EARLY CHARM RESULTS AT BELLE II*

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Time-dependent analyses of D mesons provide access to the fundamental Standard Model parameters and probe natural non-SM scales at 10–100 TeV energies. Outstanding vertexing performances are the key enablers of this program. We prove the capabilities of the Belle II detector by measuring the lifetimes of the D^0 and D^+ mesons. The results are the most precise to date, owing to a vertexing resolution 2 times better than that of Belle and BaBar. First results obtained on relevant channels with early data sets are discussed.

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1. Introduction

Charm physics encompasses the study of composite particles containing the charm quark. Such particles provide unique avenues to probe physics within the Standard Model (SM) and beyond. The charm quark is the only up type quark that exhibits mixing (although it is heavily suppressed). The weak decay of an up type quark in a bound state can be studied only in open charm particles. After the observation of D^0–$\bar{D}^0$ mixing by Belle [1] and BaBar [2] in 2007 and the observation of Charge Parity Violation (CPV) in charm in 2019 by LHCb [3], the interest in the charm sector has increased manifold.

The experimental facility at The High Energy Accelerator Research Organization (KEK) at Tsukuba in Japan provides for a rich laboratory to study the charm physics. This facility is comprised of the particle accelerator SuperKEKB and the Belle II detector. The design instantaneous luminosity of SuperKEKB is 6.5×10^{35} cm^{-2}s^{-1}, which is more than 30 times that of its predecessor. Belle II is a hermetic detector and is expected

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to have much better performances in the reconstruction of final states with neutral particles (*e.g.* γ, π^0, η) and missing energy. The effects of the improved VerteX Detector (VXD) at Belle II can already be seen in the world's most precise measurement of $D^{0,+}$ lifetime [4]. Belle II aims to collect a data set of 50 ab^{-1}, which is 50 times that of Belle. The complete data set corresponds to almost 10^{11} D meson decays which will be extensively studied with the aim to unearth new physics.

2. SuperKEKB and the Belle II detector

The SuperKEKB [5] is an asymmetric e^+e^- super B-factory. The e^- (7 GeV) and e^+ (4 GeV) beams collide at the center-of-mass energy equivalent to the mass of $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV). Such collisions produce an abundant sample of b, c, and τ part events. The design luminosity of SuperKEKB is 6.5×10^{35} cm^{-2}s^{-1} and it has achieved a world record of instantaneous luminosity of 3.81×10^{34} cm^{-2}s^{-1}. Achieving such a high luminosity has been possible due to the nano-beam scheme [6] realized with the help of super-conducting final-focus quadrupole magnets. Such a setup provides an effective constraint on the D meson production vertex. The beam pipe at the interaction point is of 10 mm radius.

The Belle II detector [7] is located around the interaction point. As shown in figure 1, the innermost detector is the VerteX Detector (VXD), which is comprised of the PiXel Detector (PXD) and the Silicon Vertex Detector (SVD). The PXD is made of two layers of DEpleted p-channel Field Effect Transistors (DEPFETs). The first layer of the PXD is at 1.4 cm from the interaction point. It is followed by four layers of the SVD. The first layer of the SVD is at a distance of 3.9 cm from the interaction point, while the fourth layer is situated at 13.5 cm. Each layer of the SVD is made of Double-Sided Silicon Strip Detectors (DSSDs). The VXD is surrounded by the Central Drift Chamber (CDC). It is a large volume drift chamber containing a gaseous mixture of 50% He–50% C_2H_6. It reconstructs particle trajectories of low momentum particles, precisely measures their momenta, and provides Particle IDentification (PID) using dE/dx in its volume. The CDC is enclosed by the Time-of-Propagation (TOP) counter, which is a Cherenkov detector and is used for PID in the barrel region. In the forward endcap region, Aerogel Ring Imaging Cherenkov (ARICH) is used for PID. Further, we have an electromagnetic calorimeter (ECL), which is made of thallium-doped cesium iodide CsI(Tl) crystals. It is used to detect photons and to separate electrons from hadrons (in particular pions). The K_{L} and muon detector (KLM) is the outermost sub detector. It is made of an alternating sandwich of iron plates and active detector material.

