

Charm physics prospects at Belle II

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Belle II is a major upgrade of the Belle experiment and will operate at the B -factory SuperKEKB in Japan. Here we discuss the expected sensitivity of Belle II for $D^0 - \bar{D}^0$ mixing and CP violation measurements in the charm sector, which will benefit from a factor 50 increase in statistics and an improved vertex detection and particle identification. The impact on the determination of CKM parameters from the measurements of purely leptonic D mesons decays is discussed. Finally a novel method of flavour tagging to substantially increase the sample of D^0 and \bar{D}^0 is presented.

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1. The Belle II experiment

Belle II is a major upgrade of the Belle experiment [1] and will operate at the B -factory SuperKEKB, located at the KEK laboratory in Tsukuba, Japan. Although Belle II has been designed to perform precise measurements in the b -quark sector, it will also be an ideal laboratory to study the properties of the charm quark. The data taking will start in 2018 and Belle II is expected to collect within the next decade a data sample of more than $10^{10} c\bar{c}$ events with a total integrated luminosity of about 50 ab^{-1} .

Given the clean environment of the e^+e^- SuperKEKB collider and the hermiticity of the detector, Belle II is expected to have great performances in the reconstruction of final states with neutral particles (e.g. γ , π^0 , η) and missing energy (e.g. leptonic and semileptonic decays of D mesons).

Moreover, Belle II will have a six-layer silicon vertex detector (2 layers of DEPFET pixel detectors and 4 layers of double-sided silicon strip detectors) whose innermost layer will be 2 times closer to the interaction point with respect to Belle. From Monte Carlo (MC) simulations it has been shown that for the processes $D^0 \rightarrow h^- h^+$ (where $h = \pi, K$) Belle II will have a D^0 proper time resolution $\sigma_t = 0.14 \text{ ps}$ [2], which is about half with respect to BaBar (0.27 ps).

2. Impact on time-dependent $D^0 - \bar{D}^0$ mixing and CP violation measurements

One of the main goals of the Belle II charm physics program is to improve the current measurements of $D^0 - \bar{D}^0$ mixing and the search for the CP violation (CPV) in the charm sector.

The time-dependent analysis of the ratio R_{WS} of the so-called ‘‘wrong sign’’ (WS) decay $D^0 \rightarrow K^+ \pi^-$ to the ‘‘right sign’’ (RS) decay $D^0 \rightarrow K^- \pi^+$ is sensitive to both the mixing parameters ($x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}$, $y' = y \cos \delta_{K\pi} - x \sin \delta_{K\pi}$, where $x = \Delta m/\Gamma$, $y = \Delta\Gamma/2\Gamma$ and $\delta_{K\pi}$ is the strong phase) and the CP -violating parameters ($|q/p|$ and $\phi = \arg(q/p)$):

$$R_{WS} = R_D + \left| \frac{q}{p} \right| \sqrt{R_D} (y' \cos \phi - x' \sin \phi) (\Gamma t) + \left| \frac{q}{p} \right|^2 \frac{x'^2 + y'^2}{4} (\Gamma t)^2, \quad (2.1)$$

where $R_D = |\mathcal{A}(D^0 \rightarrow K^+ \pi^-) / \mathcal{A}(D^0 \rightarrow K^- \pi^+)|^2$.

An ensemble of 1000 toy MC experiments, including the smearing of the decay times by the 0.14 ps expected proper time resolution, was generated to test the sensitivity of Belle II with the full data set [2]. The preliminary estimates of the expected sensitivity with 50 ab^{-1} of data are: $\sigma_{x'} = 0.15\%$, $\sigma_{y'} = 0.10\%$, $\sigma_{|q/p|} = 0.05\%$ and $\sigma_\phi = 5.7^\circ$.

The time-dependent decay rate of the WS decay $D^0 \rightarrow K^+ \pi^- \pi^0$ has been also studied (in this phase of the study, possible CP violation and backgrounds have been neglected). The decay rate for the WS decays at a given point in the Dalitz plot $(s_{12}, s_{13}) = (m_{K^+\pi^-}^2, m_{K^+\pi^0}^2)$ may be written as:

$$\frac{d\Gamma(D^0 \rightarrow K^+ \pi^- \pi^0)}{dt ds_{12} ds_{13}} \propto r_0^2 \left| \mathcal{A}_{\bar{f}}^{\text{DCS}} \right|^2 + r_0 (Ay'' + Bx'') (\Gamma t) + \frac{(x''^2 + y''^2)}{4} \left| \mathcal{A}_{\bar{f}}^{\text{CF}} \right|^2 (\Gamma t)^2, \quad (2.2)$$

where x'' and y'' are the mixing parameters rotated by the strong phase $\delta_{K\pi\pi^0}$ and A , B and r_0 are terms depending only on the decay amplitudes (in Equation 2.2 $|q/p| = 1$ and $\phi = 0$ since CP violation has been neglected).

