



Rediscovery of $B^0 \rightarrow J/\psi K_L^0$ at Belle II

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Abstract

We present preliminary results on the reconstruction of the $B^0 \rightarrow J/\psi K_L^0$ decay, where $J/\psi \rightarrow \mu^+\mu^-$ or e^+e^- . Using a dataset corresponding to a luminosity of $62.8 \pm 0.6 \text{ fb}^{-1}$ collected by the Belle II experiment at the SuperKEKB asymmetric energy e^+e^- collider, we measure a total of 267 ± 21 candidates with $J/\psi \rightarrow \mu^+\mu^-$ and 226 ± 20 with $J/\psi \rightarrow e^+e^-$. The quoted errors are statistical only.

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I. INTRODUCTION AND MOTIVATION

The Standard Model (SM) of electroweak interactions describes Charge-Parity (CP) violation as a consequence of an irreducible phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. In this framework, measurements of CP asymmetries in the proper-time distribution of neutral B decays to CP eigenstates containing a charmonium and K^0 meson provide a direct measurement of $\sin(2\phi_1)$, where the angle ϕ_1 of the Unitarity Triangle is given by $\arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ and V_{ij} are elements of the CKM matrix.

CP violation in the B meson system has been established by the *BABAR* [1] and Belle [2] collaborations using a variety of such decays, among which the $B^0 \rightarrow J/\psi K^0$ one stands out for its clear experimental signatures and clean theoretical interpretation, directly linking the measurement of the time-dependent CP asymmetry to the angle ϕ_1 .

The value of $\sin(2\phi_1)$ measured with $B^0 \rightarrow J/\psi K^0$ is basically free of hadronic uncertainties and almost completely insensitive to the effects of new physics, so it constitutes a reference point for the SM [3]. Improving the precision of the measurement of $\sin(2\phi_1)$ is one of the goals of the Belle II experimental program to verify the SM prediction that $\sin(2\phi_1)$ be equal in the tree-level $J/\psi K^0$ decays and in other penguin-dominated decays described by the same CKM elements, with a discrepancy being indicative of New Physics.

The $B^0 \rightarrow J/\psi K_L^0$ decay provides an independent measurement of $\sin(2\phi_1)$ from $B^0 \rightarrow J/\psi K_S^0$. In addition, the former decay having opposite CP eigenvalue of the latter, the decay $B^0 \rightarrow J/\psi K_L^0$ has a time-dependent CP asymmetry identical but opposite in sign of that of $B^0 \rightarrow J/\psi K_S^0$, providing an important check of systematics effects on these measurements.

In this paper, we present preliminary results leading to the rediscovery of the $B^0 \rightarrow J/\psi K_L^0$ decay at SuperKEKB using, for the first time in Belle II, K_L^0 mesons reconstructed from hadronic neutral clusters in the K_L^0 and muons (KLM) subdetector. We identify signal events based on the variable ΔE , representing the difference between the reconstructed B meson and the beam energy in the center of mass. In this preliminary result, the systematics uncertainties have not been evaluated yet.

II. THE BELLE II DETECTOR

The Belle II detector is described in detail in Ref. [4]. The detector has a cylindrical structure around the beam pipe, placed partially inside a solenoidal superconducting magnet providing a 1.5T magnetic field. The innermost sub-detector is the vertex detector (VXD), formed by two layers of silicon pixel sensors and four layers of silicon strips, devoted to tracking and vertexing. It is surrounded by a large central drift chamber (CDC), with small cells and filled with helium ethane mixture, which provide precise measurement of momenta of charged tracks as well as particle identification via energy loss measurement (dE/dx). Two Cherenkov detectors provide additional particle identification: the Time of Propagation (TOP) counter in the barrel region, and the Aerogel Ring Imaging Cherenkov (ARICH) in the forward region. The final detector inside the solenoid is the electromagnetic calorimeter (ECL), comprised of CsI(Tl) crystals, dedicated to photon and electron identification and

measurement. The return yoke of the magnet is instrumented with scintillator strips and resistive plate chambers, to provide identification of K_L^0 mesons and muons (KLM). The coordinate system's axis coincides with the solenoid axis, and is roughly oriented with the electron beam. The polar angle ϑ is defined with respect to the z axis, and the azimuthal angle ϕ is measured in the transverse plane from the horizontal x axis.

III. DATA AND MONTE CARLO SAMPLES

The dataset used for this analysis has been collected by Belle II in 2019 and 2020 at the SuperKEKB asymmetric energy e^+e^- collider [5]. The integrated luminosity collected at a centre-of-mass (CM) energy corresponding to the $\Upsilon(4S)$ resonance is $62.8 \pm 0.6 \text{ fb}^{-1}$, with an additional 9.2 fb^{-1} collected about 60 MeV below the resonance (off-resonance dataset). This corresponds to $(68.21 \times 10^6) \pm 0.09\%(\text{stat}) \pm 1.3\%(\text{syst})$ $B\bar{B}$ pairs. [6].

