Observation of the decay $B^0 \to \eta' K^*(892)^0$

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Abstract

We report a search for charmless hadronic decays of neutral $B$ mesons to $\eta'K^*(892)^0$. The results are based on a 711 fb$^{-1}$ data sample that contains $772 \times 10^6 B\bar{B}$ pairs, collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy $e^+e^-$ collider. We observe the decay for the first time with a significance of 5.0 standard deviations and obtain its branching fraction $B[B^0 \rightarrow \eta'K^*(892)^0] = [2.6 \pm 0.7(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-6}$. We also measure the $CP$ violating asymmetry as $A_{CP}[B^0 \rightarrow \eta'K^*(892)^0] = -0.22 \pm 0.29(\text{stat}) \pm 0.07(\text{syst})$.

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Two-body charmless decays of $B$ mesons are known to be a powerful probe for testing the standard model (SM) predictions as well as to search for new physics [1]. Decays to final states containing $\eta$ and $\eta'$ mesons exhibit a distinct pattern of interferences among the dominant contributing amplitudes and are also sensitive to a potentially large flavor-singlet contribution [2].

Owing to the $\eta$-$\eta'$ mixing, $b \to s$ penguin and $b \to u$ tree processes contribute to charmless $B$ decays with an $\eta$ or $\eta'$ in the final state [3]. The interference of these processes is constructive for the $\eta'/K$ and $\eta K^*$ final states, whereas it is destructive for $\eta K$ and $\eta' K^*$. Therefore, the $B \to \eta K$ and $B \to \eta' K^*$ decays are suppressed and thus provide a good test bed to search for possible contributions from new physics that could be manifested in the loop diagram. The destructive penguin amplitude could also interfere with the small $b \to u$ tree diagram, giving rise to a large direct $CP$ violation. Recent measurements in $B \to \eta K$ from $\mathcal{B}$abar [4] and Belle [5] seem to confirm this picture. Direct $CP$ violation in the $B \to \eta' K^*$ decay has not yet been probed, which constitutes a good sample to test the aforementioned interference scheme to expose new physical contributions for the $\eta^{(*)}_c K^{(*)}$ system. Furthermore, the study of time-dependent $CP$ asymmetry in $B^0 \to \eta' K^*(892)^0$, $K^*(892)^0 \to K^0 \pi^0$ can add useful information to an existing intriguing effect seen in the loop-dominated $b \to s q \bar{q} (q = u, d, s)$ decays compared to the tree-level $b \to c \bar{s} s$ transition [5, 8].

The decay $B^0 \to \eta' K^*(892)^0$ has been studied extensively within the framework of perturbative QCD [5], QCD factorization [11], soft collinear effective theory [12], as well as $SU(3)$ flavor symmetry [2], and predicted branching fractions are in the range $(1.2-6.3) \times 10^{-6}$. In the past, both Belle [13] and $\mathcal{B}$abar [14] have searched for $B^0 \to \eta' K^*(892)^0$ with the latter reporting the first evidence with a significance of 4.0 standard deviations ($\sigma$).

The results reported herein are based on a data sample containing $772 \times 10^6 B \bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector [17] at the KEKB asymmetric energy $e^+e^-$ (3.5 on 8.0 GeV) collider [18]. The Belle detector consists of six nested subdetectors: a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight detectors: a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters and iron plates to detect $K^0_L$ mesons and muons (KLM). All but the KLM are located inside a 1.5T solenoidal magnetic field. Two inner-detector configurations were used: a 2.0 cm beampipe and a three-layer SVD for the first sample of $152 \times 10^6 B \bar{B}$ pairs, while a 1.5 cm beampipe, a four-layer SVD and a small-cell CDC for the remaining $620 \times 10^6 B \bar{B}$ events [17]. The latter sample has been reprocessed with an improved track reconstruction algorithm, which significantly increased the signal reconstruction efficiency.

