PROCEEDINGS OF SCIENCE

Time-dependent studies with early Belle II data

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After the 2018 commissioning run, in which 0.5 fb^{-1} of data were collected at a center-of-mass energy corresponding to the mass of the $\Upsilon(4S)$, the construction of the Belle II detector was completed with the installation of a silicon vertex detector that covers most of the solid angle around the interaction region. The first physics run started in the spring of 2019. We utilize this data set to characterize the performance of the detector in tracking of charged particles, reconstruction of known resonances, and capability of identifying displaced decay vertices. In order to assess the B physics capabilities of the experiment, one of the first benchmarks to be reached consists in the measurement of the B^0-$\bar{B}^0$ mixing frequency. We present the first results based on samples of B mesons that decay to a semileptonic final state. A rediscovery of the $B^0 \to J/\psi K_S^0$ decay which is one of the CP-eigenstates is also reported.

18th International Conference on B-Physics at Frontier Machines - Beauty2019 -
29 September / 4 October, 2019
Ljubljana, Slovenia

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1. Introduction

In the Standard Model (SM), CP violation of the quark sector is induced by the complex phase appearing in the CKM matrix which describes the quark mixing [1]. B^0-$\bar{B}^0$ mixing is induced by the box diagram between $\bar{b}d$ and $b\bar{d}$ quarks. When a B^0 meson pair is produced by the decay of $\Upsilon(4S)$, mixing occurs simultaneously in two B^0 mesons due to quantum entanglement. The number of the mixed B^0-B^0 and unmixed B^0-$\bar{B}^0$ events depends on a decay time difference of B^0 mesons Δt:

$$N_{\mathrm{mixed}} \propto e^{-|\Delta t|/\tau_{B^0}}(1-\cos(\Delta m_d \Delta t), \tag{1.1}$$

$$N_{\mathrm{unmixed}} \propto e^{-|\Delta t|/\tau_{B^0}}(1+\cos(\Delta m_d \Delta t), \tag{1.2}$$

where Δm_d is the mass difference between the two mass eigenstates of the B^0-$\bar{B}^0$ system; and τ_{B^0} is the B^0 lifetime.Considering the unitarity between the matrix components in the system containing the b-quark, $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0$, the CP violation is parameterized as non-zero angles of the unitary triangle, $\phi_1 = \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$, $\phi_2 = \arg[-V_{ud}V_{ub}^*/V_{td}V_{tb}^*]$ and $\phi_3 = \arg[-V_{cd}V_{cb}^*/V_{ud}V_{ub}^*]$ [2]. Time-dependent CP violation is induced by quantum interference between amplitudes of decay to the CP-eigenstate through the B^0-$\bar{B}^0$ mixing and that without mixing. For decays of B^0 and $\bar{B}^0$ mesons produced via $\Upsilon(4S) \to B^0\bar{B}^0$ transitions, the decay rate has a time dependence [3, 4]

$$\mathscr{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times \left(1 + q\big[\mathscr{S}\sin(\Delta m_d \Delta t) + \mathscr{A}\cos(\Delta m_d \Delta t)\big]\right), \tag{1.3}$$

where $\mathscr{S}$ and $\mathscr{A}$ are CP-violating parameters; $q = 1$ for B^0 and -1 for $\bar{B}^0$ which decays into the CP-eigenstates. In these proceedings, we describe the mixing measurement to demonstrate performance of Δt and q measurements to perform a CP violation study. Reconstruction of the $B^0 \to J/\psi K_S^0$ and $B^0 \to J/\psi K^*(892)^0$ is shown as a "golden mode" of the $\sin 2\phi_1$ measurement and its reference mode, respectively. 2.6 fb^{-1} of the data set collected with the Belle II detector at asymmetric energy collision of 7.0 GeV e^- and 4.0 GeV e^+ at superKEKB storage rings [5] is used.

2. Belle II detector

The Belle II detector is a large-solid-angle magnetic spectrometer that consists of a 6-layer vertex detector (VXD), a 56-layer central drift chamber (CDC), two types of particle identification devices based on Cherenkov light emission in quartz and aerogel radiators installed in barrel (TOP) and endcap (ARICH) region, respectively, and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [6]. During the commissioning run in 2018, a small part of the VXD is installed to check the effect of the beam background. After that, we installed the VXD and Δt can be measured using the data taken during the physics run in 2019.

