

A study of the $B^0 \rightarrow K_S^0 \pi^0$ decay at Belle II

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Abstract. The decay $B^0 \rightarrow K_S^0 \pi^0$ proceeds via $b \rightarrow s$ loop diagrams. Such flavour changing neutral current transitions are highly suppressed in the standard model and provide an indirect route to search for new physics. In particular, the expected large yield of this charmless decay at Belle II will allow us to precisely measure the CP violation asymmetry. We report herein preliminary results based on a simulation sample.

Keywords: CPV

1 Introduction

In the standard model (SM), the decay $B^0 \rightarrow K_S^0 \pi^0$ proceeds via $b \rightarrow s$ loop diagrams [1]. Such flavour changing neutral current transitions are highly suppressed and provide an important route to indirectly search for new physics by checking the consistency between measurements and corresponding theory predictions as new particles may enter the quantum loop [1]. Within the SM, CP violation (CPV) arises due to a single irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [2]. At a flavor-factory experiment such as Belle II, neutral B meson pairs are coherently produced in the process $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$. When one of these B mesons decays to a CP eigenstate f_{CP} and the other to a flavor-specific final state f_{tag} , the time-dependent decay rate is given as

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 + q\{\mathcal{A} \cos(\Delta m_d \Delta t) + \mathcal{S} \sin(\Delta m_d \Delta t)\}], \quad (1)$$

where $\Delta t = t_{CP} - t_{\text{tag}}$ is the proper decay time difference between f_{CP} and f_{tag} , $q = \pm 1$ is the flavor of f_{tag} being +1 (−1) for B^0 (\bar{B}^0) decaying to f_{tag} , Δm_d is the B^0 - \bar{B}^0 mixing frequency, and τ_{B^0} is the B^0 lifetime. The quantity \mathcal{A} is a measure of direct CPV and \mathcal{S} denotes CPV due to interference between decays with and without $B\bar{B}$ mixing. The key challenge in performing a time-dependent CP analysis for $B^0 \rightarrow K_S^0 \pi^0$ arises due to the absence of primary charged final-state particles at the B decay vertex. Instead, we calculate Δt as $(z_{\text{rec}} - z_{\text{tag}})/\beta\gamma c$, where $\beta\gamma$ is the Lorentz boost, z_{rec} is the z position of the B vertex reconstructed from the intersection of the K_S^0 trajectory with the interaction region, and z_{tag} is calculated using the remaining tracks.

The CKM and color suppression of the tree-level $b \rightarrow su\bar{u}$ transition means that the $B^0 \rightarrow K_S^0 \pi^0$ decay is dominated by the top-quark mediated $b \rightarrow s\bar{d}\bar{d}$

loop diagram, which carries a weak phase $\arg(V_{tb}V_{ts}^*)$. Here V_{ij} are the CKM matrix elements. If subleading contributions are small, $\mathcal{S}_{K_S^0\pi^0}$ is expected to be equal to $\sin(2\phi_1)$ and $\mathcal{A}_{K_S^0\pi^0} \approx 0$. Therefore, a precise measurement of the direct CP asymmetry and branching fraction in this decay channel represents an important consistency test of the SM. With the data size anticipated at Belle II, we expect to have significantly smaller uncertainties compared to what Belle [3, 4] and BaBar [5, 6] have achieved for these quantities.

2 Event sample and selection

We use 7×10^5 $B^0\bar{B}^0$ Monte Carlo (MC) events for the signal study. We also use $e^+e^- \rightarrow u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}, B^0\bar{B}^0$ and B^+B^- MC events, each equivalent to an integrated luminosity of 400fb^{-1} , to identify backgrounds. The MC events are simulated with the geometry and background condition for the Belle II detector [7] at SuperKEKB. The detector elements relevant to reconstruct the $B^0 \rightarrow K_S^0\pi^0$ decay are the vertexing and tracking system as well as the electromagnetic calorimeter.

A K_S^0 candidate is reconstructed in its $\pi^+\pi^-$ decay by requiring the reconstructed invariant mass to lie between 482 and 513 MeV/c^2 , which corresponds to a $\pm 6\sigma$ window around the nominal K_S^0 mass, where σ is the invariant-mass resolution. To reconstruct $\pi^0 \rightarrow \gamma\gamma$ candidates, we apply a photon energy threshold of 30, 60, and 80 MeV for the barrel, backward and forward endcap region, respectively, of the calorimeter. We require the reconstructed π^0 mass to lie between 120 and 145 MeV/c^2 . We also require the magnitude of the cosine of the π^0 helicity angle to be less than 0.98; this helps suppress misreconstructed π^0 candidates.

B -meson candidates are reconstructed by combining K_S^0 and π^0 candidates. For this purpose, we use two kinematic variables, namely the beam-energy-constrained mass (M_{bc}) and the energy difference (ΔE), defined as

$$\begin{aligned} M_{bc} &= \sqrt{E_{\text{beam}}^2 - \vec{p}_B^2}, \\ \Delta E &= E_B - E_{\text{beam}}, \end{aligned} \quad (2)$$

where E_{beam} is the beam energy, E_B and \vec{p}_B are the reconstructed energy and momentum of the B meson respectively, all calculated in the center-of-mass frame. We retain candidate events satisfying the following criteria: $|\Delta E| < 0.3\text{ GeV}$ and $5.24 < M_{bc} < 5.29\text{ GeV}/c^2$.