We reconstruct $B^0 \to \eta' K^*(892)^0$ candidates from the subsequent decay channels $\eta' \to \eta \pi^+\pi^-$, $\eta \to \gamma\gamma$ and $K^*(892)^0 \to K^+\pi^-$. Since the background contribution in $\eta' \to \rho\gamma$ is significantly larger than in $\eta' \to \eta \pi^+\pi^-$, the former decay channel is not considered in our study. Because of a low expected signal yield and a poor signal-to-noise ratio, we do not reconstruct $K^*(892)^0 \to K^0\pi^0$. Consequently, time-dependent $CP$ violation in $B^0 \to \eta' K^*(892)^0$ is not treated in this paper.

Charged track candidates are required to have a transverse momentum greater than 0.1 GeV/$c$ and an impact parameter with respect to the interaction point (IP) of less than 0.2 cm in the $r-\phi$ plane and 5.0 cm along the $z$ axis. Here, the $z$ axis is defined as the direction opposite the $e^+$ beam. To distinguish charged kaons from pions, we use a likelihood ratio $R_{K/\pi} = L_K/(L_K + L_\pi)$, where $L_K$ ($L_\pi$) denotes the likelihood for a track being a kaon (pion) and is calculated using specific ionization in the CDC, time-of-flight information from the TOF and the number of photoelectrons from the ACC. Based on this quantity, we select charged tracks to reconstruct the $\eta'$ and $K^*(892)^0$ candidates. Since few fake $\eta'$ arising from misidentification of pions are expected, we apply looser conditions for pion candidates in the $\eta'$ reconstruction. Typical average efficiencies and fake rates in the entire
momentum range for the kaon and pion selections are 90% and 5%, respectively. When applying the looser selection for pions, these are 95% and 10%, respectively. To reconstruct $\eta$ candidates, photons originating from their decays are required to have an energy greater than 0.1 GeV in the ECL and an energy balance—the ratio between the absolute difference and the sum of the two photon energies—of less than 0.9. The $\eta$ candidates must satisfy $0.510 \text{ GeV}/c^2 < M_\eta < 0.575 \text{ GeV}/c^2$, corresponding to $\pm 2.5\sigma$ around the nominal $\eta$ mass $[15]$. The $\eta'$ candidates are required to satisfy $0.950 \text{ GeV}/c^2 < M_{\eta'} < 0.965 \text{ GeV}/c^2$, corresponding to $\pm 2.5\sigma$ around the nominal $\eta'$ mass $[18]$. Finally, the $K^*(892)^0$ candidates must have $0.820 \text{ GeV}/c^2 < M_{K^*(892)^0} < 0.965 \text{ GeV}/c^2$.

We identify $B$ candidates using two kinematic variables: the beam-energy constrained mass, $M_{bc} = \sqrt{E_{\text{beam}}^2 - |\sum_i p_i|^2}$, and the energy difference, $\Delta E = \sum_i E_i - E_{\text{beam}}$, where $E_{\text{beam}}$ is the beam energy, and $p_i$ and $E_i$ are the momentum and energy, respectively, of the $i$-th daughter of the reconstructed $B$ candidate in the $e^+e^-$ center-of-mass (CM) frame. In order to improve the $\Delta E$ resolution, the invariant mass of the $\eta$ ($\eta'$) candidate is constrained to its world-average value $[15]$. Signal events typically peak at the nominal $B$-meson mass for $M_{bc}$ and at zero for $\Delta E$. We retain events with $M_{bc} > 5.22 \text{ GeV}/c^2$ and $-0.20 \text{ GeV} < \Delta E < 0.15 \text{ GeV}$ for further analysis.

The average number of reconstructed $B$ candidates per event is 1.1. In events with multiple $B$ candidates, we select the one having the smallest value of $\chi^2 = \chi^2_{\eta'} + \chi^2_{K^*(892)^0}$, where $\chi^2_{\eta'}$ and $\chi^2_{K^*(892)^0}$ are the vertex-fit quality measures for $\eta'$ and $K^*(892)^0$ candidates, respectively. The probability to select the correct signal candidate is about 94% after all selection criteria.