To study the selection efficiency, we used a sample of 40000 signal $B^0 \rightarrow J/\psi[\mu^+\mu^-]K_L^0$ and $B^0 \rightarrow J/\psi[e^-e^-]K_L^0$ Monte Carlo (MC) events, corresponding to 2.88 ab^{-1} for each mode. In addition, we used 40 fb^{-1} of generic $(B^0\bar{B}^0 + B^+B^- + c\bar{c})$ events for background characterization. In the following, we refer to these samples as “signal MC” and “generic MC”, respectively.

IV. EVENT SELECTION

A. J/ψ selection

Signal candidate events are selected first by reconstructing $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$, decays requiring the invariant mass of the J/ψ candidate to be consistent with its PDG value.

We correct for final state radiation effects in $J/\psi \rightarrow e^+e^-$ decays. Due to the post-correction residual radiative tail, we also apply different mass selection cuts ($m_{\mu\mu} \in [3.06, 3.12] \text{ GeV}/c^2$ and $m_{ee} \in [3.04, 3.12] \text{ GeV}/c^2$ respectively) to the two J/ψ decay channels. A tight particle identification requirement from the combined information of all detectors is then applied to one of the J/ψ tracks, and a looser requirement is applied to the second track. Typical efficiencies of the requirements for muons are around 90 % and 95 % for tight and loose selection, respectively. The corresponding values for electrons are 95 % and 97 %.

B. K_L^0 selection

The K_L^0 mesons leave measurable signals in the ECL and KLM detectors. In the present analysis, we only make use of neutral clusters in the KLM.

The energy deposition mechanism of K_L^0 in the KLM does not allow a usable measurement of the particle energy, but only of its direction relative to the assumed origin at the interaction point. We calculate the momentum of the K_L^0 candidate from its direction and the J/ψ reconstructed momentum, by requiring momentum conservation and using the B^0 mass

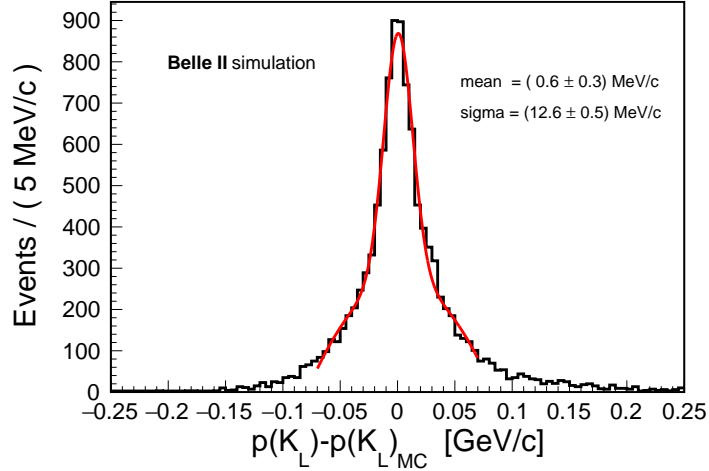


FIG. 1. Difference between calculated K_L^0 momentum and true K_L^0 for truth-matched events in signal MC.

constraint in the $B^0 \rightarrow J/\psi K_L^0$ decay. The procedure correctly reconstructs the generated K_L^0 momentum, with a typical resolution of about 15 MeV/c, albeit with some non-gaussian tails, as shown in Figure 1. The K_L^0 is reconstructed with an angular resolution of about 100 mrad.

We enhance the purity of the KLM cluster using a multivariate boosted decision tree (BDT) based on a number of KLM cluster shape and topological variables and trained on signal $B^0 \rightarrow J/\psi K_L^0$ and generic background simulated events. The BDT output variable, `klongID`, is shown in Figure 2 for all reconstructed K_L^0 candidates and for those truth-matched to a true K_L^0 , respectively. We use the requirement `klongID` ≥ 0.25 in the following. Further optimization of the BDT is in progress.

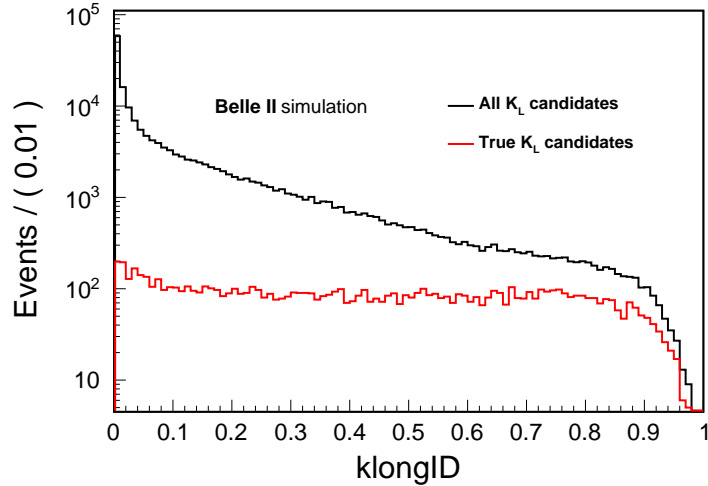


FIG. 2. `klongID` distribution of all K_L^0 candidates (black curve) and truth-matched candidates (red curve) in the generic MC.

