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We report a search for $B^0 \rightarrow \eta \eta$ with a data sample corresponding to an integrated luminosity of 698 fb$^{-1}$ containing 753 x 10$^6$ $BB$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. The branching fraction is measured to be $B(B^0 \rightarrow \eta \eta) = (7.6^{+2.7+1.4}_{-2.3-1.6}) \times 10^{-7}$ at the level of 3.3 standard deviations above zero, which provides the first evidence for the decay $B^0 \rightarrow \eta \eta$.

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INTRODUCTION

The $CP$ violation measurements using charmless hadronic decays of $B$ mesons are primarily important for testing the Standard Model (SM) and searching for physics beyond the SM.

The $B^0 \rightarrow \eta \eta$ decay mode mainly proceeds via the $b \rightarrow u$ Cabibbo- and color-suppressed tree diagram and the $b \rightarrow d$ penguin diagram shown in Fig. 1(a) and Fig. 1(b) respectively. The expected branching fraction of this decay mode is $(0.3-3.1) \times 10^{-6}$, estimated from the calculations based on QCD factorization [1], soft collinear effective theory [2], SU(3) flavor symmetry [3] and flavor $U(3)$ symmetry [4].

This mode plays an important role in improving the flavor SU(3) calculations of $|S_{ccs} - S_f|$, where the final state $f$ is $\eta K$ or $\phi K$, the $CP$-violating parameter $S_f \sim \sin 2\phi_1$ is measured in the time-dependent analysis [5], and the $CP$-violating parameter $S_{ccs}$ is measured in the Cabibbo-Kobayashi-Maskawa (CKM)-favored $b \rightarrow c\bar{c}s$ decays. The bound on this difference can be improved by more precise measurements of the branching fraction of $B^0 \rightarrow \eta \eta$ [6, 7].

This mode has been studied by Belle and BABAR [8, 9]. The best previous upper limit on this branching fraction is $B(B^0 \rightarrow \eta \eta) < 1.0 \times 10^{-6}$ at 90% confidence level (CL) [9].

We update our previous result [8] using the full data set of the Belle experiment running on the $\Upsilon(4S)$ resonance at the KEKB asymmetric-energy $e^+e^-$ collider [10]. This data set corresponds to 753 x 10$^6$ $BB$ pairs, which is a factor of five larger than in the previous Belle study.

DETECTOR AND DATASET

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 barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K_L^0$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [10]. Two inner detector configurations were used. A 2.0 cm beampipe and a 3-layer silicon vertex detector was used for the first sample of 133 x 10$^6$ $BB$ pairs, while a 1.5 cm beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used to record the remaining 620 x 10$^6$ $BB$ pairs [11].

RECONSTRUCTION

The $B^0 \rightarrow \eta \eta$ candidate is reconstructed from the subdecay channels of $\eta \rightarrow \gamma \gamma (\eta \gamma \gamma)$ and $\eta \rightarrow \pi^+\pi^-\pi^0 (\eta \pi \pi)$. Photons used for $\eta \rightarrow \gamma \gamma$ and $\pi^0 \rightarrow \gamma \gamma$ are required to have an energy greater than 50 (100) MeV in the barrel (end-cap) region of the ECL [10]. The ECL timing information, which measures the time of energy deposit relative to the beam-collision time, is used to reject out-of-time photons.

Charged tracks are required to have a transverse momentum greater than 0.1 GeV/c and an impact parameter with respect to the interaction point of less than 0.3 cm in the $r-\phi$ plane and 3.0 cm along the $z$ axis, which is opposite the $e^+$ beam. Charged pions are identified using information obtained from the CDC ($dE/dx$, the TOF, and the ACC (number of photoelectrons). This information is combined to form a likelihood $L$ for hadron identification (PID). We require that charged pions satisfy $L_K/(L_{\pi} + L_K) < 0.4$, where $L_K$ ($L_{\pi}$) denotes the likelihood for a track with the kaon (pion) hypothesis.

A $\pi^0$ candidate is required to have a $\gamma \gamma$ invariant mass between 117 and 155 MeV/$c^2$, which corresponds to $\pm 3\sigma$ around the nominal $\pi^0$ mass [12]. To improve the $\pi^0$ momentum resolution, we perform a mass-constrained fit and require that the resulting goodness-of-fit parameter
(χ²) be less than 50.