The dominant background arises from the $e^+e^- \rightarrow q\overline{q}$ continuum process, where $q$ denotes $u$, $d$, $s$ or $c$. To suppress this background, we employ a neural network $[19]$ combining the following six variables. We use the cosine of the angle in the CM frame between the thrust axis of the $B$ decay and all other reconstructed particles and a Fisher discriminant formed out of 16 modified Fox-Wolfram moments $[20]$. These two quantities distinguish the spherical topology of $B$ decay events from the jet-like continuum events. As the $B$ meson has a finite lifetime, the separation along the $z$ axis between the signal $B$ vertex and that of the recoiling $B$ is used to separate signal from continuum events in which most of the particles originate from the IP. The expected $B$-flavor dilution factor that ranges from zero for no flavor tagging to unity for unambiguous flavor assignment, calculated using recoiling $B$ decay information $[21]$, also helps in distinguishing signal from continuum background. Owing to the difference in spin configurations of the decay, some discrimination power is inherent in the distribution of the following two observables: the cosine of the angle between the $B$ flight direction and the $z$ axis in the CM frame, and the cosine of the angle between the daughter $\gamma$ and parent $B$ momenta in the $\eta$ rest frame.

The training and optimization of the neural network are accomplished with signal and continuum Monte Carlo (MC) events. The signal sample is generated using the EvtGen program $[22]$ based on a model of the two-body decay of a pseudoscalar to a vector and a pseudoscalar, that incorporates the effect of final state radiation. The neural network output ($C_{NB}$) lies in the range $[-1.0, +1.0]$, with the events near $-1.0$ (+1.0) being more continuum (signal)-like. We apply a criterion $C_{NB} > -0.3$ to substantially remove continuum events. With this requirement, we retain about 91% of signal while rejecting 82% of the $q\overline{q}$ background. The remainder of the $C_{NB}$ distribution has a strong peak near +1.0 for signal and hence is difficult to model with a simple function. Instead, we use the transformed quantity

$$C_{NB}' = \ln\left(\frac{C_{NB} - C_{NB,\text{low}}}{C_{NB,\text{high}} - C_{NB}}\right),$$

where $C_{NB,\text{low}} = -0.3$ and $C_{NB,\text{high}} = +1.0$, to improve the robustness of the analytical modeling.
To study potential backgrounds from $B$ decays, we use a mixture of generic and rare $B\bar{B}$ MC samples. The former is dominated by decays induced by $b \to c$ transition with relatively large branching fractions while the latter consists of rare decays induced by $b \to u, d, s$ transitions. The number of background events expected from both samples is quite small. Some rare $B\bar{B}$ backgrounds exhibit a peaking structure in the $M_{bc}$ and $\Delta E$ distributions. The $B^+ \to \eta' K^+$, $B^0 \to \eta' K^0_S$ and $B^0 \to \eta' K^+ \pi^-$ decays might mimic our signal. The $\Delta E$ peak is expected to be shifted from zero in the first two decays because of the loss of final-state particles or particle misidentification. To suppress their contributions, we reconstruct the $B^+ \to \eta' K^+$ and $B^0 \to \eta' K^0_S$ with each of these hypotheses and reject the event if the reconstructed $B$ meson has $M_{bc} > 5.27 \text{GeV}/c^2$ and $|\Delta E| < 0.20 \text{GeV}$. From the study with a large-statistics MC sample, we expect about ten $B^+ \to \eta' K^+$ and four $B^0 \to \eta' K^0_S$ events before this rejection and only five and one, respectively, with it while keeping 99% of signal events.

Contributions from the $B^0 \to \eta' K^+ \pi^-$ (nonresonant) decay cannot be suppressed with the above method as the final state is identical to signal. In the fit procedure (described later) to extract signal, we fix the nonresonant background yield to two events, which corresponds to a branching fraction of $3.0 \pm 1.0 \times 10^{-6}$, estimated using the MC sample. For the validation of this expected number, we have checked the background contribution using experimental data in the mass sideband of $1.0 \text{GeV}/c^2 < M_{K^*(892)} < 1.2 \text{GeV}/c^2$, and later extrapolated into the region used for our analysis. The $M_{K^*(892)}$ distribution in the nonresonant background decay is obtained by assuming a phase-space model. The nonresonant background contribution in the full data sample is estimated to be $3\pm4$ events, which is equivalent to a branching fraction of $(4.7\pm5.4) \times 10^{-6}$ and consistent with the two events from the MC sample. The difference of expected nonresonant background yields between the two strategies is incorporated into the systematic uncertainty.