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3. General analysis strategy

To select the signal events, we reconstruct the decay of the mother B^0 meson with kinematic variables calculated using the information of the daughters such as momentum, energy and particle identification from the Belle II detector. For the decay in which B meson is fully reconstructed, beam-constrained mass $M_{\rm bc} = \sqrt{(E_{\rm beam}/c^2)^2 - |p^{\rm CM}/c|^2}$ and energy difference $\Delta E = E_{\rm beam} - E^{\rm CM}$ are used, where $p^{\rm CM}$ and $E^{\rm CM}$ are B momentum and energy in the $\Upsilon(4S)$ center-of-mass system (CMS), respectively. $E_{\rm beam}$ is a measured beam energy in CMS. For the semileptonic B meson decays, a mother state is not fully reconstructed due to neutrino emission. On the other hand, such event is characterized by high-momentum lepton directly from B meson decay and low-momentum pion from $D^* \to D\pi$ decay so selections for daughter particle momentum are introduced. We then calculate missing mass of the decay M_ν by assuming that B meson is at rest instead of the $M_{\rm bc}$ and ΔE. Signal contribution is extracted from the experimental data by performing the fit to these variables with the probability density functions (PDFs) of the signal and background. To distinguish jet-like $e^+e^- \to q\bar{q}$ continuum background events from the $B\bar{B}$ events which has spherical event topology, ratio of second and 0-th order of the Fox-Wolfram moment $R2$ [7] is used. For determination of the selection criteria and a part of the PDF of the signal and background, Monte Carlo (MC) simulated events are used. The signal events are generated using the EVTGEN [8] hadronic event generator package. For the background, a large number of the $B\bar{B}$ and $q\bar{q}$ processes are simulated. Interactions of the particles in the Belle II detector are reproduced using the GEANT4 [9] with detector configuration.

Since the B^0 flavor q is not specified from observed decay products in the the CP-eigenstates, it is determined using the information of inclusive properties of particles that are not associated with the signal B^0 candidate after the selection. For the determination, we perform a multivariable analysis for measured information of the non-signal B meson daughters. Due to the asymmetric energies of the e^+ and e^- beams, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.28$. Since the $B^0\bar{B}^0$ pair is almost at rest in the $\Upsilon(4S)$ CMS, the decay time difference Δt can be determined from the separation along z of the B^0 and $\bar{B}^0$ decay vertices: $\Delta t \simeq \Delta z/(\beta\gamma c)$. The vertex positions of the CP and opposite-side are reconstructed from all charged tracks in the event using a vertex reconstruction algorithm. Performance of the vertex reconstruction [10] is demonstrated by measuring a resolution of d_0 as difference between electron and positron tracks in the Bhabha events, where d_0 is an impact parameter of the charged track defined as a closest approach of the track to the origin in x-y plain. They are (14.2 ± 0.1) μm and (12.5 ± 0.1) μm for the data and MC, respectively, and much smaller than Δz of the $B\bar{B}$ which is expected to be order of 100 μm.

4. Measurement of B^0-$\bar{B}^0$ mixing

Mixing rate is measured using flavor information of the B meson decay events in which both decay into the semileptonic B meson decays since the B meson flavor is determined using charge of the lepton. After applying the selections, 35492 ± 2209 events are extracted as shown in Figure 1. After determination of the flavors for both of the B^0 and Δt, $N_{\rm unmixed} = 1642 \pm 113$ events are selected as unmixed and $N_{\rm mixed} = 253 \pm 45$ events are mixed events. From these, fraction of mixed events with reconstruction efficiencies $\varepsilon_{\rm mixed}$ and $\varepsilon_{\rm unmixed}$, $\chi_d = \frac{N_{\rm mixed}/\varepsilon_{\rm mixed}}{N_{\rm mixed}/\varepsilon_{\rm mixed} + N_{\rm unmixed}/\varepsilon_{\rm unmixed}}$ is

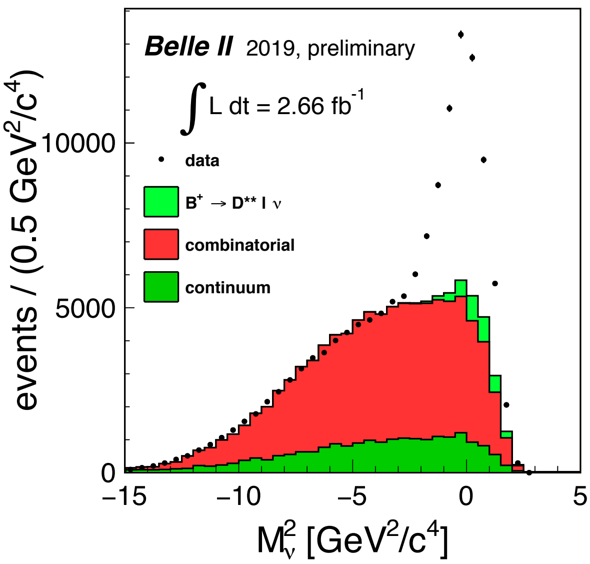

Figure 1: Distribution of M_ν^2 for selected $B^0 \to D^{*0}\ell\nu(\ell = e,\mu)$ candidates. Points with error bars show the data and histograms show the fit result for signal yield extraction.