Photons that are not included in the final set of π⁰ candidates are combined to form ηγ candidates. To reduce combinatorial background from low-energy photons, ηγ candidates are required to have cos θη < 0.9, where θη is the angle in the η rest frame between the directions of the B meson and the more energetic photon. The ηπ candidates are reconstructed by combining two oppositely charged pion candidates with a π⁰ candidate. We require the invariant mass of ηγ (ηπ) candidates be in the range 476–579 (527–568) MeV/c², which corresponds to ±2.5σ (±3.0σ) around the nominal η mass [12]. For each such η candidate, a mass-constrained fit is performed to improve the momentum resolution; the resulting χ² of the ηγ (ηπ) candidates must be less than 50 (200).

For each B⁰ → ηπ candidate, we define two kinematic variables to distinguish signal from background: these are the energy difference (ΔE ≡ E_B − E_beam) and the beam-constrained mass (M_{bc} ≡ \sqrt{E_{beam}^2 − |p_B|^2} c^2 / c^2), where E_{beam} and E_B (|p_B|) are the beam energy and the energy (momentum) of the B meson candidate, respectively, in the e^+e^- center-of-mass (CM) frame. We retain B candidates satisfying −0.3 GeV < ΔE < 0.2 GeV and M_{bc} > 5.25 GeV/c².

**BACKGROUND SUPPRESSION**

The large background arising from continuum e^+e^- → q̅q (q = u, d, s, c) process is the dominant background here. To suppress this background, a neural network [13] is employed by combining the following four quantities: the event-shape variables formed from 16 modified Fox-Wolfram moments [14], the cosine of the angle between the flight direction of the B candidate and z axis in the e^+e^- CM frame, the tagging information of the flavor [15], and the cosine of the angle between the thrust axes [16] in the e^+e^- CM frame of the signal-B and the other-B candidates. The training and optimization of this neural network are accomplished with signal and continuum Monte Carlo (MC) simulated events. The signal MC sample is generated with EvtGen [17], taking the final-state radiation into account via PHOTOS [18]. After training, independent samples are used to test the neural network performance. The neural network output (C_{NB}) for an event ranges from −1 to +1; a value near +1 (−1) is more likely signal (continuum).

We require C_{NB} > −0.8 to suppress the continuum background. This requirement preserves approximately 97.7%, 97.6% and 97.2% of the signal while suppressing 68.3%, 64.5%, and 58.5% of the continuum background in ηγγ, ηγπ and ηππ respectively. The remaining of the C_{NB} distribution has a strong peak that falls off rapidly below 1 for signal, we use a transformed quantity to improve its modeling with an analytic shape:

\[
C'_{NB} = \frac{C_{NB} - C_{NB}^{-\text{min}}}{C_{NB}^{-\text{max}} - C_{NB}^{-\text{min}}}.
\]

where C_{NB}^{-\text{min}} = −0.8 and C_{NB}^{-\text{max}} is the maximum value of C_{NB} obtained from a large sample of signal MC decays. After applying all selection criteria, the average number of signal candidates per event is 1.08, 1.10 and 1.13 for ηγγ, ηγπ and ηππ, respectively, in the signal MC. We choose the candidate having the smallest value for the sum of the χ² values from the two η mass-constrained fits. We refer to the right-combination (RC) as the correctly-reconstructed B meson decays and the self-cross-fraud (SCF) as the misreconstructed signal components. MC simulation show that the SCF fraction is 6.8%, 9.3% and 13.4% in ηγγ, ηγπ and ηππ, respectively.

**FIT MODEL**

The branching fraction of B⁰ → ηπ is obtained using a simultaneous fit to the ηγγ, ηγπ and ηππ decay channels. In this fit, the branching fraction is determined by an unbinned extended maximum likelihood (ML) fit to the distributions of ΔE, M_{bc} and C_{NB}. The branching fraction of this mode is obtained using a simultaneous fit to the ηγγ, ηγπ and ηππ decay channels. The extended ML function is defined as

\[
\mathcal{L}_\text{fit} = e^{-\sum_j N_j} \prod_i \left( \sum_j N_j P_j(\Delta E, M_{bc}, C'_{NB}) \right),
\]

where \(P_j(\Delta E, M_{bc}, C'_{NB})\) is the probability density function (PDF) of the signal or background component (specified by index j), N_j is the fractional yield of this component for event i, and M is the total number of

| Fit variables | Yield | ΔE | M_{bc} | C'_{NB} |
|---------------|-------|-----|--------|---------|
| Signal MC     | RC    | N_{sig} | CB + G | CB      | AG + AG |
| SCF           |       |       |        | AG + 1st CC | NV + ARG | AG + AG |
| b → c        |       |       | N_{arg} | HistPDF | HistPDF | G |
| b → u, d, s  |       | 2nd CC | NV     | G |

