
- $D^0 \rightarrow \phi\gamma$: first observation by Belle with 78 fb$^{-1}$ (PRL 92, 101803 (2004))
  - measured yield: $27.6^{+7.4+0.5}_{-6.5-1.0}$
  - relative error on yield 25% (as would be the error on $A_{CP}$)
- $A_{CP}$ sensitivity at 50 ab$^{-1}$: $\approx 1\%$
Rare and forbidden decays

- Shaded regions indicate the decays with $\gamma$ or $\pi^0$
- Mostly done by CLEO
- Belle II can improve these UL by several orders of magnitude
$D^0 \rightarrow \gamma\gamma$

- SM predictions: long distance effects dominate
  $$Br \sim \text{few} \times 10^{-8}$$

- BaBar, 470 fb$^{-1}$
  $$Br < 2.2 \times 10^{-6} \text{ @ 90\% CL}$$

- Belle II at 50 fb$^{-1}$:
  $\rightarrow$ depends how background behaves
  - if UL would scale with $\mathcal{L}$:
    $$UL \sim 2 \times 10^{-8}$$
  - if UL would scale with $\sqrt{\mathcal{L}}$:
    $$UL \sim 2 \times 10^{-7}$$
Perspectives for charm measurements at Belle II have been discussed.

We focused on D-mixing and CPV.

Using Belle results and a rough extrapolation to 50 ab$^{-1}$ we found:

- Sensitivities of most measurements will still be statistically limited.
- In $t$-dependent Dalitz analysis of $D^0 \to K_s^0 \pi^+ \pi^-$ the model dependent systematics will probably dominate and saturate the sensitivity.
- Belle II is in favor (compared to LHCb) in $A_{CP}$ measurements because of equal $D$ and $\overline{D}$ production; the sensitivity would reach in some cases a 0.03% level.

Belle II can also be competitive in searches of rare and forbidden decays of D-mesons with $\gamma$ or $\pi^0$ in the final state.
Belle II detector in comparison to Belle

SVD: 4 DSSD lyr → 2 DEPFET lyr + 4 DSSD lyr
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyr)

In colour: new or upgraded components
Time-dependent measurements: $D^0 \rightarrow K^+ \pi^-$

- Wrong sign (WS) final state:
  via DCS decays or via mixing

- Proper decay time distribution

$$\frac{dN}{dt} \propto [R_D + y' \sqrt{R_D(\Gamma t)} + \frac{x'^2 + y'^2}{4} (\Gamma t)^2] e^{-\Gamma t}$$

- DCS
- interference
- mixing

$R_D$ ratio of DCS/CF decay rates

$x' = x \cos \delta + y \sin \delta$

$y' = y \cos \delta - x \sin \delta$

$\delta$ strong phase between DCS and CF

WS events ($400 \text{ fb}^{-1}$)

PRL 96, 151801 (2006)

WS/RS ratio ($976 \text{ fb}^{-1}$)

PRL 112, 111801 (2014)
Time-dependent measurements: $D^0 \rightarrow K^+\pi^-$

**CP violation**

- $D^0$ and $\bar{D}^0$ samples analyzed separately
  \[ \Rightarrow R_D^\pm, x'^\pm, y'^\pm \]
- direct CPV in DCS decays:
  \[ A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} \]

- CPV in mixing and interference $\rightarrow$ by solving 4 equations for 4 unknowns:
  \[ x'^\pm = (1 \pm 1/2 A_M) \cdot (x' \cos \phi \pm y' \sin \phi) \]
  \[ y'^\pm = (1 \pm 1/2 A_M) \cdot (y' \cos \phi \mp x' \sin \phi) \]

$\rightarrow x', y', \phi, |q/p| = 1 + 1/2 A_M$
Time-dependent measurements: \( D^0 \rightarrow K^+K^-, \pi^+\pi^- \)

- Measurement of lifetime difference between flavor specific and decays into \( CP \) final states
  - choice of flavor specific: kinematically similar \( D^0 \rightarrow K^-\pi^+ \)
- Timing distributions are exponential
  - mixing parameter: 
    \[
    y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1
    \]
  - \( y_{CP} = y \), if \( CP \) conserved

If \( CP \) violated \( \rightarrow \) difference in lifetimes of \( D^0/\overline{D^0} \rightarrow K^+K^-, \pi^+\pi^- \)

- asymmetry in lifetimes:
  \[
  A_\Gamma = \frac{\tau(D^0\rightarrow K^-K^+)-\tau(D^0\rightarrow K^+K^-)}{\tau(D^0\rightarrow K^-K^+)+\tau(D^0\rightarrow K^+K^-)}
  \]

If direct \( CPV \) negligible:
- \( y_{CP} = y \cos \phi - \frac{1}{2}A_M x \sin \phi \)
- \( A_\Gamma = \frac{1}{2}A_M y \cos \phi - x \sin \phi \)
Time-dependent measurements: \( D^0 \rightarrow K_s^0 \pi^+\pi^- \)

- This three body decay proceeds via many intermediate states, like
  - CF: \( D^0 \rightarrow K^{*-}\pi^+ \)
  - DCS: \( D^0 \rightarrow K^{*+}\pi^- \)
  - CP: \( D^0 \rightarrow \rho^0 K_s^0 \)

- Matrix element is Dalitz space dependent, so also time distribution is

\[
\frac{dN_{D^0\rightarrow f}}{dt} \propto e^{-\Gamma t} \left| A(m_-^2, m_+^2) + \frac{q}{p} \left( \frac{y + ix}{2} \Gamma t \right) \overline{A}(m_-^2, m_+^2) \right|^2
\]

- Total amplitude \( A \) parametrized as a sum of quasy-two-body amplitudes of resonances \( A_r \)

\[
A(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r} A_r(m_-^2, m_+^2)
\]

- Both mixing parameters, \( x \) and \( y \) as well as CPV parameters \( \phi \) and \( |q/p| \) can be measured

- 3D fit in \( (m_-^2, m_+^2, t) \); many free parameters