¹Throughout this proceeding, charge-conjugate modes are implicitly included.

An ensemble of 10 experiments, each consisting of $\sim 2.2 \cdot 10^5$ signal events corresponding to the full Belle II dataset (assuming similar efficiency to BaBar) [3], was generated for this study, taking into account the expected proper time resolution. The estimates of the expected sensitivity are: $\sigma_x = 0.049\%$ and $\sigma_y = 0.057\%$.

These results well represent a significant improvement with respect to the Belle and BaBar achievements [4].

3. Impact on time-integrated CP violation measurements

Belle II will have excellent efficiency for reconstructing multi-body final states with tiny and well-controlled detector-based asymmetries. Thus the experiment is ideal for searching for time-integrated CPV in many final states. The expected precision of Belle II for the measurement of a CP asymmetry $A_{CP} = [\Gamma(D \rightarrow X) - \Gamma(\bar{D} \rightarrow \bar{X})]/[\Gamma(D \rightarrow X) + \Gamma(\bar{D} \rightarrow \bar{X})]$ is obtained by properly scaling the Belle uncertainty by the integrated luminosity [2].

In particular, if σ_{stat} is the statistical error of the Belle measurements, σ_{syst} is the systematic error that scales with the luminosity (e.g. background shapes measured with control samples) and σ_{irred} is the systematic error that doesn't scale (e.g. vertexing and tracking resolution due to the detector misalignment), the expected uncertainty of Belle II $\sigma_{\text{Belle II}}$ with the full integrated luminosity is given by:

$$\sigma_{\text{Belle II}} = \sqrt{(\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2) \cdot (\mathcal{L}_{\text{Belle}}/50 \text{ ab}^{-1}) + \sigma_{\text{irred}}^2}. \quad (3.1)$$

A list of D^0 , D^+ and D_s^+ modes for which Belle has measured A_{CP} and the expected uncertainty of Belle II $\sigma_{\text{Belle II}}$ is given in Table 1.

Two processes are specially interesting for Belle II: $D^0 \rightarrow K_S^0 K_S^0$ (A_{CP} is enhanced up to 1% in Standard Model (SM) predictions [5]) where we expect $\sigma_{\text{Belle II}} = 0.21\%$, and $D^+ \rightarrow \pi^+ \pi^0$ (the SM predicts $A_{CP} = 0$ [6], so CPV could be enhanced by New Physics contributions) where we expect $\sigma_{\text{Belle II}} = 0.40\%$.

4. Impact on purely leptonic decays

The clean environment of a B -factory and the knowledge of the center-of-mass energy will allow Belle II to measure precisely the branching fractions of the leptonic decays $D_q^- \rightarrow l^- \bar{\nu}_l$ (with $q = d, s$) and to extract the quantities $f_{D_q} |V_{cq}|$ (where f_{D_q} are the decay constants and V_{cq} are the CKM matrix elements). By using the f_{D_q} values computed with lattice QCD techniques, Belle II will significantly improve the Belle measurement of $|V_{cs}|$ (that is the world's most precise determination so far) and will measure $|V_{cd}|$ with less than 2% uncertainty [2].

The so-called ‘‘charm tagger’’ method was used in Belle to measure the charmed leptonic decays [7] and it is foreseen to be used also in Belle II. It consists in the reconstruction of a ‘‘tag side’’ D_{tag} (hadronic decays of D^0 , D^+ or Λ_c^+) recoiling against the signal $D_q^- \rightarrow l^- \bar{\nu}_l$. The remaining pions, kaons and protons are grouped together into the so-called ‘‘fragmentation side’’ X_{frag} (the fragmentation side is constructed imposing the conservation of the strangeness and baryonic numbers of the entire process). The missing momentum $P_{\text{miss}} = P_{CM} - P_{\text{tag}} - P_{\text{frag}} - P_{l^-}$ is then constructed, and for the signal processes $D_q^- \rightarrow l^- \bar{\nu}_l$ the quantity $P_{\text{miss}}^2 \equiv m_{\nu}^2$ peaks at $0 \text{ GeV}/c^2$.

Channel	Belle measurement		$\sigma_{\text{Belle II}}$ 50 ab ⁻¹
	\mathcal{L} (fb ⁻¹)	A_{CP} (%)	
$D^0 \rightarrow K^+ K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.06
$D^0 \rightarrow \pi^+ \pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.06
$D^0 \rightarrow \pi^0 \pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \rightarrow K_S^0 \pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.03
$D^0 \rightarrow K_S^0 \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \rightarrow K_S^0 \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \rightarrow K_S^0 K_S^0$	921	$-0.02 \pm 1.53 \pm 0.17$	± 0.21
$D^0 \rightarrow K^+ \pi^- \pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$	281	-1.80 ± 4.40	± 0.33
$D^0 \rightarrow \pi^+ \pi^- \pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \rightarrow \rho^0 \gamma$	976	$+0.056 \pm 0.152 \pm 0.006$	± 0.02
$D^0 \rightarrow \phi \gamma$	976	$-0.094 \pm 0.066 \pm 0.001$	± 0.01
$D^0 \rightarrow \bar{K}^{*0} \gamma$	976	$-0.003 \pm 0.020 \pm 0.000$	± 0.003
$D^+ \rightarrow \pi^0 \pi^+$		to be published	± 0.40
$D^+ \rightarrow \phi \pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \rightarrow \eta \pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \rightarrow \eta' \pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \rightarrow K_S^0 \pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03
$D^+ \rightarrow K_S^0 K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D_s^+ \rightarrow K_S^0 \pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \rightarrow K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