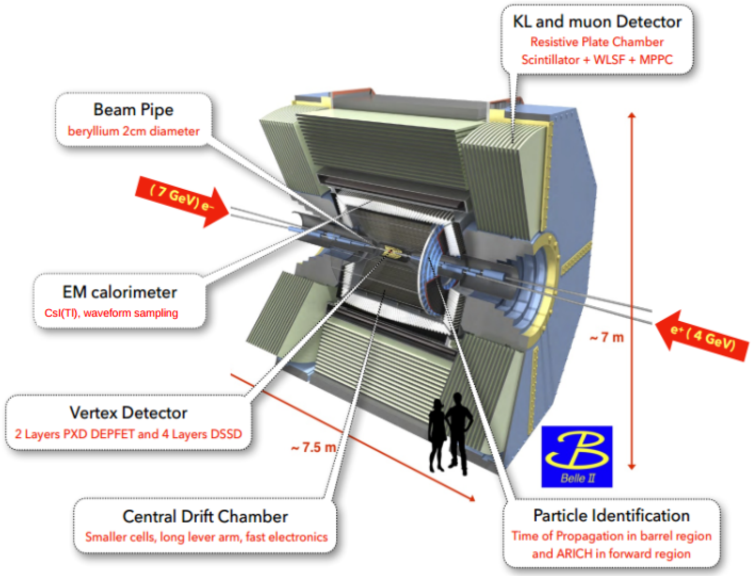

Fig. 1. A schematic diagram of the Belle II detector [7].

3. Charm measurements at Belle II

The charm physics program at Belle II aims for precision measurements of time integrated CPV, mixing as well as mixing induced CPV. The new and improved VXD provides two times better impact parameter resolution than Belle and BaBar [8]. Due to this, the decay time resolution of D^0 mesons is twice better than Belle and BaBar. This improvement will facilitate better measurements in time-dependent analysis and indirect CPV. All other upgrades (*e.g.* the VXD) are expected to improve the overall performance with improved track reconstruction efficiency, better PID and better K^0_S reconstruction even with increased beam background. To date, Belle II has collected over 350 fb^{-1} of data. In the following sub-sections, important results on the measurement of $D^{0,+}$ lifetime and first reconstructions of D meson decays, charmed baryon decays, *etc.* at Belle II are highlighted.

3.1. Measurement of $D^{0,+}$ lifetime

Belle II has reported the most precise measurements of D^0 and D^+ lifetime measurements to date with 72 fb^{-1} of data [4]. For this analysis, D^* tagged $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ are used. D^0 candidates are reconstructed using pairs of oppositely charged tracks. These tracks are required to have at least one hit in the PXD and SVD, and at least 20 hits in the CDC. The D^0 mesons thus reconstructed are combined with low-momentum pions to reconstruct D^* meson. Similarly, the $D^+ \to K^-\pi^+\pi^+$

candidates are also reconstructed. A global decay chain vertex fit [9] is performed for both channels with an additional π^0 mass constraint applied for the D^+ channel. The D mesons from B decays are removed using the criteria of the center-of-mass momentum of the D^* to be greater than 2.5 (2.6) GeV/c^2 for $D^0(D^+)$ channels. The remaining background comes mainly from a random combination of particles. The signal region for the D^0 channel is taken to be [1.851, 1.878] GeV/c^2, which contains 171×10^3 candidates with a purity of 99.8%, while the signal window for D^+ channel is taken to be [1.855, 1.883] GeV/c^2 and it contains 59×10^3 signal candidates and purity of 90%, as shown in figure 2. A binned least squares fit is performed in both cases and it is found that the background in the signal region is only about 0.2 (9)% for the $D^0(D^+)$ channels.

