# Search for $B^0 \to X(3872)\gamma$

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We report the results of a search for the decay $B^0 \to X(3872)(\to J/\psi\pi^+\pi^-)\gamma$. The analysis is performed on a data sample corresponding to an integrated luminosity of 711 fb$^{-1}$ and containing $772 \times 10^6 B\bar{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider running at the $\Upsilon(4S)$ resonance energy. We find no evidence for a signal and place an upper limit of $\mathcal{B}(B^0 \to X(3872)\gamma) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 5.1 \times 10^{-7}$ at 90% confidence level.

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Rare decays of $B$ mesons are sensitive probes to study possible new physics beyond the Standard Model (SM). In the SM, the decay $B^0 \to c\bar{c}\gamma$ proceeds dominantly through an exchange of a $W$ boson and the radiation of a photon from the $d$ quark of the $B$ meson (Fig. 1). Many theoretical predictions of branching fractions depend on the factorization approach of QCD interactions in the decay dynamics. In the case of $B^0 \to J/\psi\gamma$, the branching fraction has been predicted to be $7.65 \times 10^{-9}$ using QCD factorization [1] and $4.5 \times 10^{-7}$ when using a perturbative QCD (pQCD) approach [2]. Possible new physics enhancements of the branching fractions may be due to right-handed currents [1] or nonspectator intrinsic charm in the $B^0$ meson [3]. Currently, the upper limit for $B^0 \to J/\psi\gamma$ is $1.5 \times 10^{-6}$ at 90% confidence level [4].

The exotic $X(3872)$ state, first observed by the Belle experiment in 2003 [5], is now one of the most well-studied charmoniumlike exotic states. Aside from pure charmonium, it may also be a $D^0\bar{D}^{*0}$ molecule [6], a tetraquark state [7], or a mixture of a molecule and a charmonium [8]. Since $X(3872)$ may, unlike the $J/\psi$, contain components other than pure charmonium, the branching fraction of $B^0 \to X(3872)\gamma$ should be smaller than that of $B^0 \to J/\psi\gamma$ which proceeds through the $b \to c\bar{c}\,d$ process. No former search for this decay has been published yet.

Our measurement is based on a data sample corresponding to an integrated luminosity of 711 fb$^{-1}$ that contains $772 \times 10^6 B\bar{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8 GeV) collider [9] running at the $\Upsilon(4S)$ resonance. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrellike arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL), all located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return yoke located outside the solenoid is instrumented to detect and identify $K_L^0$ mesons and muons (KLM). The detector is described in detail elsewhere [10].

Two inner detector configurations are used in this analysis. A beam pipe of radius 2.0 cm and a 3-layer SVD were used for the first data set of 140 fb$^{-1}$, while a beam pipe of 1.5 cm radius and a 4-layer SVD silicon detector were used to record the remaining data set of 571 fb$^{-1}$ [11]. All the Monte Carlo (MC) samples in this

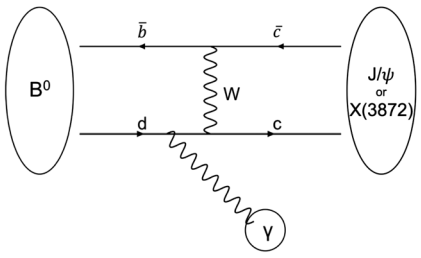



FIG. 1. A Feynman diagram of $B^0 \to c\bar{c}\gamma$.

analysis are generated by the EvtGen package [12] and the response of the Belle detector is simulated by the Geant3 package [13]. QED final-state radiation (FSR) is simulated using the photos package [14]. These samples are used to optimize the selection criteria and determine the signal detection efficiency. Simulation assumes that the $X(3872)$ decays to $J/\psi\pi^+\pi^-$ entirely via $J/\psi\rho^0$. The $J/\psi$ then decays to two channels: $\mu^+\mu^-$ or $e^+e^-$. Charge-conjugate modes are implied throughout this paper. We generate one million events for each channel. In any given event of signal MC, only one of the two $B$ mesons will decay via the signal mode while the other $B$ meson decays generically. A signal MC event is considered a correctly reconstructed one if it matches the particle type and the momentum difference between the signal MC and the reconstructed tracks is less than 0.05 GeV/$c$.

