Search for $B$ Meson Decays to $\omega K^{*0}$

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We report a search for the charmless vector-vector decay \( B^0 \to \omega K^* \) with \( 520 \times 10^6 \) \( B \overline{B} \) pairs collected with the Belle detector at the KEKB \( e^+e^- \) collider. We measure the branching fraction in units of \( 10^{-6} \):

\[
B(B^0 \to \omega K^*) = 1.2^{+0.9}_{-0.8} \pm 0.2 \left( < 2.7 \right),
\]

where the first error is statistical, the second systematic, and the upper limit is at the 90% confidence level.

Recently, \( b \to s \bar{q}q \) penguin decays have received much attention in the literature. These decays proceed via an internal loop diagram and thus are potentially sensitive to new types of propagators and couplings. Such decays have sometimes yielded unexpected results, e.g., the \( b \to s \bar{u}u \) decay \( B^0 \to K^+\pi^- \) exhibits substantial direct \( CP \) violation \cite{1,2}, and the \( b \to s \bar{s}s \) decay \( B \to \phi K^* \) exhibits large transverse polarization \cite{3,4}. This latter observation implies that non-factorizable contributions to the decay amplitude play a significant role. Here we search for the \( b \to s \bar{d}d \) decay \( B^0 \to \omega K^{*0} \) (Fig. 1), which has not yet been observed \cite{5,6}. The expected standard model (SM) rate is small \cite{7}, and observing an enhancement above this rate could indicate new physics. Furthermore, \( B^0 \to \omega K^{*0} \) decays can be useful for determining the Cabibbo-Kobayashi-Maskawa (CKM) angle \( \phi_3 (= \gamma) \) \cite{8}.

This analysis uses 479 fb\(^{-1}\) of data containing \( 520 \times 10^6 \)
$B \bar{B}$ pairs. The data was collected with the Belle detector \cite{10} at the KEKB \cite{11} $e^+e^-$ asymmetric-energy (3.5 GeV on 8.0 GeV) collider with a center-of-mass (CM) energy at the $\Upsilon(4S)$ resonance. The production rates of $B^0\bar{B}^0$ and $B^+B^-$ pairs are assumed to be equal.

The Belle detector is a large-solid-angle spectrometer. It consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect $K\pi$ pairs. The data was collected with the Belle detector \cite{15} and define signal regions $-0.10 \text{ GeV} < \Delta E < 0.06 \text{ GeV}$ and $5.27 \text{ GeV} c^2 < M_{bc} < 5.29 \text{ GeV} c^2$.

The dominant source of background arises from random combinations of particles in continuum $e^+e^- \rightarrow q\bar{q}$ events ($q = u, d, s, c$). To discriminate spherical-like $B\bar{B}$ events from jet-like $q\bar{q}$ events, we use event-shape variables, specifically, 16 modified Fox-Wolfram moments combined into a Fisher discriminant, $F_{13}$. Additional discrimination is provided by $\theta_B$, the polar angle in the CM frame between the $B$ direction and the negative direction of the positron beam axis. True $B$ mesons follow a $1 - \cos^2 \theta_B$ distribution, while candidates in the continuum are approximately uniformly distributed in $\cos \theta_B$.

The displacement along the beam axis between the signal $B$ vertex and that of the other $B$, $\Delta z$, is also used. This variable provides discrimination against continuum events, whose tracks typically have a common vertex.

Further discrimination against continuum background is achieved through the use of $b$-flavor tagging information. The flavor of the $B$ meson accompanying the signal candidate is identified via its decay products: charged leptons, kaons, and $\Lambda$s. The Belle tagging algorithm \cite{14} yields the flavor of the tagged meson, $q$ ($= \pm 1$), and a flavor-tagging quality factor, $r$. The latter ranges from zero for no flavor discrimination to one for unambiguous flavor assignment. For signal events, $q$ is usually consistent with the flavor opposite to that of the signal $B$, while it is random for continuum events. Thus, the quantity $q r F_B$ is used to separate signal and continuum events, where $F_B$ is the flavor of the signal $B$ as indicated by the charge of the final state kaon: $F_B = +1(-1)$ for $B^0 (\bar{B}^0)$.