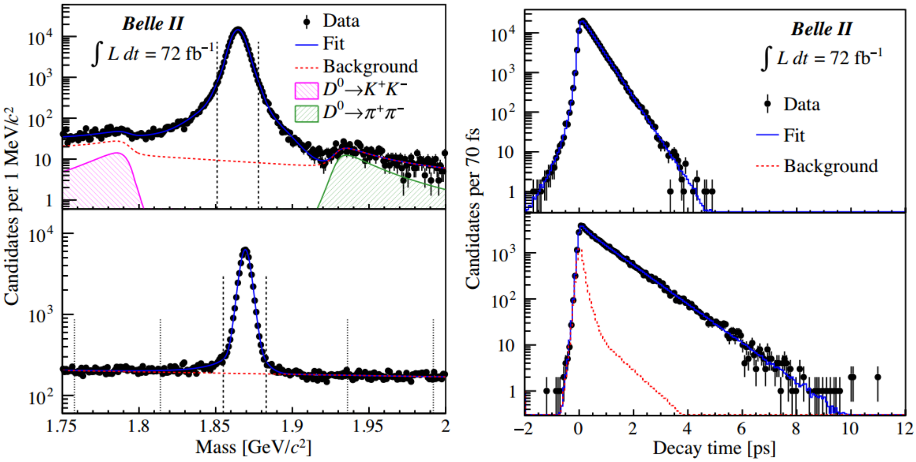

Fig. 2. Distributions of $m(K^-\pi^+)$ for $D^0 \to K^-\pi^+$ (top left) and $m(K^-\pi^+\pi^+)$ for $D^+ \to K^-\pi^+\pi^+$ (bottom left) with fit projections overlaid. The signal windows and the side bands (only for the D^+) are shown with vertical, grey lines. For candidates populating the respective signal regions, distributions of the decay time of $D^0 \to K^-\pi^+$ (top right) and $D^+ \to K^-\pi^+\pi^+$ (bottom right) with fit projections overlaid.

For measuring the lifetime, an unbinned maximum likelihood fit to (t, σ_t) is performed for candidates in the signal window, where t is the decay time and σ_t is the decay time uncertainty. For $D^0 \to K^-\pi^+$, as the background under the signal is only 0.2%, it is neglected and a systematic is assigned to the final result. For $D^+ \to K^-\pi^+\pi^+$, the background is assumed that the side-band events represent the background in the signal region. The decay-time distributions with fit projections overlaid are shown on the right in figure 2, top (bottom) for $D^0(D^+)$. The measured values of the lifetimes are: $\tau(D^0) = 410.5 \pm 1.1(\text{stat.}) \pm 0.8(\text{syst.})$ fs and $\tau(D^+) = 1030.4 \pm 4.7(\text{stat.}) \pm 3.1(\text{syst.})$ fs. These measurements are the most precise results on the lifetime of $D^{0,+}$ to date and are also consistent with previous measurements [4]. Such precision shows the excellent vertexing capability of Belle II and will impact future decay-time-dependent analyses of neutral-meson mixing and mixing-induced CP violation.

3.2. Measurement of time-integrated CPV

Time-integrated CPV in the charm sector was observed by LHCb in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ in 2019 [3]. It is important to look for CPV with other final states of D mesons to understand origin of CPV. Belle II will specially contribute to the decays with neutrals in the final state, and CP asymmetry (A_{CP}) is expected to reach the precision of $O(10^{-3}$–$10^{-4})$ [10]. In addition, Belle II will also explore CPV measurements in the charm baryon sector. The A_{CP} measurements for various decays measured by Belle and their projections with 50 ab^{-1} of the Belle II data are shown in Table 1.

Table 1. Time-integrated CP asymmetries measured by Belle (columns No. 2 and 3), and the expected projections with 50 ab^{-1} of the Belle II data [10].

