Study of $B^+ \to J/\psi\ K^{*+}(\to K_S^0\pi^+)$ decays

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Abstract

We report a study for reconstruction of the decay chain of $B^0 \to J/\psi K^{*+}$ followed by $J/\psi \to \mu^+\mu^-$, $K^{*+} \to K_S^0\pi^+$ and $K_S^0 \to \pi^+\pi^-$. The vertex displacement in the same decay where the signal $B^+$ vertex is reconstructed using all the available tracks or using only the tracks coming from $K_S^0$ gives an opportunity to investigate possible Data/MC difference in the vertex resolution.

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1. INTRODUCTION

Checking possible difference between experimental data and Monte Carlo simulation (MC) for the $B$ decay vertex resolution is a key ingredient to perform time-dependent $CP$ violation measurements. Among the $b \to s$ or $b \to d$ penguin diagram induced neutral $B$ meson decays, there are several decay modes for which only $K_S^0 \to \pi^+\pi^-$ gives charged track information to reconstruct $B$ decay vertex, for example, $B^0 \to K_S^0 K^0_S K^0_S$, $K_S^0 \pi^0$, $K_L^0 K_L^0$, $K_L^0 \pi^0 \gamma$ and so on. For these decay modes, the $B$ decay vertex is reconstructed by the kinematical fit involving proper constraint on the interaction point (IP) and straight track of $K_S^0$ using its daughter charged pion pair. It is important to confirm there is no significant difference between data and MC for the $K_S^0 \to \pi^+\pi^-$ based $B$ vertex resolution to figure out the vertex resolution function for time-dependent $CP$ violation. Here, the vertex resolution is different from usual cases such as $B^0 \to J/\psi K^0$, $\pi^+\pi^-$ and so on where there are charged daughter tracks directly coming from the $B$ decay vertex. The $B^0 \to J/\psi K^{*+}$ followed by $J/\psi \to \mu^+\mu^-$, $K^{*+} \to K_S^0 \pi^+$ and $K_S^0 \to \pi^+\pi^-$ mode has an advantage compared to the $B \to D^{(*)}\pi$ mode as a calibration sample because it is free from finite charm meson lifetime that gives a sizable smearing in addition to the detector resolution itself. The vertex displacement in the same decay where the signal $B^+$ vertex is reconstructed using all the available tracks or using only the tracks coming from $K_S^0$ gives an opportunity to investigate possible Data/MC difference in the vertex resolution.

2. EVENT SELECTION AND RELEVANT QUANTITIES’ DISTRIBUTIONS FOR THE SIGNAL MC

For charged tracks except for the $K_S^0 \to \pi^+\pi^-$ daughters, we require $|d_x| < 2$ cm and $|d_z| < 5$ cm. For $J/\psi \to \mu^+\mu^-$ reconstruction, both tracks are required to be identified as muons to satisfy $\text{muonID} > 0.2$. The $J/\psi \to \mu^+\mu^-$ candidates are selected by requiring $M_{\mu^+\mu^-} < 3.05 \text{ GeV}/c^2 < M_{\mu^+\mu^-} < 3.15 \text{ GeV}/c^2$ where $M_{\mu^+\mu^-}$ is the di-muon invariant mass. We require $0.491 \text{ GeV}/c^2 < M_{\pi^+\pi^-} < 0.504 \text{ GeV}/c^2$ to select $K_S^0 \to \pi^+\pi^-$ candidates. In order to select $K^{*+} \to K_S^0 \pi^+$ (and c.c.), the pion candidate track is required to satisfy $\text{pionID} > 0.05$ to reject obvious kaon and proton tracks. The $K^{*+}$ candidates are selected by
requiring $0.8 \text{ GeV}/c^2 < M_K\pi < 1.0 \text{ GeV}/c^2$ where $M_K\pi$ denotes the $K\pi$ invariant mass. The events having at least one candidate satisfying $-0.3 \text{ GeV} < \Delta E < 0.3 \text{ GeV}$ and $5.2 \text{ GeV}/c^2 < M_{bc} < 1.0 \text{ GeV}/c^2$ where $M_{bc}$ denotes the $K$ invariant mass. The 45 events having at least one candidate satisfying $-0.06 \text{ GeV} < \Delta E < 0.04 \text{ GeV}$ and $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ are retained for further analysis. When multiple candidates are found in one event, we select the one having the highest $\chi^2$-$p$-value. The resultant $M_{bc}$ and $\Delta E$ distributions are shown in Fig. 1. We define $B$ candidate signal box as $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ and $-0.06 \text{ GeV} < \Delta E < 0.04 \text{ GeV}$.

