Charm mixing study at Belle and prospects at Belle II

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Abstract We report D^0-mixing precision at Belle using a full data sample of 772×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy e^+e^- collider and the expected precision at Belle II, with a total integrated luminosity of 50 ab^{-1} and using the golden modes: $D^0 \to K^+\pi^-, K_S\pi^+\pi^-, K^+K^-, \pi^+\pi^-, K^-\pi^+\pi^0$.

1 SuperKEKB and Belle II

SuperKEKB, the high luminosity frontier machine is the major upgrade of KEKB factory using the so-called Nano-Beam Scheme by reducing the vertical spot size to nearly 50 *nm*. It is designed to improve the beta function and beam current by a factor of twenty and two respectively, in order to achieve a peak luminosity of $\mathscr{L} = 8.0 \times\ 10^{35} cm^{-2} s^{-1}$, a factor of forty than KEKB.

Belle II is a major upgrade of Belle experiment [1] located at the collision point of SuperKEKB machine. It will start collecting data from early 2019, and will accumulate data of integrated luminosity of 50 ab^{-1} by 2025.

Given the clean environment of SuperKEKB collider and the hermiticity of the detector, Belle II is expected to have low background, high trigger efficiency, and excellent performances in the reconstruction of the neutral particles (e.g. γ, π^0, η). Belle II has successfully finished taking its first data in July 2018 without the vertex detector, and is ready for physics data taking with full detector in early 2019. By 2025, Belle II will collect 60 times higher charm sample than Belle which will allow for rich charm physics program.

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2 D^0 decay time resolution

The Belle II vertex detector consists of four outer layers of double-sided silicon strip detector and two inner layers of pixel detectors. The inner most layer will sit close to the interaction point at a radius of 1.4 cm, and the outer most layer of the silicon detector will have a larger outer radius than that of Belle [1], and will cover the full Belle II angular acceptance. The vertex detector will contribute to better reconstruction efficiency with a large improvement of D^0 decay vertex and the interaction point resolutions compared with Belle and BaBar. This will precisely determine the D^0 decay time, which is essential in time-dependent measurements. According to Monte Carlo (MC) simulation for the processes $D^0 \to h^- h^+$ (where h = π, K), Belle II will have D^0 decay time resolution of 140 fs [2], which is a factor of two improvement over Belle and BaBar (270 fs).

3 Time dependent $D^0 - \bar{D}^0$ mixing studies

The D^0 meson final state can be accessed either through D^0 via Doubly Cabibbo Suppressed (DCS) decay or $D^0 - \bar{D}^0$ mix and then $\bar{D}^0$ decays to the final state via Cabibbo Favored (CF) decay. By measuring the D^0 decay rate as a function of D^0 proper time, one can extract the sensitivity to mixing. With multibody final state, the Dalitz analysis allows to access to more than one channel at the same time. The sensitivity estimation at Belle II is extracted by scaling the Belle results. In detail, if σ_{stat} is the statistical error of the Belle measurements, σ_{syst} is the systematic error that scales with the luminosity and σ_{irred} is the systematic error that does not scale with luminosity (e.g. vertex resolution due to the detector misalignment), the expected uncertainty of Belle II with the full integrated luminosity is given by:

$$\sigma_{BelleII} = \sqrt{(\sigma_{stat}^2 + \sigma_{syst}^2).\frac{\mathscr{L}_{Belle}}{50\ ab^{-1}} + \sigma_{irred}^2}, \tag{1}$$

4 D^0 mixing precision at Belle and estimated precision at Belle II

4.1 $D^0 \to K^+\pi^-$ decay

To study the sensitivity of Belle II for the mixing parameters x, y, and CP violating parameters $\left|\frac{q}{p}\right|$, ϕ in $D^0 \to K^+\pi^-$ decays, we perform a toy MC study by generating separate samples of $D^{*+} \to D^0\pi_{\mathrm{slow}}$, $D^0 \to K^+\pi^-$ and its charge conjugate decays corresponding to 5 ab^{-1}, 20 ab^{-1}, and 50 ab^{-1} of data. The probability density functions (PDFs) used to generate such decays are contributed by two processes: a DCS process and a CF process following mixing. The PDFs are given by

$$\frac{dN(D^0 \to f)}{dt} = e^{-\overline{\Gamma}t} \left\{ R_D + \left|\frac{q}{p}\right| \sqrt{R_D}(y'\cos\phi - x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{q}{p}\right|^2 \frac{(x'^2+y'^2)}{4}(\overline{\Gamma}t)^2 \right\} \tag{2}$$

$$\frac{dN(\overline{D}^0 \to \bar{f})}{dt} = e^{-\overline{\Gamma}t} \left\{ \overline{R}_D + \left|\frac{p}{q}\right| \sqrt{\overline{R}_D}(y'\cos\phi + x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{p}{q}\right|^2 \frac{(x'^2+y'^2)}{4}(\overline{\Gamma}t)^2 \right\} \tag{3}$$