**TABLE I: List of PDFs used to model ΔE, M_{bc} and C'_{NB} distributions for various event categories.** G, AG, CB, NV, i-th CC, ARG and HistPDF stand for Gaussian, asymmetric Gaussian, Crystal Ball, i-th Chebyshev polynomial, ARGUS function [21] and histogram, respectively. N_i is the yields of signal or background components.
events in the sample. The background components include continuum events, the $b \to c$ process, charmless $b \to u, d, s$ processes other than $B^0 \to \pi^0 \eta$, and $B^0 \to \eta^0 \eta$ (treated separately). Compared to continuum, the other background processes are small and are modeled using MC simulations. The expected yields of $b \to c$ processes are 6, 6 and 2 events in $\eta\gamma \eta\gamma$, $\eta\gamma \eta\pi$, and $\eta\pi \eta\pi$, respectively, after passing all selection criteria based on MC simulations. The charmless $b \to u, d, s$ processes (excluding $B^0 \to \pi^0 \eta$), while having larger expected yields, exhibit no peaking structure in the $\Delta E$ and $M_{bc}$.

We find that the correlations among the fit variables are small enough to ignore. Thus, the three-dimensional PDF, $P_j$ is expressed as the product of one-dimensional PDFs as

$$P_j = P_j(\Delta E) \cdot P_j(M_{bc}) \cdot P_j(C_{NB}).$$

Table II lists the PDF shapes used to model $\Delta E$, $M_{bc}$ and $C_{NB}$ for all components in the fit.

We fix the parameters of the RC-signal PDF shapes to values obtained from the signal MC. Here, the peak positions and resolutions are adjusted according to data-MC differences observed in a high-statistics control sample of $B^0 \to \bar{D}^0(\rightarrow K^+\pi^- \pi^0)\eta$ decays.

The continuum $q\bar{q}$ background PDF parameters that are allowed to vary are the slope of $\Delta E$, the shape of $M_{bc}$ and the mean and width of the $C_{NB}$ Gaussian function. All of the other background PDF parameters are fixed based on MC simulation.

The yields of signal and continuum $q\bar{q}$ are allowed to vary in the fit. The yields of the other backgrounds and the relative amount of SCF to RC signal are fixed. To test the stability of the fitter, we perform the fit to ensembles of 1000 pseudoexperiments using the extracted fitted yields from data and random samples of events for each component chosen from the simulated MC samples. We observe a fit bias of 1.7% for $B$, which is corrected and assigned as a systematic uncertainty.

**FIT TO DATA**

We extract $+3.6^{+0.8}_{-0.9}$, $9.2^{+3.2}_{-2.7}$ and $2.7^{+0.9}_{-0.8}$ signal events and $3860.5^{+63.1}_{-62.4}$, $3779.7^{+62.0}_{-61.5}$ and $621.4^{+25.4}_{-24.8}$ continuum background events for $\eta\gamma \eta\gamma$, $\eta\gamma \eta\pi$, and $\eta\pi \eta\pi$, respectively. The complete results of the ML fit are enumerated in Table II. Figure 3 shows the PDF and data distributions projected in the signal-enhanced region of $|\Delta E, M_{bc}| < 3\sigma$ and $C_{NB} > 2.0$, 2.0 and 1.5 for $\eta\gamma \eta\gamma$, $\eta\gamma \eta\pi$, and $\eta\pi \eta\pi$, respectively. In the fit, the signal yield of each sub-decay mode (with index $k$) is written in terms of the common branching fraction as

$$n_{\text{sig},k} = B(B^0 \to \eta\eta) \times N_{\bar{B}B} \times \epsilon_{\text{rec},k} \times \prod B_{\eta_k},$$

where $N_{\bar{B}B}$ is the number of $\bar{B}B$ pairs, $\epsilon_{\text{rec}}$ is the signal efficiency obtained from MC simulation, $n_{\text{sig}}$ is the number of signal events and $\prod B_{\eta_k}$ is the product of the two $\eta$-decay branching fractions. The efficiency $\epsilon_{\text{rec}}$ is corrected by the modest differences between data and MC in the particle identification efficiency $\epsilon_{\text{rec}}$. The resulting branching fraction is $B(B^0 \to \eta\eta) = (7.6^{+2.7}_{-2.2}) \times 10^{-7}$, where the error is statistical only.