Although the number of layers in the KLM cluster is among the input BDT variables, we

also explicitly apply the requirement $N_{\text{layers}} \geq 2$, which helps eliminate spurious clusters.

V. ΔE FITS

Once a signal candidate has been selected we calculate the difference between the B^0 candidate energy and the beam energy in the CM frame, i.e., $\Delta E \equiv E_B^* - E_{\text{beam}}^*$, which for genuine $B^0 \rightarrow J/\psi K_L^0$ is expected to be close to zero.

In a small number of cases (about 2%), there are two $B^0 \rightarrow J/\psi K_L^0$ candidates after the selection; in these cases, we choose the K_L^0 with the largest `klongID`. An alternative choice we have considered is to select the candidate with the smallest $|\Delta E|$. In most cases the, two criteria select the same candidate, which in the MC is also correctly matched to the true $B^0 \rightarrow J/\psi K_L^0$ decay. We conclude that the choice of the best candidate does not induce a bias in the selection.

A. PDF model for signal

We model the signal ΔE distribution with a Crystal Ball (CB) probability density function (PDF) [7, 8]. The signal PDF coefficients are determined by an unbinned maximum likelihood (ML) fit to the ΔE distribution in a high-statistics MC sample of $J/\psi K_L^0$ events. An example of such fits, after a selection requiring `klongID` ≥ 0.25 , is shown in Figure 3. Here and in the following, the fits are performed in the range $\Delta E \in [-20, 80]$ MeV.

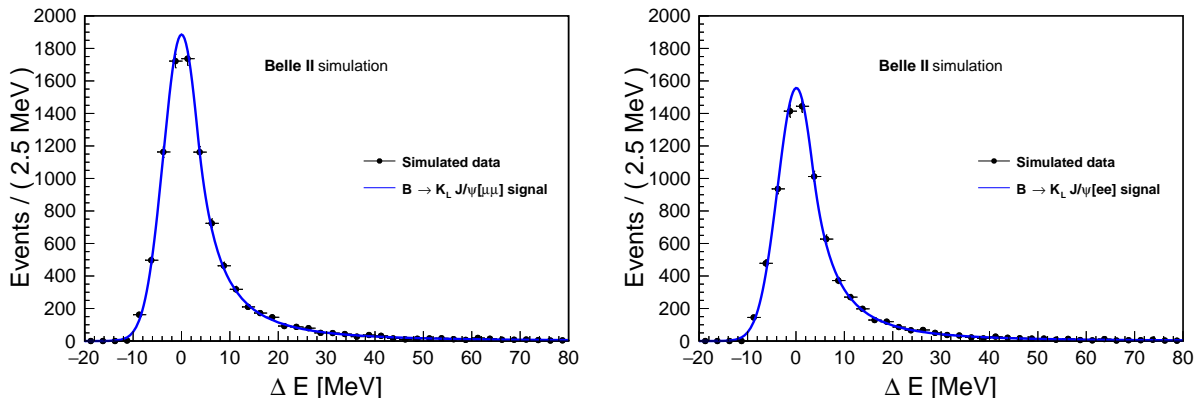


FIG. 3. Signal ΔE distribution of $B^0 \rightarrow J/\psi K_L^0$ candidate events for $J/\psi \rightarrow \mu^+\mu^-$ final states (left) and $J/\psi \rightarrow e^+e^-$ final states (right) from the signal MC sample.

B. Background description and parameterization

Background to $B^0 \rightarrow J/\psi K_L^0$ is essentially due to $B^0\bar{B}^0$ and B^+B^- decays, which according to MC simulation roughly contribute equally. Thanks to the strong J/ψ signature, no events

from the $e^+e^- \rightarrow c\bar{c}$ generic sample nor the off-resonance data survive the analysis selection cuts.

We parameterize the background with an Argus PDF [9] for the combinatorial part and a CB PDF to describe a possible peaking component, which according to the simulation could be expected mainly from $B \rightarrow J/\psi K^{*0}$ and $B \rightarrow J/\psi K^{*+}$ decays.

The fraction of the peaking component in the background is determined from fits to the ΔE distributions of generic MC events (in which $B^0 \rightarrow J/\psi K_L^0$ events are excluded from the $B^0\bar{B}^0$ sample). We find the peaking background fraction $f_{\text{peak}} = (0.4 \pm 3.1)\%$ and $f_{\text{peak}} = (0.0 \pm 3.1)\%$ in the $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$ final states, respectively.