measured to be $(17.3 \pm 3.6)\%$, that is consistent with the world average of 18.6% [11]. Figure 2 shows the fraction of the unmixed events in each Δt region. Oscillation pattern is seen as evolution of the Δt and it is consistent with an expectation assuming the world averages of the B^0 lifetime and mixing.

5. Reconstruction of the decays for *CP*-violation measurement

Using the data sample, $B^0 \to J/\psi K_S^0$ and $B^0 \to J/\psi K^*(892)^0$ are reconstructed. J/ψ candidates are selected with the invariant mass of the lepton pairs of e^+e^- or $\mu^+\mu^-$. K_S^0 candidates are selected by multivariable analysis for track pairs which have an opposite-sign charge and creation point is displaced from the interaction point of e^+e^-. $K^*(892)^0$ is reconstructed from charged kaon and pion. These are *CP*-eigenstates and their control sample decays that have relatively large branching fractions. Figure 3 shows the $M_{\rm bc}$ and ΔE distributions of the $B^0 \to J/\psi K_S^0$ candidates from the data. From a two-dimensional un-binned maximum likelihood fit is performed to extract the signal yield. Gaussian function is used as PDF for the signal. ARGUS [12] and linear functions are used for the background components in the $M_{\rm bc}$ and ΔE, respectively. The signal yield of 26.9 ± 5.2 events are extracted and almost no correlations are seen between the PDF shape parameters. Figure 4 shows the $M_{\rm bc}$ and ΔE distributions of $B^0 \to J/\psi K^*(892)^0$ candidates from the data. After applying the selection for the ΔE, a one-dimensional un-binned maximum likelihood fit to the $M_{\rm bc}$ distribution is performed with the Gaussian and ARGUS PDFs for the signal and background, respectively, and 48.6 ± 7.0 events signal yield is extracted. These yields are consistent with expectations from branching fractions and signal reconstruction efficiencies from the MC studies.

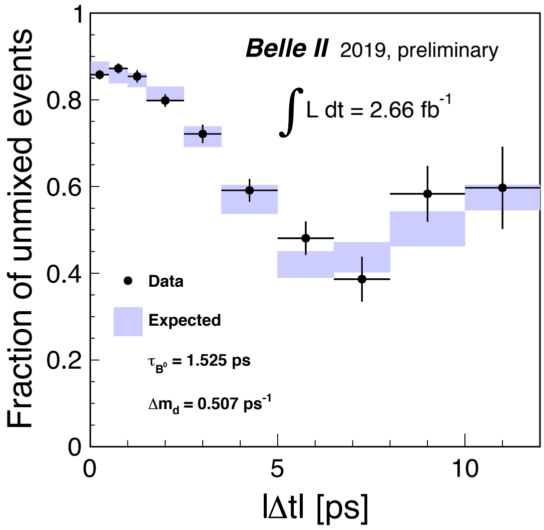

Figure 2: Fraction of unmixed events as a function of Δt for selected candidate events in which both B^0 mesons decay into semileptonic modes. Points with error bars show the data and shaded region is an expectation from the MC by assuming $\tau_{B^0} = 1.525$ ps and $\Delta m_d = 0.507$ ps^{-1} scaled with the integrated luminosity of the data.

6. Summary

Using 2.6 fb^{-1} of the data taken after installing the VXD, time-dependent mixing rate of the B^0-$\bar{B}^0$ is measured. Obtained oscillation pattern from the data is consistent with an expectation by assuming the world average of the B^0 lifetime and mixing so that performance of the B decay vertex reconstruction is demonstrated. Reconstruction of the CP-eigenstate for the $\sin 2\phi_1$ measurement and control sample decay has been done and significant signal yields are extracted from the fit to the kinematic observables.

