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

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Abstract. The decay $B^0 \to K_S^0 \pi^0$ proceeds via $b \to s$ 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 $B^0 \to K_S^0 \pi^0$ proceeds via $b \to s$ 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 $\Upsilon(4S) \to B^0 \bar{B}^0$. 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 decay rate is given as

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

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}, and Δm_d is the $B\bar{B}$ mixing frequency. The quantity $\mathcal{A}$ is a measure of direct CPV and S_f denotes CPV due to interference between decays with and without $B\bar{B}$ mixing. The CKM and color suppression of the tree-level $b \to su\bar{u}$ transition means that the $B^0 \to K_S^0 \pi^0$ decay is dominated by the top-quark mediated $b \to sd\bar{d}$ 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. The time-dependent *CP* asymmetries of the decay $B^0 \to K^0_S \pi^0$ have been measured by BABAR [3] and subsequently by Belle [4]; both experiments have also measured its branching fraction [5, 6]. With the integrated luminosity anticipated at Belle II, we expect to have significantly smaller experimental uncertainties.

2   Event sample and selection

We use 0.7 Million $B^0 \bar{B}^0$ Monte Carlo (MC) events for the signal study. We also use $e^+ e^- \to u\bar{u}$, $d\bar{d}$, $c\bar{c}$, $s\bar{s}$, $B^0 \bar{B}^0$ and $B^+ B^-$ MC events, each equivalent to $400\,\text{fb}^{-1}$ luminosity, to identify backgrounds.

   A K^0_S candidate is reconstructed in its $\pi^+ \pi^-$ decay by requiring the reconstructed invariant mass to lie between 482 and $513\,\text{MeV}/c^2$, which corresponds to a $\pm 6\sigma$ window around the nominal K^0_S mass. To reconstruct $\pi^0 \to \gamma\gamma$ candidates, we apply a photon energy threshold of 30, 60, and 80 MeV for the barrel, backward and forward endcap region, respectively. We require the reconstructed π^0 mass to lie between 120 and $145\,\text{MeV}/c^2$. 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^0_S and π^0 candidates. For this purpose two kinematic variables are used, namely the beam-energy-constrained mass (M_{bc}) and the energy difference (ΔE), defined as

$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - \vec{p}_B^2}, \qquad (2)$$
$$\Delta E = E_B - E_{\text{beam}},$$

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

   The dominant source of backgrounds in this analysis comes from $e^+ e^- \to q\bar{q}$ ($q = u$, d, s or c) continuum process. This background are suppressed by means of event topology. Continuum events produce final-state particles collimated into two back-to-back jets, whereas $e^+ e^- \to \Upsilon(4S) \to B\bar{B}$ are spherically distributed. We use a boosted decision tree (BDT) classifier to suppress continuum background. We apply a criterion on the BDT output based on the figure-of-merit optimisation. Figure 1 shows 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-liklihood 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} [1].
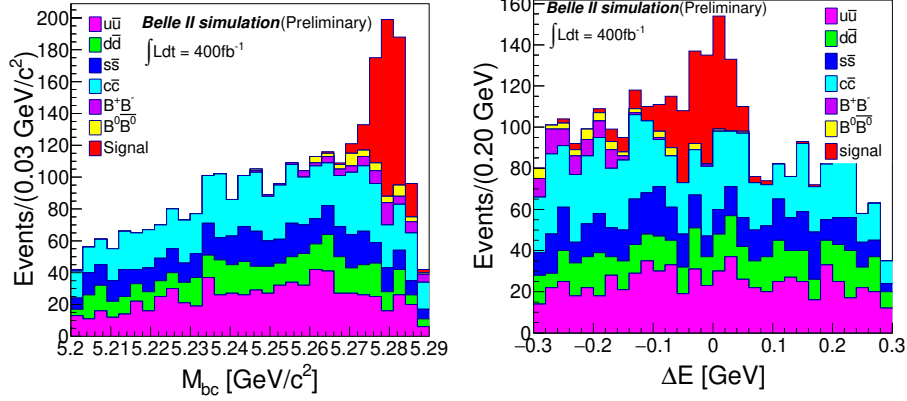
Fig. 1: M_{bc} and ΔE distributions obtained after the continuum suppression.

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

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

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 M_{bc} and ΔE distributions. We fix the yield and PDF shape of the $B\bar{B}$ background category in the fit.

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

Event category	M_{bc}	ΔE
Signal	Crystal Ball + Gaussian	Double-sided Crystal Ball + Gaussian
$B\bar{B}$	Two-dimensional kernel estimation PDF	
$q\bar{q}$	ARGUS	Chebychev polynomial

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

4   Summary

The decay $B^0 \to K_S^0 \pi^0$ is golden chanel at Belle II for a precise measurement of time-dependent CP asymmetry and branching fraction. We have deployed
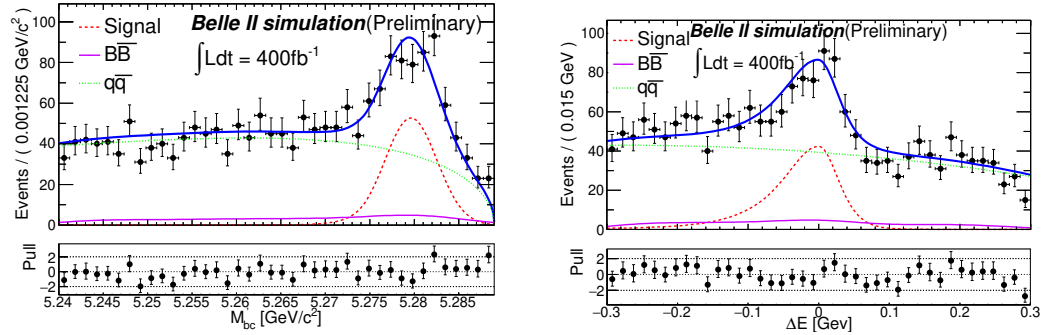
Fig. 2: Projections of M_{bc} and ΔE obtained with the maximum-likelihood fit.

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

a multivariate analysis method to suppress backgrounds and performed an un-binned maximum-liklihood fit to extract the signal yield. We are now developing a time-dependent CPV analysis framework and expect to have the preliminary result soon.

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