where $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$, and δ is the strong phase difference between $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^-\pi^+$ amplitudes. The decay times are smeared by the expected decay time resolution of Belle II, and the resulting decays times are fitted with mixing parameters x, y in the case of no CP violation, or together with $\left|\frac{q}{p}\right|$, ϕ allowing CP violation. The fit results are then compared with the generated values. The RMS of the residual distributions are taken as the precision Belle II should achieve for these parameters. The sensitivity estimation from the toy study along with the previous Belle measurements [3] are listed in Table 1.

Table 1 The sensitivity of the mixing parameters x', y' and CP violating parameters $|q/p|$, ϕ for $\overline{D}^0 \to K^-\pi^+$ decays at Belle II, under the condition of no CP Violation (CPV) and with CPV.

Condition	Parameter	Belle measurement	Belle II estimation		
		976 fb^{-1}	5 ab^{-1}	20 ab^{-1}	50 ab^{-1}
No	$\sigma x'^2$ (10^{-5})	22	7.5	3.7	2.3
CPV	$\sigma y'$ (%)	0.34	0.11	0.056	0.035
	$\sigma x'$ (%)		0.37	0.23	0.15
CPV	$\sigma y'$ (%)		0.26	0.17	0.10
allowed	$\sigma\lvert q/p\rvert$		0.20	0.09	0.05
	$\sigma\phi$ (^{o})		16	9.2	5.7

4.2 $D^0 \to K^-\pi^+\pi^0$ decay

The wrong-sign (WS) decay $D^0 \to K^-\pi^+\pi^0$ proceeds directly via a DCS decay, and indirectly via mixing followed by a CF decay, where the later amplitude provides sensitivity to mixing. Assuming Belle II has similar efficiency as BaBar, the sensitivity estimation of the mixing parameters is performed with Toy MC study by generating an ensemble of 10 experiments, with each experiment consisting of 225000 $D^0 \to K^+\pi^-\pi^0$ decays corresponding to 50 ab^{-1} of Belle II data. The generated decay times are smeared by the expected Belle II resolution of 140 fs, and then fitted using a time-dependent fit to the $(m^2_{K^-\pi^+}, m^2_{K^-\pi^0})$ Dalitz plot as done in BaBar

[4] to measure the effective mixing parameters $x'' = x.\cos\delta_{K\pi\pi^0} + y.\sin\delta_{K\pi\pi^0}$ and $y'' = y.\cos\delta_{K\pi\pi^0} - x.\sin\delta_{K\pi\pi^0}$. Here $\delta_{K\pi\pi^0}$ is the strong phase difference between the amplitudes for $D^0 \to K^+\rho^-$ and $\overline{D}^0 \to K^+\rho^-$. From the fit of ten experiments, the mixing sensitivity are obtained as $\sigma x = 0.057\%$ and $\sigma y = 0.049\%$ [5], which are almost an order of magnitude improvement than BaBar if the effect of background is not included. A typical time-dependent Dalitz plot fit is illustrated in Fig. 1.

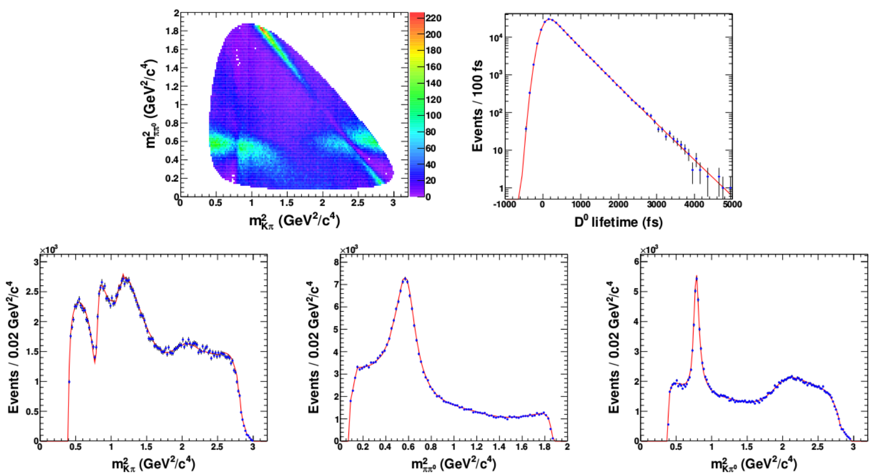

Fig. 1 The top row shows the time-dependent Dalitz plot fit and the decay time fit to the lifetime-smeared sample of wrong-sign $D^0 \to K^-\pi^+\pi^0$ decays. The bottom row shows projections of the fitted Dalitz variables.