Selection criteria for the final-state charged particles in $B^0 \to X(3872)\gamma$ are based on information obtained from the tracking systems (CDC and SVD) and the hadron identification systems (CDC, ACC, and TOF). Charged final-state particles are identified using information provided by the CDC, the TOF, the ACC, the ECL, and the KLM. The pion candidates are identified using information from the ACC (number of photoelectrons), the CDC ($dE/dx$), and the TOF. The muon candidates are identified using track penetration depth and hit information in the KLM. The electron candidates are identified using the transverse shape and size of the showers in the ECL, the CDC ($dE/dx$), the ACC, the ratio of ECL energy to the CDC track momentum, and the position matching between the CDC track and the ECL cluster. These pieces of information are combined to form a likelihood $\mathcal{L}$ for charged particle identification.

We require $\pi^\pm$ candidates to satisfy $\mathcal{L}_{\pi/K} = \mathcal{L}_\pi/(\mathcal{L}_\pi + \mathcal{L}_K) > 0.6$, while rejecting highly electronlike ($\mathcal{L}_e > 0.95$) or muonlike ($\mathcal{L}_\mu > 0.95$) tracks. For muon tracks, we require the particle identification likelihood $\mathcal{L}_\mu > 0.9$. We define electron tracks as those with the particle identification likelihood $\mathcal{L}_e > 0.9$. Charged tracks are required to originate from the nominal interaction point, which can avoid poorly measured tracks or tracks which do not come from $B$ decays. For charged pion tracks, we require the impact parameters in the radial direction ($dr$) and in the beam direction ($dz$) to satisfy $dr < 2.0$ cm and $|dz| < 5.0$ cm, respectively. For lepton tracks, we require $|dr| < 0.2$ cm and $|dz| < 2.0$ cm.

We reconstruct $J/\psi$ candidates in the $\ell^+\ell^-$ decay channel ($\ell \in \{e, \mu\}$) and include bremsstrahlung photons that are within 50 mrad of the $e^+$ or $e^-$ tracks. The invariant mass window used to select $J/\psi$ candidates in the $\mu^+\mu^-(e^+e^-)$ channel is $3.03\ (2.95)\,\mathrm{GeV}/c^2 \le M_{\mu\mu}(M_{ee}) \le 3.13\,\mathrm{GeV}/c^2$. These intervals are asymmetric in order to include parts of the radiative tails. A lower mass requirement for the $e^+e^-$ channel is used because electron tracks are more sensitive to energy loss due to bremsstrahlung. The lower bound corresponds to 1.7 and 1.4 standard deviations for dimuon and dielectron channel, respectively; the upper bound corresponds to 2.5 and 2.1 standard deviation for dimuon and dielectron channel, respectively. We also require $\chi^2_{\ell\ell}/\mathrm{n.d.f.} < 20$, where $\chi^2_{\ell\ell}/\mathrm{n.d.f.}$ is the $\chi^2$ per degree of freedom of the $J/\psi \to \ell^+\ell^-$ vertex fit. The $J/\psi$ candidate is then combined with a $\pi^+\pi^-$ pair to reconstruct an $X(3872)$ candidate. The invariant mass windows used to select $X(3872)$ candidates are $3.7\ \mathrm{GeV}/c^2 < M_{\mu\mu\pi\pi} < 3.95\ \mathrm{GeV}/c^2$ and $3.5\ \mathrm{GeV}/c^2 < M_{ee\pi\pi} < 3.95\ \mathrm{GeV}/c^2$. We require the dipion invariant mass to satisfy $M_{\pi\pi} > M_{\ell\ell\pi\pi} - M_{\ell\ell} - 150\ \mathrm{MeV}/c^2$. This selection was introduced in an earlier analysis [15] to reduce combinatorial backgrounds from misidentified $\gamma$ conversions, which correspond to $M_{\pi\pi} > 625\ \mathrm{MeV}/c^2$ for the $X(3872)$. After the $M_{\pi\pi}$ selection is applied, about 15.9% (for dimuon channel) and 15.8% (for dielectron channel) of the true signal is removed, while about 43.0% (for dimuon channel) and 42.7% (for dielectron channel) of the combinatorial background in the signal region is rejected. The $\chi^2$/n.d.f. of the $\rho^0$ vertex fit is constrained within $\chi^2_{\pi\pi}/\mathrm{n.d.f.} < 80$. Selections on $\Delta M = M_{\ell\ell\pi\pi} - M_{\ell\ell}$ can also be employed to reduce combinatorial backgrounds. We require $0.755\ \mathrm{GeV}/c^2 < M_{\mu\mu\pi\pi} - M_{\mu\mu} < 0.795\ \mathrm{GeV}/c^2$ and $0.745\ \mathrm{GeV}/c^2 < M_{ee\pi\pi} - M_{ee} < 0.805\ \mathrm{GeV}/c^2$. After the $\Delta M$ selection is applied, about 0.73% (for dimuon channel) and 0.43% (for dielectron channel) of the true signal is removed, while about 80.8% (for dimuon channel) and 75.2% (for dielectron channel) of the combinatorial background in the signal region is rejected. The value of $\chi^2/\mathrm{n.d.f.}$ of the $X(3872)$ vertex fit is required to be within $\chi^2_{\ell\ell\pi\pi}/\mathrm{n.d.f.} < 100$.