Table 1: A list of A_{CP} measurement performed by Belle with the expected uncertainty for Belle II (as defined in Equation 3.1). For most of the decay modes considered the scaled uncertainty on A_{CP} is less than 0.1%.

This methods will allow Belle II also to improve the search for the invisibles decays of D^0 mesons (e.g. $D^0 \rightarrow \nu \bar{\nu}$).

5. The ROE method for the flavour tagging of D^0 and \bar{D}^0

A new flavour tagging method, called ‘‘ROE method’’, has been developed in order to determine the flavour of D^0 and \bar{D}^0 at the production time in a $c\bar{c}$ event [2]. This method, which is complementary to the one using the pion charge in the strong decay $D^{*+} \rightarrow D^0 \pi^+$ decay, is sketched in Figure 1 and exploits events where a signal D^0 is reconstructed and only one K^\pm is identified in the rest of the event (ROE). In such case the charge of the kaon tags the flavour of the neutral D meson (a K^+ in the ROE tags a D^0 , instead a K^- tags a \bar{D}^0).

A full simulation was performed using the MC data in order to study and evaluate the performances of this new flavour tagging technique. The expected performances are the following: tagging efficiency $\varepsilon \sim 27\%$, mistagging fraction $\omega \sim 13\%$ and effective tagging efficiency $Q = \varepsilon(1 - 2\omega) \sim 20\%$. When comparing such performance with the D^{*+} tagging method, which

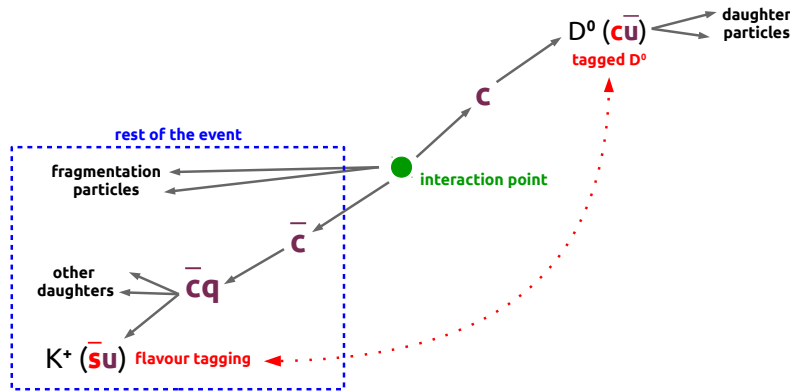


Figure 1: The ROE method for the flavour tagging: only the events with a single K^\pm candidate in the ROE are selected to tag the flavour of the neutral D meson in a $c\bar{c}$ event.

yields $Q \sim 80\%$, it should be taken into account that only 25% of the D^0 mesons comes from a D^{*+} decay in a $c\bar{c}$ event at the B -factories.

Since a fraction of D^0 can be doubly tagged using both methods, it will be possible to measure ε and ω for the ROE method on the Belle II data, using the D^{*+} method as reference. An integrated luminosity of $\sim 13 \text{ fb}^{-1}$ will be enough to measure the mistagging of the ROE method with an uncertainty $\sigma_\omega \lesssim 1\%$.

It has been estimated that, by combining the results obtained using the D^{*+} tag and the ROE method, a 15% reduction of the statistical uncertainty on $A_{CP}(D^0 \rightarrow K^- \pi^+)$ can be achieved. We can interpret this reduction of the statistical uncertainty as having an “effective” luminosity higher by 35% than the nominal one of SuperKEKB.

6. Conclusions

The Belle II experiment will start to collect data in 2018 and its charm physics program will cover a large number of topics. Thanks to the large dataset (50 ab^{-1}) and the introduction of new experimental techniques it is expected to improve the $D^0 - \bar{D}^0$ mixing and CP violation measurements performed at the B -factories, reaching the precision of the SM predictions for many final states. Also the measurement of the charmed leptonic decays will benefit the large amount of data that Belle II will collect, improving the existing determination of the CKM matrix element V_{cs} and V_{cd} .

To sum up, it is foreseen that Belle II will be, in the next years, one of the top players in the charm sector measurements.

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