We use Monte Carlo (MC) simulated signal \cite{15} and data sideband events (defined as $5.20 \text{ GeV} c^2 < M_{bc} < 5.26 \text{ GeV} c^2$, $|\Delta E| < 0.2 \text{ GeV}$) to form $F$ and obtain the $\cos \theta_B$, $\Delta z$, and $q r F_B$ distributions. Our signal MC is generated to be 50% longitudinally polarized ($f_L = 0.5$). Probability density functions (PDFs) derived from $F$, the $\cos \theta_B$ distributions, and the $\Delta z$ distributions are multiplied to form signal ($L_S$) and continuum background ($L_{\bar{q}q}$) likelihood functions. These are combined to form a likelihood ratio $R = L_S / (L_S + L_{\bar{q}q})$. We divide the events into six bins of $q r F_B$ and determine the optimum $R$ selection criteria for each bin by maximizing

\[ R = \frac{L_S}{L_S + L_{\bar{q}q}} \]

FIG. 1: Penguin diagram for $B^0 \rightarrow \omega K^{*0}$ decays.
components of the \( q \) for event ground (b decay background). We choose the best candidate in an event to be the one that minimizes the quantity preserves 50% of the signal while rejecting 99% of background events estimated to be in the signal region. We refer that 8.5% of signal decays have at least one particle included unbinned ML fit to \( \Delta E \) (1).

![Figure 2: Projections of \( \Delta E \) (a), \( M_{bc} \) (b), \( M_{\pi\pi} \) (c) and \( M_{K\pi} \) (d) for events in the signal region of the other three variables. The solid curve is the fit function, the dashed curve is the \( B^0 \rightarrow \omega K^{*0} \) component, the dot-dashed curve is the \( B^0 \rightarrow \omega K^{*+}\pi^- \) component, and the dotted curve is the sum of the \( q\bar{q} \), \( b \rightarrow c \) and \( b \rightarrow s, u, d \) components.

The likelihood function for event \( i \) is defined as

\[
\mathcal{L} = \frac{e^{-(\sum Y_j)}}{N!} \prod_{i=1}^{N} \sum_{j} Y_j P_j^i,
\]

where \( Y_j \) is the yield of events from component \( j \) and \( N \) is the total number of events in the sample.

The results of the fit are shown in Fig. 2. We find strong peaking in \( \Delta E \), \( M_{bc} \) and \( M_{\pi\pi} \), which have shapes consistent with those observed in MC simulations. However, we do not observe a strong \( K^{*0} \) resonance. Instead, we observe a high density of events in the upper sideband of the \( M_{K\pi} \) distribution, which the fit assigns to non-resonant decays. The branching fraction is evalu-
Calculate the data/MC efficiency ratio for the 
520
ε
dici
cyber of
ated using the following quantities: 
Y
ωKπ
floating the non-resonant
tions by
SCF and
The sources of systematic error are listed in Table I. The errors on the PDF shapes are obtained by varying 
PDF shape calibration 6
Shape of 
PDF shape calibration 1
The effects of higher 
resonances by calcu-
lated in the positive branching fraction, we use a fourth-order Chebyshev polynomial. In
The Breit-Wigner shape is obtained in the same way as for the four-dimensional fit. For the non-resonant component, we find the shape of the signal + non-resonant and b → s, u, d components are identical to those used in the four-dimensional fit, with the exception that here, we do not model the true-signal and SCF events separately.

To verify the large non-resonant contribution, we fit the background-subtracted 
M
Kπ
distribution to extract the signal yield. To obtain this distribution, we bin the data in 
M
Kπ from [0.75, 1.25] GeV/c² and, for each bin, perform a two-dimensional extended unbinned ML fit to 
ΔE and 
M
bc. The likelihood function consists of three components: signal + non-resonant, 
q
q + b → c, and 
b → s, u, d. We use a single PDF to describe the signal + non-resonant component, since their individual shapes are almost identical in 
ΔE and 
M
bc. A single PDF is also used to model 
q
q + b → c, since in several of the bins, the statistics are too low to model them independently. The 
ΔE and 
M
bc PDFs for the signal + non-resonant and 
b → s, u, d components are identical to those used in the four-dimensional fit, with the exception that here, we do not model the true-signal and SCF events separately. For the 
q
q + b → c PDF, we use a first order Chebyshev polynomial for 
ΔE and an ARGUS function for 
M
bc. We fix the shapes of the signal + non-resonant and 
b → s, u, d components from MC simulation. In the final fit, we fix the fraction of 
b → s, u, d, while allowing the other two normalizations, and the 
ΔE and 
M
bc shapes of the 
q
q + b → c PDF, to vary.