We perform an unbinned extended maximum likelihood fit to the $M_{bc}$, $\Delta E$, $C'_{\text{NB}}$ and $\cos \theta_H$ distributions of candidate events to extract the signal yield. The helicity angle $\theta_H$ is defined as the angle between the momenta of the daughter charged kaon and the parent $B$ meson in the $K^*(892)^0$ rest frame. From an ensemble test of many pseudoexperiments, we find that $\cos \theta_H$ plays an important role in disambiguating the signal and nonresonant components, especially when the expected signal yield is small. We define a probability density function (PDF) for each event category $j$ (signal, continuum $q\bar{q}$, generic $B\bar{B}$, rare $B\bar{B}$ and nonresonant background) as:

$$P^i_j \equiv P_j(M_{bc})P_j(\Delta E)P_j(C'_{\text{NB}})P_j(\cos \theta_H),$$

where $i$ denotes the event index. As the correlation between each pair of fit observables is found to be small, the product of four individual PDFs is used as a good approximation for the true PDF. The likelihood function used in the fit is

$$\mathcal{L} = \exp \left( -\sum_j N_j \right) \prod_i \left[ \sum_j N_j P^i_j \right],$$

where $N_j$ is the yield for event category $j$. For the signal, the correctly reconstructed $B$ meson decays are referred to as the right-combination (RC) component while the misreconstructed decays are denoted as the self-crossfeed (SCF) component. They are treated distinctly in the fitter with a combined PDF $N_{\text{sig}} \times \left[ f P_{\text{RC}} + (1-f) P_{\text{SCF}} \right]$, where $N_{\text{sig}}$ is the total signal yield and $f$ is the RC fraction fixed to the value (94.5%) determined from MC simulations.

Table lists the PDF shapes used to model the $M_{bc}$, $\Delta E$, $C'_{\text{NB}}$ and $\cos \theta_H$ distributions for each event category. The PDF distributions that are difficult to parametrize analytically are modeled using MC events either as histograms or smoothed shapes obtained with a kernel density estimation algorithm (Keys) [23].

The yields for all event categories except for the rare $B\bar{B}$ and nonresonant components are allowed to vary in the fit. The relative contributions of the rare $B\bar{B}$ and nonresonant
background categories are very small and thus fixed to their MC values (1.2% and 0.7%, respectively). All signal shape parameters are fixed during the signal extraction after correcting them for possible differences between data and MC simulations using a high-statistics control sample whose final states are similar to the signal. For $M_{bc}$ and $C'_{NB}$, $B^0 \rightarrow \eta'K_S^0$ is used as the control sample. The $B^0 \rightarrow D^0\rho^0$ decay with $D^0 \rightarrow K^+\pi^-\pi^0$ and $\rho^0 \rightarrow \pi^+\pi^-$ is used to estimate the $\Delta E$ correction factors as the ones obtained from $B^0 \rightarrow \eta'K_S^0$ are not sufficiently accurate.

Table I: List of PDFs used to model $M_{bc}$, $\Delta E$, $C'_{NB}$ and $\cos\theta_H$ for the event categories. G (2G), BifG (2BifG), CB, P$_i$, ARGUS, and Hist denote single (double) Gaussian, single (double) bifurcated Gaussian, Crystal Ball [24], $i$-th order Chebyshev polynomial, ARGUS function [25], and histogram, respectively.