A high-energy photon produces an electromagnetic shower in the ECL, and it is detected as an isolated energy cluster which is not associate with charged particles. The energy of the photon candidate coming from the $B^0$ is required to be larger than 0.6 GeV in the center-of-mass (CM) frame. We also reject the photon candidate if the ratio of the energies deposited in arrays of $3 \times 3$ and $5 \times 5$ calorimeter cells ($E_9/E_{25}$) is less than 0.87. To reduce background from the decay $\pi^0 \to \gamma\gamma$, a $\pi^0$ veto is applied with $\mathcal{L}_{\pi^0} < 0.3$, where $\mathcal{L}_{\pi^0}$ is a $\pi^0$ likelihood [16]. The $B$ meson candidate is then reconstructed by combining the $X(3872)$ candidate and the high-energy photon candidate. $B$ meson candidates are identified with kinematic variables calculated in the CM frame (and denoted with an asterisk *). The energy difference is calculated as $\Delta E = E^*_{\mathrm{recon}} - E^*_{\mathrm{beam}}$, where $E^*_{\mathrm{recon}}$ and $E^*_{\mathrm{beam}}$ are the reconstructed $B$ meson energy and beam energy. We use a modified beam-energy-constrained mass $M_{\mathrm{bc}}$ defined as

$$M_{\mathrm{bc}} = \sqrt{\left(\frac{E^*_{\mathrm{beam}}}{c^2}\right)^2 - \left(\frac{\vec{P}^*_X}{c} + \frac{\vec{P}^*_\gamma}{|\vec{P}^*_\gamma|c^2}(E^*_{\mathrm{beam}} - E^*_{\mathrm{X}})\right)^2}, \quad (1)$$

where $\vec{P}_X^*$ and $E_X^*$ are the reconstructed momentum and energy of the $X(3872)$ candidate, and $\vec{P}_\gamma^*$ is the reconstructed momentum of the photon candidate. The use of this modified definition reduces the linear correlation between the $M_{\rm bc}$ and $\Delta E$ from 0.400 (0.332) to −0.013 (0.114) for the dimuon (dielectron) channel, as estimated with MC signal events. This also improves $M_{\rm bc}$ resolution. The selection region is defined by $M_{\rm bc} > 5.2$ GeV/$c^2$ and $-0.5$ GeV $< \Delta E < 0.2$ GeV. The signal region is defined by $M_{\rm bc} > 5.27$ GeV/$c^2$ and $-0.15$ GeV $< \Delta E < 0.1$ GeV.