The dominant source of backgrounds in this analysis comes from $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$ or c) continuum process. This background is suppressed by exploiting the difference in event topology. Continuum events result in final-state particles collimated into two back-to-back jets, whereas the final-state particles from $e^+e^- \rightarrow \mathcal{Y}(4S) \rightarrow B\bar{B}$ are uniformly distributed over the 4π solid angle. We use a boosted decision tree (BDT) [8] classifier to combine event-shape variables and apply a criterion on the BDT output by maximising the signal significance. Figure 1 shows M_{bc} and ΔE distributions obtained after the continuum suppression requirement is applied.

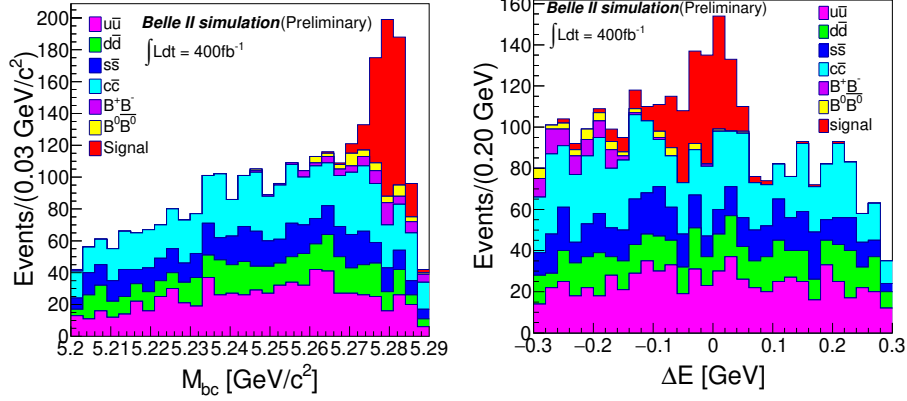


Fig. 1: M_{bc} and ΔE distributions obtained after the continuum suppression.

3 Signal yield extraction

To extract the signal yield, we use an extended unbinned maximum-likelihood fit to the two-dimensional distribution of M_{bc} and ΔE . As the signal M_{bc} is correlated with ΔE , we reduce the correlation by using the modified M_{bc} introduced in Ref. [9]. We can now consider the product of two individual probability density functions (PDFs) to be a good approximation for the total PDF. The extended likelihood function is given as

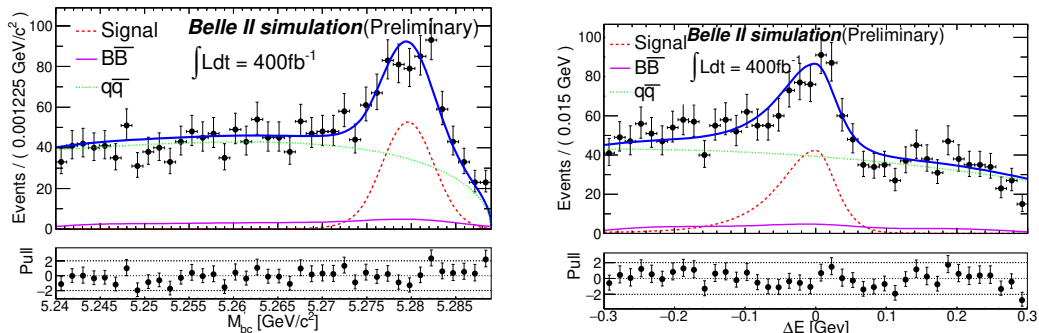
$$\mathcal{L} = \frac{e^{-\sum_j n_j}}{N!} \prod_i \left[\sum_j n_j \mathcal{P}_j^i \right], \quad (3)$$

where N is the total number of candidate events, n_j is the yield of event category j , and \mathcal{P}_j^i is the PDF of the same category for event i . Table 1 lists various PDFs used to model the M_{bc} and ΔE distributions. We fix the yield and PDF shape of the $B\bar{B}$ background category in the fit. Figure 2 shows the M_{bc} and ΔE

Table 1: List of PDFs used to model M_{bc} and ΔE distributions.

| Event category | M_{bc} | ΔE |
|----------------|--|--------------------------------------|
| Signal | Crystal Ball [10] + Gaussian | Double-sided Crystal Ball + Gaussian |
| $B\bar{B}$ | Two-dimensional kernel estimation PDF [11] | |
| $q\bar{q}$ | ARGUS [12] | Chebyshev polynomial |

projections of the fit. In Table 2 we compare the fitted yields of signal and $q\bar{q}$ background with their expected values.

Fig. 2: Projections of M_{bc} and ΔE obtained with the maximum-likelihood fit.Table 2: Expected and fitted yield for signal and $q\bar{q}$ background.

| Category | Expected yield | Fitted yield |
|------------|----------------|---------------|
| Signal | 317 | 316 ± 32 |
| $q\bar{q}$ | 1519 | 1499 ± 47 |

4 Summary

The $B^0 \rightarrow K_S^0 \pi^0$ decay constitutes an important channel at Belle II for the precise measurement of time-dependent CP asymmetry, as well as its branching fraction. We have deployed a multivariate analysis method to suppress backgrounds and performed an unbinned maximum-likelihood fit to extract the signal yield. We are now developing a time-dependent CPV analysis framework.

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