| Component                | $M_{bc}$ | $\Delta E$ | $C'_{NB}$ | $\cos\theta_H$ |
|--------------------------|----------|------------|-----------|-----------------|
| Signal (RC)              | CB       | CB+BifG    | 2BifG     | Hist            |
| Signal (SCF)             | Hist     | Hist       | Hist      | Hist            |
| Continuum $q\bar{q}$     | ARGUS    | P$_1$      | 2G        | Hist            |
| Generic $B\bar{B}$       | ARGUS    | P$_2$      | BifG      | Hist            |
| Rare $B\bar{B}$          | Hist     | Hist       | BifG      | Hist            |
| Nonresonant background   | Hist     | Hist       | Hist      | Hist            |

Figure 1 shows the $M_{bc}$, $\Delta E$, $C'_{NB}$ and $\cos\theta_H$ projections of the result of the fit to data. We obtain $31 \pm 9$ signal, $2564 \pm 95$ continuum $q\bar{q}$, and $253 \pm 82$ generic $B\bar{B}$ events. From the extracted yields, we obtain a significance of 6.0$\sigma$, where the significance is defined as $\sqrt{-2\ln(L_0/L_{max})}$ with $L_{max}$ ($L_0$) being the likelihood value when the signal yield is allowed to vary (fixed to zero). We calculate the branching fraction $B[B^0 \rightarrow \eta'K^*(892)^0]$ as

$$B = \frac{N_{sig}}{2 \times N_{B^0\bar{B}^0} \times \varepsilon_{rec} \times \varepsilon_{PID} \times \varepsilon_{C_{NB}}} = [2.6 \pm 0.7\,(stat) \pm 0.2\,(syst)] \times 10^{-6},$$

where $2 \times N_{B^0\bar{B}^0}$ is the total number of $B^0$ and $\bar{B}^0$ ($772 \times 10^6$); $\varepsilon_{rec}$ (1.7%) is the signal reconstruction efficiency including all daughter branching fractions, $\varepsilon_{PID}$ is a correction to the efficiency that takes into account the difference between data and MC simulations for pion and kaon identification (94.0%), and $\varepsilon_{C_{NB}}$ is a similar correction factor for the continuum suppression requirement (98.5%). Figure 2 shows the statistical significance convolved with a Gaussian function of width equal to the systematic uncertainty. In the significance calculation, we consider additive systematic uncertainties that affect only the extracted signal yield. There are also multiplicative uncertainties for all efficiency terms and the number of $B^0\bar{B}^0$ pairs [Eq. 3]. The total significance after taking the systematics into account is 5.0$\sigma$.

In addition to the decay branching fraction, we also measure the CP violation asymmetry ($A_{CP}$) by splitting the obtained yields according to the flavor of the decaying $B$ meson, based on the charge of the daughter kaon from the $K^*$ decay. From $N[B^0 \rightarrow \eta'K^*(892)^0] = 12 \pm 6$ and $N[B^0 \rightarrow \eta'K^*(892)^0] = 19 \pm 6$, we obtain $A_{CP}$ for the decay as

$$A_{CP} = \frac{N[B^0 \rightarrow \eta'K^*(892)^0] - N[B^0 \rightarrow \eta'K^*(892)^0]}{N[B^0 \rightarrow \eta'K^*(892)^0] + N[B^0 \rightarrow \eta'K^*(892)^0]} = -0.22 \pm 0.29\,(stat) \pm 0.07\,(syst),$$

where $N[B^0 \rightarrow \eta'K^*(892)^0]$ are the event yields for branching fractions corresponding to Tables II and III, respectively. The uncertainties due to PDF shape parameters are
FIG. 1: Projections of the fit results onto (a) $M_{bc}$, (b) $\Delta E$, (c) $C_{NB}'$ and (d) $\cos \theta_H$. Each distribution is shown in the signal enhanced regions of the other three observables: $M_{bc} > 5.27\text{ GeV}/c^2$, $-0.10\text{ GeV} < \Delta E < 0.06\text{ GeV}$ and $2.0 < C_{NB}' < 8.0$. Data are points with error bars; the fit results are shown by solid curves. Contributions from signal, continuum $q\bar{q}$, generic $B\bar{B}$ and rare $B\bar{B}$ including nonresonant background are shown by dashed, dotted, dash-dotted, dash-double-dotted curves, respectively.