There are two main types of background events: the generic $B\bar{B}$ spherical events and the jetlike $q\bar{q}$ continuum events. The dominant background in the selection region is from the $B \to J/\psi X$ inclusive decays. Other types of $B\bar{B}$ and continuum backgrounds also contribute. Since the signal and background shapes are different, we use a multivariate analyzer based on the neural network package named NeuroBayes [17] to distinguish the signal and background. We train the neural network using the signal MC and $B \to J/\psi X$ MC samples, with the following 33 input variables: (1) 25 modified Fox-Wolfram moments treating the information of particles involved in the signal $B$ candidate separately from those in the rest of the event [18], (2) the cosine of the angle between the $B$ candidate and the beam axis, (3) the angle between the thrust axis of the decay particles of the $B$ candidate and that of the remaining particles in the event, (4) the event sphericity [19], (5) the missing mass, momentum and energy in the event, (6) the sum of the transverse energy of the event, and (7) the flavor tagging information [20]. Variables (1)–(6) are calculated in the $\Upsilon(4S)$ rest frame. NeuroBayes returns an output in the range $-1$ to $+1$, where values closer to $+1$ are signallike and values closer to $-1$ are backgroundlike. The applied selection on the NeuroBayes output is determined by optimizing a figure of merit (FOM) defined as

$$\mathrm{FOM} = \frac{\text{efficiency}}{0.5n + \sqrt{N_{\rm bkg}}}, \tag{2}$$

where $N_{\rm bkg}$ is the number of background events and efficiency is obtained from the signal MC. In this equation, $n$ is the number of standard deviations corresponding to one-sided Gaussian tests, and $n = 1.28$ corresponds to 90% confidence level [21]. The optimized selection and its related systematic uncertainty are channel dependent.

If multiple candidates are found in an event after background suppression, we select the candidate which has the smallest $|\Delta M - 775$ MeV/$c^2|$. Before applying the selection, the multiplicity per event is 1.080 for the dimuon channel and 1.116 for the dielectron channel in signal MC samples. After the selection is applied, about 1.8% (for the dimuon channel) and 2.0% (for the dielectron channel) of the true signal is removed, and about 43.1% (for the dimuon channel) and 47.0% (for the dielectron channel) of the combinatorial background in the signal region is rejected. With all of the selections applied, the dimuon signal MC sample comprises 92% correctly-reconstructed signal $B$ events ("true" signal) and 8% self-crossfeed (SCF) events (not correctly reconstructed ones), and the dielectron sample comprises 89% true signal and 11% SCF events.

The branching fraction is calculated as

$$\mathcal{B} = \frac{N_{\rm sig}}{\epsilon \times \eta \times N_{B\bar{B}}}, \tag{3}$$

where $N_{\rm sig}$, $N_{B\bar{B}}$, $\epsilon$ and $\eta$ are the number of signal, the number of $B\bar{B}$ pairs ($= 772 \times 10^6$), the signal reconstruction efficiency, and an efficiency calibration factor, respectively. We assume that the charged and neutral $B\bar{B}$ pairs are equally produced at the $\Upsilon(4S)$.