The results are shown in Fig. 3. We perform a χ² fit to this background-subtracted 
M
Kπ distribution. The Breit-Wigner shape is obtained in the same way as for the four-dimensional fit. For the non-resonant component, we use a fourth-order Chebyshev polynomial. In

| Type                                      | Fractional error (%) |
|-------------------------------------------|----------------------|
| Track reconstruction efficiency           | 4.80                 |
| π₀ reconstruction efficiency              | 4.00                 |
| K⁺π⁻ identification efficiency            | 1.33                 |
| ΔE PDF shape calibration                  | 3.46                 |
| M
bc PDF shape calibration                  | 2.12                 |
| Shape of 
PDFs                                 | 3.45                 |
| Shape of true-signal PDF                  | 0.69                 |
| Shape of 
PDFs                                 | 9.02                 |
| Fraction of 
b → s, u, d background       | 2.59                 |
| SCF fraction                              | 5.66                 |
| Possible fitting bias                     | 1.50                 |
| Effect of higher 
resonances |

| N
M
Kπ                                      | 1.31                 |
| Total                                     | 16.1                 |

of the likelihood function in the positive branching fraction region. The systematic error is included by convolving the likelihood function with a Gaussian having a standard deviation equal to the systematic uncertainty. The statistical significance of the signal, defined as \( \sqrt{-2 \ln \mathcal{L}/\mathcal{L}_{\text{max}}} \), where \( \mathcal{L}_{\text{max}} \) (\( \mathcal{L} \)) is the value of the likelihood function when \( Y_{\omega K^{*0}} \) is allowed to vary (set to 0), is 1.6σ.

To verify the large non-resonant contribution, we fit the background-subtracted 
M
Kπ distribution to extract the signal yield. To obtain this distribution, we bin the data in 
M
Kπ from [0.75, 1.25] GeV/c² and, for each bin, perform a two-dimensional extended unbinned ML fit to 
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q + b → c PDF, we use a first order Chebyshev polynomial for 
ΔE and an ARGUS function for 
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b → s, u, d components from MC simulation. In the final fit, we fix the fraction of 
b → s, u, d, while allowing the other two normalizations, and the 
ΔE and 
M
bc shapes of the 
q
q + b → c PDF, to vary.

The results are shown in Fig. 3. We perform a χ² fit to this background-subtracted 
M
Kπ distribution. The Breit-Wigner shape is obtained in the same way as for the four-dimensional fit. For the non-resonant component, we use a fourth-order Chebyshev polynomial. In

FIG. 3: Signal yields obtained from the 
ΔE-
M
bc distribution in bins of 
M
Kπ for events in the \( \omega \) signal region. The solid curve is the fit function, the dashed curve is the \( B^0 \rightarrow \omega K^{*0} \) component, and the dot-dashed curve is the \( B^0 \rightarrow \omega K^+\pi^- \) component.
the final fit, we float the non-resonant shape parameters along with the fractional signal yield. We obtain $Y_{\omega K^0}/(Y_{\omega K^0}+Y_{\omega K^+}) = (9.3\pm10.6)\%$, which is very similar to the result of the four-dimensional fit: $(10.3^{+7.7}_{-7.0})\%$.

In summary, we present a measurement of the branching fraction of $B^0 \to \omega K^{*0}$ decays using $520 \times 10^6 B\bar{B}$ pairs. The statistical significance of our signal yield is only $1.6\sigma$, and thus we set an upper limit of $B < 2.7 \times 10^{-6}$ at the 90% C.L. Our result is in agreement with theoretical estimates [7]. The limit obtained is below the previous constraint from BaBar [6] by a factor of 1.6. In addition, we observe a large rate for non-resonant $B^0 \to \omega K^+ \pi^-$ decays.

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