FIG. 2: Distributions of (a) fit likelihood and (b) $-2\ln(L_0/L_{\text{max}})$ as a function of the branching fraction. Solid curves are after taking the systematic uncertainty into account while dashed ones are only with the statistical uncertainty.

estimated by varying all fixed parameters within their uncertainties. To assign a systematic uncertainty for the fixed histogram PDFs, we perform a series of fits with the contents of each histogram bin fluctuated according to a Poisson distribution. The uncertainties due to the calibration factors used to correct for the signal PDFs are obtained by varying the factors by their uncertainties. We calculate the uncertainty due to the fixed SCF fraction by varying the latter by $\pm 50\%$. The uncertainties that arise from the fixed yield of rare $B\bar{B}$ component are obtained by varying each of the fractions by $\pm 50\%$. The fit bias is evaluated by performing an ensemble test comprising 300 pseudoexperiments, where the signal, rare $B\bar{B}$ and nonresonant background components are picked up randomly from the corresponding MC samples and the PDF shapes are used to generate events for other categories. Due to limited MC statistics, we assign 0.8% uncertainty on the absolute scale of the efficiency. The uncertainty due to the data-MC discrepancy for continuum suppression is obtained using the control sample of $B^0 \rightarrow \eta'K_0^0$. We compare the results of two cases: one with the same $C_{NB}$ requirement as for signal and the other without any requirement. The
difference is then incorporated as a systematic error. The decay $B^0 \to \overline{D}^0 \rho^0$, $\overline{D}^0 \to K^+\pi^−\pi^0$, in which final state particles are common to signal, is used to determine the systematic uncertainty associated with the $\varepsilon_{\text{PID}}$ requirement and, for the $CP$ measurement, that due to detector bias. The systematic uncertainty of the $\eta$ reconstruction efficiency is calculated by comparing data-MC differences of the yield ratio between $\eta \to 3\pi^0$ and $\eta \to \gamma\gamma$. We use partially reconstructed $D^*+ \to D^0(K_0^S\pi^+\pi^-)\pi^+$ decays to obtain the uncertainty due to charged-track reconstruction (0.35% per track). Finally, we calculate the total systematic uncertainty by adding all contributions in quadrature.

TABLE II: Summary of the considered systematic uncertainties for the branching fraction. The upper (lower) part of the table shows the additive and multiplicative uncertainties as described in the text.

| Source                              | Uncertainties (%) |
|-------------------------------------|-------------------|
| Signal PDF                          | ±2.2              |
| $q\overline{q}$ PDF                 | +0.7 −0.9         |
| Generic $B\overline{B}$ PDF         | ±1.1              |
| Rare $B\overline{B}$ PDF            | +0.4 −0.5         |
| Histogram PDF                       | ±0.7              |
| $M_{bc}$ PDF shape calibration      | +1.2 −1.5         |
| $\Delta E$ PDF shape calibration    | +1.1 −0.8         |
| $C'_{\text{NB}}$ PDF shape calibration | +2.4 −2.6   |
| SCF fraction                        | +2.3 −2.2         |
| Rare $B\overline{B}$ fraction       | +2.5 −2.6         |
| Nonresonant background fraction     | ±2.9              |
| Fit bias                            | ±2.8              |
| MC statistics                       | ±0.8              |
| $\varepsilon_{C_{\text{NB}}}$      | ±2.1              |
| $\varepsilon_{\text{PID}}$         | ±3.4              |
| $\eta$ reconstruction               | ±1.5              |
| Track reconstruction                | ±1.4              |
| $N_{B^0\overline{B}^0}$            | ±1.4              |
| Total                               | +8.1 −8.2         |

In summary, we have measured the branching fraction of $B^0 \to \eta'K^*(892)^0$ using the full $\Upsilon(4S)$ data sample collected with the Belle detector. We employ a four-dimensional maximum likelihood fit for extracting the signal yield. Our measurement $\mathcal{B}[B^0 \to \eta'K^*(892)^0] = [2.6 ± 0.7(\text{stat}) ± 0.2(\text{syst})] \times 10^{-6}$ constitutes the first observation of this decay channel with a significance of 5.0σ. We have also measured the $CP$ asymmetry $\mathcal{A}_{CP}[B^0 \to \eta'K^*(892)^0] = −0.22 ± 0.29(\text{stat}) ± 0.07(\text{syst})$, which is consistent with no $CP$ violation.