![Belle II simulation](image1)

**FIG. 1.** $M_{bc}$ (left) distribution in $-0.06 \text{ GeV} < \Delta E < 0.04 \text{ GeV}$ region and $\Delta E$ (right) distribution in $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ for the signal MC events.

Calling the TreeFit program, we can reconstruct $B$ decay vertex where $J/\psi \rightarrow \mu^+ \mu^-$ is dominant to determine the vertex position. While, to see the $K_S^0 \rightarrow \pi^+ \pi^-$ contribution to obtain the $B$ vertex, the $z_0$ and $d_0$ errors are 1000 times inflated for the $J/\psi$ daughter muon and the pion promptly coming from $K^{*+}$ decay tracks[1]. The $z$-residual to be defined as the difference between the reconstructed and generated $z$ coordinates and its distributions for two different vertex reconstruction methods are shown in Fig.2.

![Belle II simulation](image2)

**FIG. 2.** Distributions of $z$-residual, difference between the reconstructed and generated $z$ coordinates of the $B$ decay vertex with usual (left) and $K_S^0 \rightarrow \pi^+ \pi^-$-based (right) cases for the signal MC events in the signal region. Fit with triple Gaussian is performed and the standard deviation is obtained by the weighted average of three Gaussian’s spread: $\sigma = 15.9 \pm 0.5 \mu m$ and $157.7 \pm 1.5 \mu m$ for usual and $K_S^0 \rightarrow \pi^+ \pi^-$-based $B$ vertex reconstruction cases, respectively.

As the quantity we can directly compare between Data and MC, the $z_{\text{diff}} \equiv z_{\text{usual}} - z_{K_S^0}$ is thought to be functional, where $z_{\text{usual}}$ and $z_{K_S^0}$ are the $z$ coordinate for the usual and the $K_S^0 \rightarrow \pi^+ \pi^-$-based $B$ decay vertex reconstruction cases. The $z_{\text{diff}}$ distribution for the signal
MC events found in the signal region is shown in Fig. 3. As expected, we found the spread of $z$ distribution is dominated by the $B$ decay vertex resolution by the $K_S^0 \rightarrow \pi^+\pi^-$-based reconstruction.

![Belle II simulation]

**FIG. 3.** Distributions of $z_{\text{diff}} = z_{\text{usual}} - z_{K_S^0}$ where $z_{\text{usual}}$ and $z_{K_S^0}$ are the $z$ coordinate for the usual and the $K_S^0 \rightarrow \pi^+\pi^-$-based $B$ decay vertex reconstruction cases. Fit with triple Gaussian is performed and the standard deviation is obtained by the weighted average of three Gaussian’s spread: $\sigma = 150.9 \pm 1.5 \mu m$.

### 3. ANALYSIS ON THE EXPERIMENTAL DATA

We analyzed the Belle II data collected on $\Upsilon(4S)$ resonance corresponding to 362 fb$^{-1}$. The resultant $M_{bc}$ and $\Delta E$ distributions is shown in Fig. 4. From the fit, we found $939 \pm 33$ signal events and $85 \pm 22$ background events in the signal region defined as $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ and $-0.06 \text{ GeV} < \Delta E < 0.04 \text{ GeV}$. Since expected background MC $M_{bc}$ distribution exhibits a small peak at the same position as signal as shown in Fig. 7, the possible difference of the estimated background events is derived by the MC distribution and it is found to be 110 events.

![Belle II (preliminary)]

**FIG. 4.** $M_{bc}$ (left) distribution in $-0.06 \text{ GeV} < \Delta E < 0.04 \text{ GeV}$ region and $\Delta E$ (right) distribution in $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ in the Belle II experimental data corresponding to 362 fb$^{-1}$. For $M_{bc}$ distribution, the fit with Gaussian signal + ARGUS background is performed and its result is drawn as the lines to express total (blue solid line) and background (red dashed line).

As for the $z_{\text{diff}}$ distribution, the background probability density function (PDF) is determined by the $M_{bc}$ sideband ($5.20 \text{ GeV}/c^2 < M_{bc} < 5.27 \text{ GeV}/c^2$ and $-0.06 \text{ GeV} < \Delta E <$
0.04 GeV) events as shown in Fig. 5. It is fitted with Gaussian and mean ($\mu$) and standard deviation ($\sigma$) are found to be $\mu = 8.4 \pm 9.0 \, \mu m$ and $\sigma = 140 \pm 7 \, \mu m$, respectively.