The calibration factor $\eta = \eta_{\rm NB} \times \eta_{\pi\rm ID} \times \eta_{\ell\rm ID} \times \eta_{\pi^0\rm veto} \times \eta_{\rm box}$ is a correction factor to the Monte Carlo that has been determined using real data and following methods: $\eta_{\rm NB}$ concerns the background suppression using NeuroBayes and is obtained using the $B^0 \to J/\psi(\to \ell^+\ell^-)K_S^0$ control sample with treating $K_S^0$ as $\gamma$. We also check using another control sample $B^0 \to \psi(2S)(\to J/\psi\pi^+\pi^-)K_S^0$, which as a topology more similar to the signal, to verify the result. The two methods are in good agreement. $\eta_{\pi\rm ID}$ concerns the charged pion identification with the requirement on $\mathcal{L}_\pi$, and is determined using a $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ control sample, $\eta_{\ell\rm ID}$ concerns the lepton identification with the requirement on $\mathcal{L}_\mu$ or $\mathcal{L}_e$, and is determined by using a $e^+e^- \to e^+e^-\ell^+\ell^-$ control sample with $e^+e^-$ undetected, and $\eta_{\pi^0\rm veto}$ concerns the $\pi^0$ veto with the requirement on $\mathcal{L}_{\pi^0}$, and is determined using a $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$ control sample. $\eta_{\rm box}$ concerns the fraction of the signal yield in the signal region to that in the selection region after all selection is applied, and is determined by using a $B^0 \to K_S^0\pi^+\pi^-\gamma$ control sample. The values of the calibration factors and the reconstructed efficiency for the signal with all the selection criteria applied are listed in Table I.

Sources of various systematic uncertainties on the branching fraction calculation are shown in Table II. The uncertainty due to the total number of $B\bar{B}$ pairs is 1.4%. The uncertainty due to the charged-track reconstruction efficiency is estimated to be 0.35% per track by using

TABLE I. Calibration factors ($\eta$) and reconstructed efficiency ($\epsilon$) for the signal with all the selection criteria applied.

| Channel | Dimuon | Dielectron |
|---|---|---|
| $\eta_{\rm NB}$ | $0.98 \pm 0.02$ | $0.99 \pm 0.03$ |
| $\eta_{\pi\rm ID}$ | $0.99 \pm 0.01$ | $0.99 \pm 0.01$ |
| $\eta_{\ell\rm ID}$ | $0.96 \pm 0.02$ | $0.98 \pm 0.02$ |
| $\eta_{\pi^0\rm veto}$ | $0.98 \pm 0.01$ | $0.98 \pm 0.01$ |
| $\eta_{\rm box}$ | $0.95 \pm 0.03$ | $0.95 \pm 0.03$ |
| $\eta$ | $0.86 \pm 0.06$ | $0.89 \pm 0.06$ |
| $\epsilon$ | $(16.8 \pm 0.01)\%$ | $(14.5 \pm 0.01)\%$ |

TABLE II. Summary of systematic uncertainties on the measured branching fraction.

| Source | Dimuon | Dielectron |
|---|---|---|
| $N_{B\bar{B}}$ | 1.4% | 1.4% |
| Tracking (4 tracks) | 1.4% | 1.4% |
| $\mathcal{B}(J/\psi \to \ell^+\ell^-)$ | 0.6% | 0.5% |
| $\gamma$ detection | 3.1% | 3.1% |
| MC gen. model | 1.1% | 1.9% |
| $\pi^\pm$ identification | 1.3% | 1.3% |
| $\ell^\pm$ identification | 2.1% | 1.8% |
| Bkg. suppression | 2.3% | 2.5% |
| $\pi^0$ veto | 0.8% | 0.8% |
| Signal region fraction | 3.5% | 3.5% |
| Total | 6.2% | 6.4% |

partially reconstructed $D^{*+} \to D^0(\pi^+\pi^- K^0_S)\pi^+$ decay samples. The uncertainty due to the subdecay $J/\psi \to \ell^+\ell^-$ branching fraction is based on the world average value [4]. The uncertainty due to the photon detection efficiency in the barrel region ($33° < \theta_\gamma < 128°$, where $\theta_\gamma$ is the polar angle of the photon) is studied using a radiative Bhabha sample, and $B^0 \to K^{*0}\gamma$ elsewhere [22]. The uncertainty due to the $X(3872) \to J/\psi\rho^0$ generation model is studied by comparing the signal MC samples generated with helicity distributions $\cos\theta$ (which is taken for the central value of efficiency), $\sin^2\theta$, and $1 + \cos^2\theta$.