Decay mode	$\mathcal{L}$ [fb^{-1}]	$A_{\mathrm{CP}}\%$ (Belle)	50 ab^{-1} (Belle II)
$D^0 \to K^-K^+$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^-\pi^+$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K_S^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.02
$D^0 \to K_S^0K_S^0$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.23
$D^0 \to K_S^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K_S^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^-\pi^+\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K_S^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03
$D^+ \to K_S^0K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D_s^+ \to K_S^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K_S^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

Figure 3 shows the ΔM distributions corresponding to the ongoing analyses of D^* tagged $D^0 \to K_S^0 K_S^0$ [11], $D^0 \to K_S^0 \pi^0$ [12], and $D^0 \to \pi^+\pi^-\pi^0$ [13] channels towards the measurement of CP asymmetry. These preliminary results are better than the results obtained from Belle in terms of yield, purity, and resolution [14]. Here, ΔM is defined as the difference between the D^* and the D^0 masses. The decay $\Xi_c^+ \to \Sigma^+\pi^+\pi^-$ is reconstructed using the Monte Carlo simulation and distribution of the mass of Ξ_c^+ is also shown.

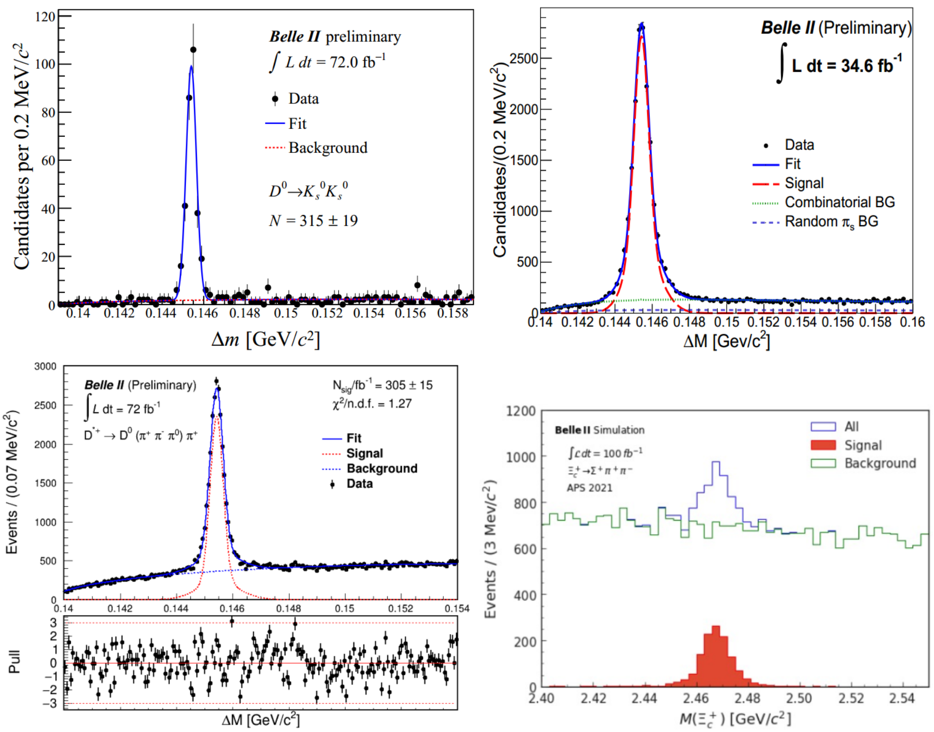

Fig. 3. ΔM distributions of $D^0 \to K_S^0 K_S^0$ (top left), $D^0 \to K_S^0 \pi^0$ (top right), and $D^0 \to \pi^+\pi^-\pi^0$ (bottom left). $m(\Sigma^+\pi^+\pi^-)$ distribution for $\Xi_c^+ \to \Sigma^+\pi^+\pi^-$ (bottom right).