FIG. 5. The $z_{\text{diff}} \equiv z_{\text{usual}} - z_{K^0_S}$ distribution in the $M_{bc}$ sideband ($5.20 \, \text{GeV}/c^2 < M_{bc} < 5.27 \, \text{GeV}/c^2$ and $-0.06 \, \text{GeV} < \Delta E < 0.04 \, \text{GeV}$) region. The Gaussian’s mean mean ($\mu$) and standard deviation ($\sigma$) are found to be $\mu = 8.4 \pm 9.0 \, \mu m$ and $\sigma = 140 \pm 7 \, \mu m$, respectively.

The signal $z_{\text{diff}}$ distribution is fitted with double Gaussian for signal and the background PDF determined by the $M_{bc}$ sideband events. The standard deviation of the signal distribution is found to be $\sigma = 142 \pm 7 \, \mu m$ where statistical error only quoted. Systematic uncertainty is estimated by varying background PDF’s $\mu$, $\sigma$ and background fraction and corresponding effects are found to be negligible, $\pm 1 \, \mu m$ and $\pm 1 \, \mu m$, respectively. Changing the background from 85 events to 110 events to estimate potential peaking background’s effect, the resultant $z_{\text{diff}}$ spread change is found to be 1 $\mu m$. Summing up them in quadrature results in $\pm 1.7 \, \mu m$, so the $z_{\text{diff}}$ standard deviation is quoted to be $\sigma = 142 \pm 7(\text{stat}) \pm 2(\text{syst}) \, \mu m$. Compared to the one in MC, $\sigma = 150.9 \pm 1.5 \, \mu m$, we see a good agreement between Data and MC. Currently the resolution function for the $K^0_S \to \pi^+\pi^-$-based $B$ decay vertex reconstruction is mainly based on the knowledge obtained by the MC and validated with a possible control sample. The result by this work gives a strong support for currently taken procedure to compose vertex resolution function for $K^0_S \to \pi^+\pi^-$-based $B$ decay vertex reconstruction by carrying out an independent study.

FIG. 6. The $z_{\text{diff}}$ distribution in the Data signal box. The signal component is described by double Gaussian and its spread is found to be $\sigma = 142 \pm 7(\text{stat}) \pm 2(\text{syst}) \, \mu m$. 

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4. MATERIALS THAT MAY BE INCLUDED IN BACKUP SLIDES

Generic MC sample is also visited to estimate amount of the background. As shown in Fig. 7, the $B^+ \rightarrow J/\psi K^{*+}$ mode is expected to have high purity ~ 90%. Comparison between Data and signal MC $z_{\text{diff}}$ distributions is shown in Fig. 8.

![Figure 7](image1.png)  
**FIG. 7.** $M_{bc}$ (left) distribution in $-0.06 \text{ GeV} < \Delta E < 0.04 \text{ GeV}$ region and $\Delta E$ (right) distribution in $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ for the background MC events where the signal MC expectation is superimposed.

![Figure 8](image2.png)  
**FIG. 8.** The $z_{\text{diff}}$ distribution to compare Data and signal MC.

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Appendix A: Event generation

Since the $B^+ \rightarrow J/\psi K^{*+}$ mode is a Pseudo-Scalar to Vector Vector ($P \rightarrow VV$) decay, the final state is a linear combination of three amplitudes. Usually the decay amplitude is
expressed by the two transverse polarization amplitudes ($H_+$ and $H_-$) and one longitudinal polarization amplitude ($H_0$) basis. Experimentally, common formula is the transversity basis that is expressed as the linear combination of $H_+$, $H_-$ and $H_0$;

\begin{align*}
  A_{\parallel} &= \frac{H_+ + H_-}{\sqrt{2}} \\
  A_{\perp} &= \frac{H_+ - H_-}{\sqrt{2}} \\
  A_0 &= H_0.
\end{align*}

(A1)

(A2)

(A3)

Since the SVVHELAMP model in the EvtGen generator is based on the $H_+$, $H_-$ and $H_0$ formalism, the $B \to J/\psi K^*$ decay’s polarization measurement presented by the $A_{\parallel}$, $A_{\perp}$ and $A_0$ basis in PDG was converted.

[1] H. Tanigawa developed the code to inflate specific tracks’ $d_0$ and $z_0$ errors to see other tracks’ contribution to determine the parent $B$ decay vertex.