4.3 $D^0 \to K_S\pi^+\pi^-$ *decay*

Mixing parameters for $D^0 \to K_S\pi^+\pi^-$ decay is obtained by fitting the time-dependent Dalitz plot. Here by calculating the observables $m_+ = (P_{K_S^0} + P_{\pi^+})^2$ and $m_- = (P_{K_S^0} + P_{\pi^-})^2$ and by performing an unbinned maximum likelihood fit to m_+, m_- and the decay time t, one can extract the information of mixing parameters x and y. Belle II sensitivity to the above parameters for the above decay is estimated by scaling from the Belle measurement [6] are listed in Table 2.

4.4 $D^0 \to K^+K^-, \pi^+\pi^-$ *decay*

Mixing in $D^0 \to CP$ eigenstates like $K^+K^-, \pi^+\pi^-$ gives an effective lifetime which differs from that decays in to flavor eigenstates such as $D^0 \to K^-\pi^+$. Hence the

Table 2 Precision obtained for x, y from Belle analysis of $D^0 \to K_S\pi^+\pi^-$ decays, and the expected precision for Belle II as obtained by scaling the Belle errors.

Data	stat.	systematic red.	systematic irred.	Total	stat.	systematic red.	systematic irred.	Total
		$\sigma_x(\%)$				$\sigma_y(\%)$		
976 fb^{-1}	0.19	0.06	0.11	0.20	0.15	0.06	0.04	0.16
5 ab^{-1}	0.08	0.03	0.11	0.14	0.06	0.03	0.04	0.08
50 ab^{-1}	0.03	0.01	0.11	0.11	0.02	0.01	0.04	0.05

observable which represents the relative lifetime difference between decays to CP and flavor specific final state is obtained as:

$$y_{cp} = \eta_{CP}\left(\frac{\Gamma_{cp}-\Gamma_{K^\pm\pi^\mp}}{\Gamma_{K^\pm\pi^\mp}}\right) = \eta_{CP}\left(\frac{\tau(D\to K^\pm\pi^\mp)}{\tau(D\to CP)}-1\right), \tag{4}$$

where η_{CP} = +1 for CP-even final state. y_{cp} is related to mixing parameter x and y as

$$y_{cp} = \frac{1}{2}\left(\left|\frac{q}{p}\right|+\left|\frac{p}{q}\right|\right)y\cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right|-\left|\frac{p}{q}\right|\right)x\sin\phi \tag{5}$$

where $\phi = arg(q/p)$. In the limit of CP conservation, $y_{cp} = y$. If CP is violated y_{CP} gets contribution from x. Belle with its full data sample has measured the $y_{cp} = (1.11\pm0.22\pm0.09)\%$ [7], and BaBar measurement of $y_{cp} = (0.72\pm0.18\pm0.12)\%$ [8]. Expected Belle II sensitivity by scaling Belle measurement has been summarized in Table 3.

Table 3 The Expected Belle II sensitivity to the D mixing parameter, y_{cp} for $\overline{D}^0 \to K^+K^-, \pi^+\pi^-$ decays.

Observable	Statistical	Systematic red.	Systematic irred.	Total
$y_{CP}(\%)$				
976 fb^{-1}	0.22	0.07	0.07	0.24
5 ab^{-1}	0.10	0.03-0.04	0.07-0.04	0.11-0.12
50 ab^{-1}	0.03	0.01	0.07-0.04	0.05-0.08

5 Expected Belle II precision vs. Current World Average

The experimental data consistently indicate that the D^0 and $\overline{D}^0$ do mix and current measurement provides constraints on many new physics models like fourth generation, extra gauge bosons, left right symmetric models [9]. Current world average value of $x = (0.32 \pm 0.14)\%$, and $y = (0.69^{+0.06}_{-0.07})\%$. The expected Belle II precision at 50 ab^{-1} is extrapolated to be $x = (0.8 \pm 0.09)\%$, and $y = (0.7 \pm 0.04)\%$ as shown in Fig. 2.

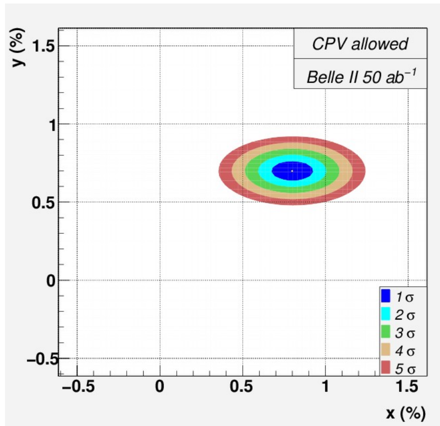

Fig. 2 Expected Belle II precision at 50 ab^{-1} data.

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