3.3. Study of wrong-sign decays

The charm quark is the only up-type quark that exhibits mixing. The neutral charm mesons can change their flavour turning into antimesons, and *vice versa*, before they decay. This phenomenon is known as D^0–$\bar{D}^0$ mixing. Such mixing occurs because the mass eigenstates of D^0 and $\bar{D}^0$ are linear combinations of the flavour eigenstates, $|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle$. Here, p and q are complex and satisfy the relation $|p|^2 + |q|^2 = 1$. In the limit of charge-parity CP symmetry, q equals p and mixing is characterized by two dimensionless parameters, $x \equiv (m_1 - m_2)/\Gamma$ and $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$, where

$m_{1(2)}$ and $\Gamma_{1(2)}$ are the mass and decay width of the CP-even (odd) eigenstate $D_{1(2)}$, respectively, and $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$ is the average decay width [15]. The wrong-sign (WS) decay of D^0 meson proceeds via: (1) a doubly Cabibbo-suppressed (DCS) process; (2) a Cabibbo-favoured (CF) process and D^0–$\bar{D}^0$ mixing follows. The corresponding right-sign (RS) decay proceeds via the CF process because the DCS process with mixing followed is negligible. Hence, the WS decays provide sensitivity towards mixing. Figure 4 shows the ΔM distribution of $D^0 \to K^+\pi^-\pi^0$. In addition, with 37.8 fb^{-1} of the early Belle II data, three WS decay modes $D^0 \to K^+\pi^-$, $D^0 \to K^+\pi^-\pi^0$, and $D^0 \to K^+\pi^-\pi^+\pi^-$ are rediscovered and the corresponding WS-to-RS ratios are measured [16] and found to be in agreement with the world average values [15].

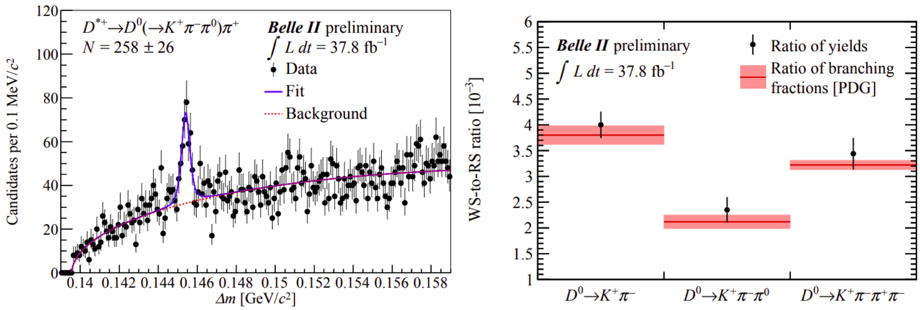

Fig. 4. ΔM distribution of $D^0 \to K^+\pi^-\pi^0$ with fit projections overlaid (left). Measured ratios (with statistical-only uncertainties) of wrong-sign (WS) to right-sign (RS) decay yields in comparison with the corresponding world-average ratios of branching fractions from the PDG [15]. For each decay mode, the wrong-sign (WS) and right-sign (RS) efficiencies are assumed to be the same (right).

3.4. Summary

Belle II has produced the world's most precise $D^{0,+}$ lifetime measurements which show the excellent vertexing capabilities of the Belle II VXD. This result will impact future decay-time-dependent analyses of neutral-meson mixing and mixing-induced CP violation. First reconstructions of a few important decay modes are discussed. The sensitivities of time-integrated CPV of some charm decays and their Belle II projections are also shown. Thanks to the persistent efforts of the members of the collaboration from all over the world, Belle II and SuperKEKB have been performing very well even through the COVID-19 pandemic. SuperKEKB has reclaimed the world record for the instantaneous luminosity of 3.81×10^{34} cm^{-2}s^{-1} and Belle II has already collected over 350 fb^{-1} of data. Although the size of the data set collected so far is smaller than that of Belle, one can already see that reconstruction performance is improved as compared to that of Belle.

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