In order to rely on MC simulations as little as possible, we estimate the fake J/ψ and fake K_L^0 backgrounds directly from data. Wrongly reconstructed J/ψ candidates can be estimated using the J/ψ mass sidebands, while fake K_L^0 mesons are estimated using an “*anti-selection*” of K_L^0 clusters, with the requirements $N_{\text{layers}} = 1$, $\mathbf{klongID} < 0.05$.

VI. RESULTS

We determine the number of signal and background $B^0 \rightarrow J/\psi K_L^0$ events with an unbinned ML fit to our 62.8 fb^{-1} dataset in the ΔE interval $[-20, +80] \text{ MeV}$, as shown in Figure 4. The background shape parameters determined in the background control sample are fixed in the fit, as well as the peaking background fraction estimated in the fit of the simulated background events. The signal shape parameters are used as starting values in the fit, but to minimize the dependence on MC the sigma and mean of the CB are left free in the fit. Finally, to extract the number of signal and background events, we also float the relative normalization of the signal and background distributions. The results are

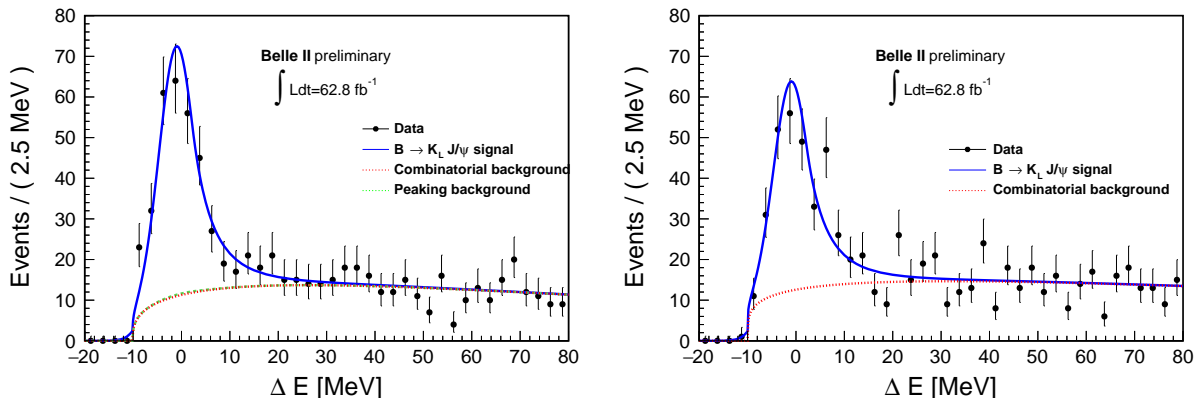


FIG. 4. ΔE distribution of $B^0 \rightarrow J/\psi K_L^0$ candidate events for $J/\psi \rightarrow \mu^+\mu^-$ final states (left) and $J/\psi \rightarrow e^+e^-$ final states (right) for a dataset corresponding to a luminosity of $62.8 \pm 0.6 \text{ fb}^{-1}$. The results of the unbinned ML fit are superimposed.

$$N_{\text{sig}}(\mu^+\mu^-) = 267 \pm 21, \quad N_{\text{sig}}(e^+e^-) = 226 \pm 20.$$

A thorough evaluation of the systematics uncertainties has not been performed yet. However, since we expect the one related to the peaking background to be relatively large, we

have done a conservative estimate of this uncertainty by varying in the final fit the fraction of peaking background (Sec.VB) by twice (95% confidence interval) its statistical error. This procedure yields $\Delta N_{\text{peaking}}(\mu^+\mu^-) = 28$, $\Delta N_{\text{peaking}}(e^+e^-) = 31$.

VII. CONCLUSIONS

In the present paper, we have shown preliminary results for the reconstruction of the $B^0 \rightarrow J/\psi K_L^0$ decay in the first 62.8fb^{-1} of integrated luminosity collected by Belle II, which constitutes a rediscovery of this decay. The signal yields are:

$$\begin{aligned} N_{\text{sig}}(\mu^+\mu^-) &= 267 \pm 21(\text{stat}) \pm 28(\text{peaking}) \\ N_{\text{sig}}(e^+e^-) &= 226 \pm 20(\text{stat}) \pm 31(\text{peaking}). \end{aligned}$$

The overall signal yield obtained with this selection is consistent with that observed by the Belle Collaboration, with similar purity.

Work is in progress to extend this study to include neutral clusters reconstructed in the ECL, which will significantly increase the signal sample.

Flavour tagging and tag and decay vertex time reconstruction will also be added to allow the study of the time-dependent CP violation and the precise measurement of $\sin(2\phi_1)$.

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