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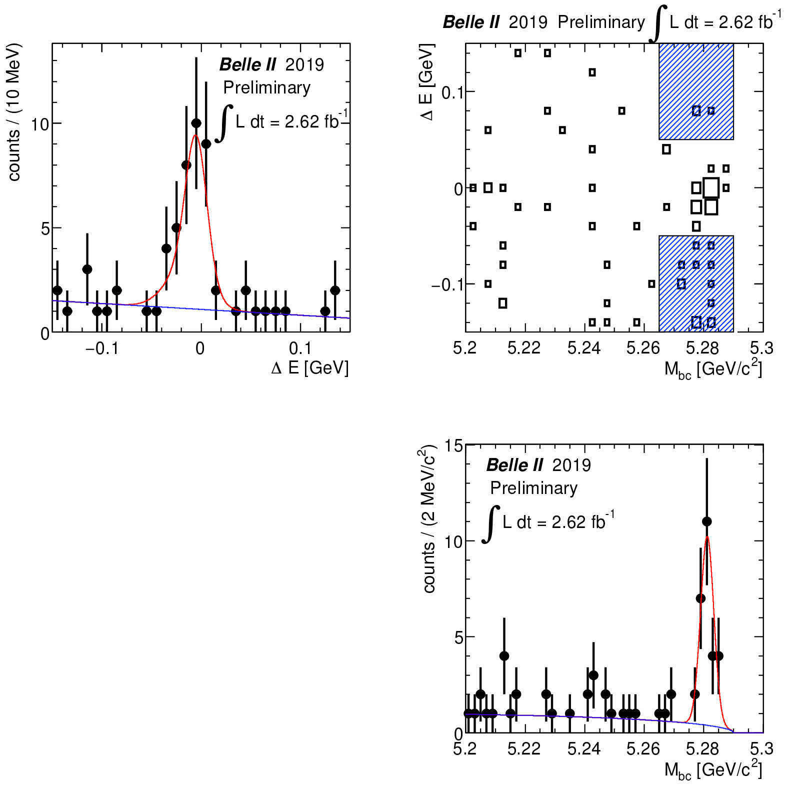

Figure 3: Distributions of the M_{bc} and ΔE for selected $B^0 \to J/\psi K_S^0$ candidates. Points with error bars show the data and red and blue curves show the fit result for the signal yield extraction and background contribution, respectively. Shaded regions are excluded for the fit to reject contribution from the $B \to J/\psi X$ background due to failure of the particle identification.

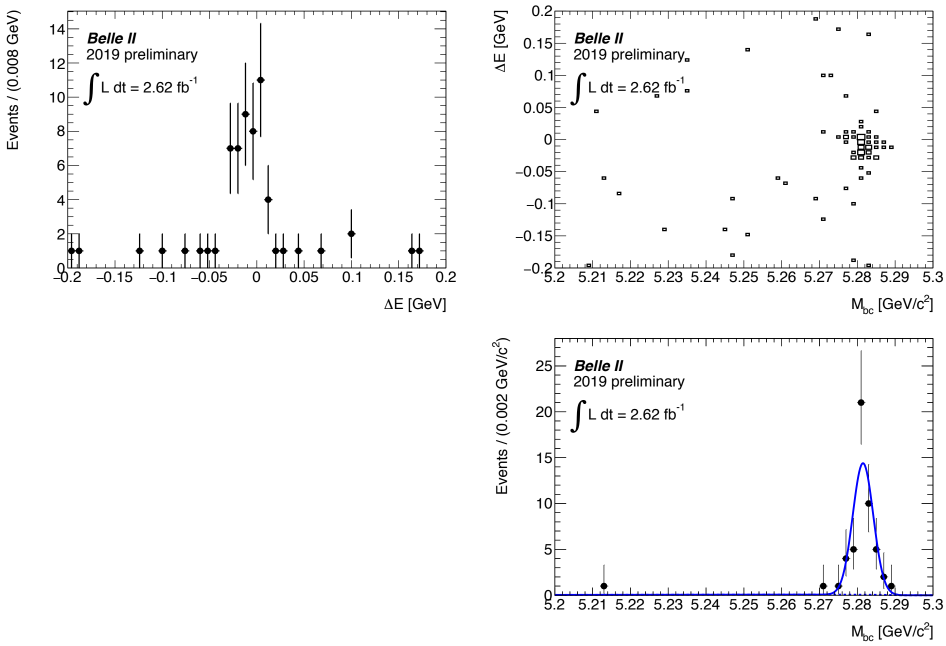

Figure 4: Distribution of the M_{bc} and ΔE for selected $B^0 \to J/\psi K^*(892)^0$ candidates. Points with error bars show the data and curve shows the fit result for the signal yield extraction.