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TABLE III: Summary of the considered systematic uncertainties for $A_{CP}$.

| Source | Uncertainties |
|--------|---------------|
| Signal PDF | ±0.013 |
| $q\bar{q}$ PDF | +0.001 −0.002 |
| Generic $B\bar{B}$ PDF | +0.005 −0.007 |
| Rare $B\bar{B}$ PDF | < ±0.001 |
| Histogram PDF | ±0.006 |
| $M_{bc}$ PDF shape calibration | ±0.003 |
| $\Delta E$ PDF shape calibration | +0.005 −0.004 |
| $C'_{NB}$ PDF shape calibration | +0.013 −0.009 |
| SCF fraction | +0.001 −0.002 |
| Rare $B\bar{B}$ fraction | +0.005 −0.004 |
| Nonresonant background fraction | +0.004 −0.003 |
| Fit bias | ±0.011 |
| Detector bias | ±0.062 |
| Total | +0.067 −0.066 |

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[1] H.-Y. Cheng and J. G. Smith, *Annu. Rev. Nucl. Part. Sci.* 59, 215 (2009).
[2] M. Beneke and M. Neubert, *Nucl. Phys. B* 651, 225 (2003).
[3] H. J. Lipkin, *Phys. Lett. B* 415, 186 (1997).
[4] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. D* 80, 112002 (2009).
[5] C.-T. Hoi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* 108, 031801 (2012).
[6] Y. Grossman and M. P. Worah, *Phys. Lett. B* 395, 241 (1997).
[7] D. Atwood and A. Soni, *Phys. Lett. B* 405, 150 (1997).
[8] M. Ciuchini, E. Franco, G. Martinelli, A. Masiero, and L. Silvestrini, *Phys. Rev. Lett.* 79, 978 (1997).
[9] A. G. Akeroyd, C. H. Chen, and C. Q. Geng, *Phys. Rev. D* 75, 054003 (2007).
[10] M. Beneke and M. Neubert, Nucl. Phys. B 675, 333 (2003).
[11] W. Wang, Y. M. Wang, D. S. Yang, and C. D. Lu, Phys. Rev. D 78, 034011 (2008).
[12] C.-W. Chiang, M. Gronau, Z. Luo, J. L. Rosner, and D. A. Suprun, Phys. Rev. D 69, 034001 (2004).
[13] J. Schümann et al. (Belle Collaboration), Phys. Rev. D 75, 092002 (2007).
[14] P. del Amo Sanchez et al. (BABAR Collaboration), Phys. Rev. D 82, 011502 (2010).
[15] A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 117 (2002); also, see the detector section in J. Brodzicka et al., Prog. Theor. Exp. Phys., 04D001 (2012).
[16] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A 499, 1 (2003), and other papers included in this volume; T. Abe et al., Prog. Theor. Exp. Phys., 03A001 (2013) and following articles up to 03A011.
[17] Z. Natkaniec et al. (Belle SVD2 Group), Nucl. Instrum. Methods Phys. Res., Sect. A 560, 1 (2006).
[18] J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012).
[19] M. Feindt and U. Kerzel, Nucl. Instrum. Methods Phys. Res., Sect. A 559, 190 (2006).
[20] The Fox-Wolfram moments were introduced in G. C. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581 (1978); the modified moments used in this paper are described in S. H. Lee et al. (Belle Collaboration), Phys. Rev. Lett. 91, 261801 (2003).
[21] H. Kakuno et al. (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 533, 516 (2004).
[22] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A 462, 152 (2001).
[23] K. S. Cranmer, Comput. Phys. Commun. 136, 198 (2001).
[24] T. Skwarnicki, DESY Report No. F31-86-02 (1986).
[25] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 241, 278 (1990).