The expected number of background events $N_{\rm bkg}$ in the signal region is estimated as

$$N_{\rm bkg} = N_{\rm sb,data} \times \frac{N_{\rm bkg,MC}}{N_{\rm sb,MC}}, \tag{4}$$

where $N_{\rm sb,data}$ and $N_{\rm sb,MC}$ are the number of data events and the background MC events in the sideband region (selection region with signal region excluded), respectively. $N_{\rm bkg,MC}$ is the number of background MC events in the signal region. The ratio of $B \to J/\psi X$ and other backgrounds are fixed to MC expectation. The expected number of background events in the signal regions are $N_{\rm bkg} = 9.3$ and 12.1 for the dimuon and dielectron channels, respectively. The observed number of events in the signal region are $N_{\rm evt} = 9$ for both dimuon and dielectron channels, and the data scatter plots with the signal regions shown as rectangle are shown in Fig. 2. The projections of the data and the estimated background are displayed in Fig. 3.

As we find no evidence for the decay $B^0 \to X(3872)\gamma$, we give an upper limit on the branching fraction at 90% confidence level (C.L.). We apply the Feldman-Cousins counting method [23] using the implementation provided in the TRolke package [24], which takes into account separately the uncertainties in the background and the efficiency. The expected number of background events $N_{\rm bkg}$ in the signal region is estimated using the sideband data and the ratio of

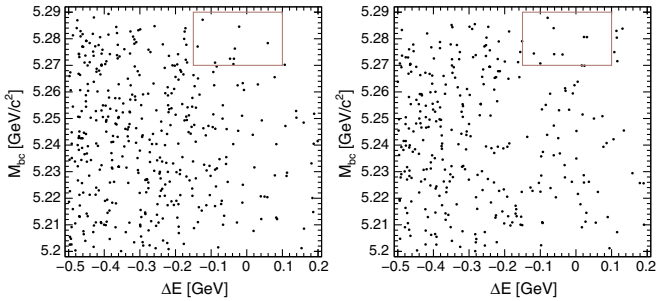
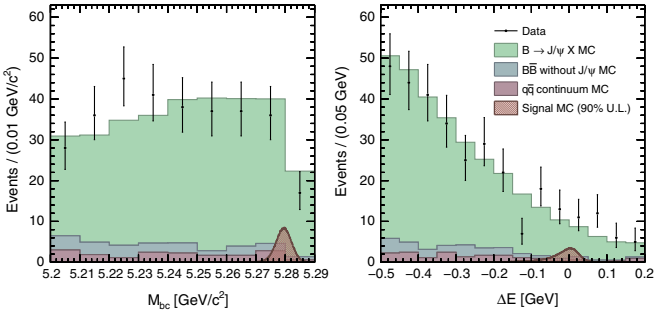
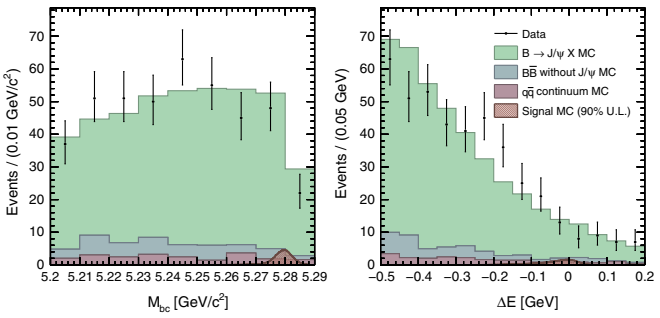



FIG. 2. Two dimensional ($M_{\rm bc}$, $\Delta E$) distributions of the selected $B^0 \to X(3872)\gamma$ candidates in the dielectron (left) and dimuon (right) channels. The signal regions are shown as rectangles.

number of events in the signal region and in the sideband region in the background MC. The uncertainties in the background levels are studied by comparing the sideband data and the sideband background MC, and are 10.9% and 17.3% for the dimuon and the dielectron channels, respectively. We thus determine the upper limit on the product of the branching fractions $\mathcal{B}(B^0 \to X(3872)\gamma) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ to be $5.1 \times 10^{-7}$ at the 90% C.L. The results are summarized in Table III.