The significance $S$ of the signal is defined as $\sqrt{-2 \log \frac{L_0}{L_{\text{max}}}}$, where $L_{\text{max}}$ ($L_0$) is the likelihood value when the signal yield set to the measured signal yield (zero), corrected for the systematic errors by involving the likelihood function with an asymmetric Gaussian distribution whose left and right variances equal the signal-yield systematic errors in Table II. The resulting significance of the branching fraction is 3.3 standard deviations above zero which provides the first evidence of this decay mode.

**SYSTEMATIC UNCERTAINTY ESTIMATION**

The systematic uncertainties in the branching fraction are listed in Table III. The uncertainty due to the fixed parameters in the PDF is estimated by varying each, one by one, according to its statistical uncertainty. Deviations from the original fit are added in quadrature. We vary the bin height for all histogram PDFs by the bin’s statistical error and repeat the fit. The resulting changes are added in quadrature and the result is taken as the systematic uncertainty. The uncertainty due to calibration factors are evaluated in a similar manner. The uncertainty due to the fixed fractions of misreconstructed events and fixed yields are calculated by varying them by $\pm 50\%$.

We determine the uncertainty due to the slightly diff-
different continuum suppression efficiencies for $C_{NB} = -0.8$ in data and MC by using the $B^0 \rightarrow D^0 \eta$ control sample. The systematic uncertainty due to the charged-track reconstruction efficiency is estimated to be 0.35% per track by using a partially reconstructed $D^{*+} \rightarrow D^0(K_S^0\pi^+\pi^-)\pi^+$ events. An uncertainty of 0.8% per track is assigned due to PID criteria. The uncertainty in the reconstruction efficiency of each $\eta \rightarrow \gamma\gamma$ or $\pi^0 \rightarrow \gamma\gamma$ decay is 3% [22].

We assign systematic uncertainties of 0.5% and 1.2%, respectively, for the branching fractions of $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ [12]. The uncertainty in the efficiency $\epsilon$ due to the limited signal MC statistics is 0.3% and the uncertainty due to the number of $BB$ pairs is 1.3%.

In order to check for potential non-resonant $B^0 \rightarrow \eta\gamma\gamma$, $B^0 \rightarrow \gamma\gamma\gamma$, $B^0 \rightarrow \gamma\eta\pi^+\pi^-$, $B^0 \rightarrow \eta\gamma\pi^+\pi^-$, $B^0 \rightarrow \gamma\pi^+\pi^-\pi^0$, $B^0 \rightarrow \pi^+\pi^-\pi^0\pi^+\pi^-\pi^0$ contamination, we relax the $\eta$ mass requirement; the invariant mass distributions are shown in Fig. 3. We choose the $\eta\gamma (\eta\pi\pi)$ mass-sideband re-

![FIG. 2: Signal-enhanced projections of the simultaneous fit: The points with the error bars are the real data, the black solid line is total PDF, the red solid line show the signal, the blue solid line represent the $q\bar{q}$, the green dashed line is $b \rightarrow u, d, s$, and the blue dashed line is $b \rightarrow c$ background.](image)

![FIG. 3: Distribution of $M_{\gamma\gamma}$ (a) and $M_{\pi^+\pi^-\pi^0}$ (b) invariant masses for events passing all selection requirements, except for $M_{\gamma\gamma}$ or $M_{\pi^+\pi^-\pi^0}$](image)


region as $0.45 - 0.48 \text{ GeV}/c^2$ or $0.58 - 0.63 \text{ GeV}/c^2$ ($0.45 - 0.52 \text{ GeV}/c^2$ or $0.57 - 0.63 \text{ GeV}/c^2$) and repeat the fitting procedure. We measure the branching fraction of the non-resonant contribution to be $(0.02^{+0.09}_{-0.05}) \times 10^{-6}$, consistent with zero. The positive uncertainty is assigned as the negative systematic uncertainty.

### CONCLUSION

In summary, we have conducted a measurement of the branching fraction of the decay $B^0 \rightarrow \eta \eta$. We obtain

$$B(B^0 \rightarrow \eta \eta) = (7.6^{+2.7+1.4}_{-2.3-1.6}) \times 10^{-7},$$

where the first uncertainty is statistical and the second is systematic. The significance of this result is 3.3 standard deviations above zero, which provides the first evidence for this decay. The measured branching fraction is in good agreement with the theoretical expectations [1-3].

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