(a) Dimuon channel.




(b) Dielectron channel.

FIG. 3. $M_{\rm bc}$ (left) and $\Delta E$ (right) distributions of the selected $B^0 \to X(3872)\gamma$ candidates (data points with error bars), with the estimated background represented as stacked histograms. The components are, from bottom to top: the $q\bar{q}$ continuum background (purple), the $B\bar{B}$ background without $J/\psi$ (blue), and the inclusive $B \to J/\psi X$ background (green). The signal distribution (hatched brown with thick boundary) is shown corresponding to 90% C.L. upper limit.

TABLE III. Summary of results from the counting method.

| Channel | Dimuon | Dielectron | Total |
|---|---|---|---|
| Observed $N_{\rm evt}$ | 9 | 9 | 18 |
| Expected $N_{\rm bkg}$ | 9.3 | 12.1 | 21.4 |
| 90% U.L. | $9.2 \times 10^{-7}$ | $6.8 \times 10^{-7}$ | $5.1 \times 10^{-7}$ |

In conclusion, we have performed a search for the decay $B^0 \to X(3872)\gamma$ based on a data sample of 711 fb$^{-1}$ $e^+e^-$ collisions collected by Belle. No significant signal is found. We set an upper limit on the product of the branching fractions $\mathcal{B}(B^0 \to X(3872)\gamma) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ of $5.1 \times 10^{-7}$ at the 90% confidence level.

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[1] Y. D. Yang, G. Lu, and R. Wang, Eur. Phys. J. C **34**, 291 (2004).
[2] Y. Li and C.-D. Lü, Phys. Rev. D **74**, 097502 (2006).
[3] S. J. Brodsky and S. Gardner, Phys. Rev. D **65**, 054016 (2002).
[4] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).
[5] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
[6] E. S. Swanson, Phys. Lett. B **598**, 197 (2004).
[7] L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, Phys. Rev. D **71**, 014028 (2005).
[8] M. Suzuki, Phys. Rev. D **72**, 114013 (2005).
[9] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 1 (2003), and other papers included in this volume.
[10] A. Abashian *et al.* (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002).
[11] Z. Natkaniec *et al.* (Belle SVD2 Group), Nucl. Instrum. Methods Phys. Res., Sect. A **560**, 1 (2006).
[12] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).
[13] R. Brun *et al.*, CERN Report No. DD/EE/84-1, 1987.
[14] E. Barberio, B. van Eijk, and Z. Was, Comput. Phys. Commun. **66**, 115 (1991).
[15] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. D **84**, 052004 (2011).
[16] P. Koppenburg *et al.* (Belle Collaboration), Phys. Rev. Lett. **93**, 061803 (2004).
[17] M. Feindt and U. Kerzel, Nucl. Instrum. Methods Phys. Res., Sect. A **559**, 190 (2006).
[18] 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).

[19] J. D. Bjorken and S. J. Brodsky, Phys. Rev. D **1**, 1416 (1970).
[20] H. Kakuno *et al.*, Nucl. Instrum Methods Phys. Res., Sect. A **533**, 516 (2004).
[21] G. Punzi, *Proceedings of the Statistical problems in particle physics, astrophysics and cosmology, Conference, PHYSTAT 2003, Stanford, USA*, eConf C030908, MODT002 (2003).
[22] N. Taniguchi, Ph.D. thesis, Kyoto University, 2008.
[23] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).
[24] J. Lundberg, J. Conrad, W. Rolke, and A. Lopez, Comput. Phys. Commun. **181**, 683 (2010).