Observation of the decay $B_s^0 \to J/\psi \eta$ and Evidence for $B_s^0 \to J/\psi' 

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We report the first observation of $B^0_s \to J/\psi \eta$ and evidence for $B^0_s \to J/\psi \eta'$. These results are obtained from 23.6 fb$^{-1}$ of data collected at the $\Upsilon(5S)$ resonance with the Belle detector at the KEKB $e^+e^-$ collider. We measure the branching fractions $B(B^0_s \to J/\psi \eta) = (3.32 \pm 0.87 \text{stat.} \pm 0.28 \text{syst.} \pm 0.42(f_s) ) \times 10^{-4}$ with a significance of 7.3$\sigma$, and $B(B^0_s \to J/\psi \eta') = (3.1 \pm 1.2 \text{stat.} \pm 0.5 \text{syst.} \pm 0.38(f_s) ) \times 10^{-4}$ with a significance of 3.8$\sigma$.

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The decays $B^0_s \to J/\psi \eta^{(f)}$ are dominated by the $b \to c\bar{c}s$ process, as shown in Figure 1. The $J/\psi \eta^{(f)}$ final states are $CP$ eigenstates, whose time distribution can be used to measure directly the $B^0_s$ width difference $\Delta\Gamma_s$ [1]. Using SU(3) flavor symmetry, an estimate of the $B^0_s \to J/\psi \eta^{(f)}$ branching fractions can be obtained relative to
the decay \( B_s^0 \rightarrow J/\psi K^0 \):

\[
\frac{B(B_s^0 \rightarrow J/\psi \eta(0))}{B(B_s^0 \rightarrow J/\psi K^0)} = \sin^2(\cos^2\phi_p \times p^\ast_3/p^\ast_{B_s^0})
\]

where \( p^\ast \) is the momentum of \( J/\psi \) or \( \eta(0) \) in the rest frame of the \( B_s^0 \) or \( B_s^0 \). Here, \( \phi_p \approx 37^\circ \) is the quark mixing angle in the flavor basis with \( B \). We constructed the quark mixing angle in the flavor basis with \( B \) and low background. Electron candidates are identified by combining information from the ECL (dE/dx), and the ACC. Muon candidates are identified through track penetration depth and hit patterns in the KLM system. Identification of pions is based on combining information from the ACC (dE/dx), the TOF and the ACC.

Two oppositely charged leptons \( e^-e^+ \) or \( \mu^-\mu^+ \) are required to be positively identified as electrons or muons. The invariant mass is required to lie in the ranges \(-0.150 \text{ GeV} / c^2 < M_{\mu\mu} < 0.036 \text{ GeV} / c^2 \) and \(-0.060 \text{ GeV} / c^2 < M_{\mu\mu} < 0.036 \text{ GeV} / c^2 \), where \( M_{\mu\mu} \) denotes the nominal \( J/\psi \) mass, and \( M_{\mu\mu} \) are the reconstructed invariant masses for \( e^-e^- \) and \( \mu^-\mu^- \), respectively.

Photon candidates are selected from ECL showers not associated with charged tracks. An energy deposition with a photon-like shape and an energy greater than 50 MeV is required. \( \pi^0 \) candidates are selected by combining two photon candidates with an invariant mass in the range \( 115 \text{ MeV} / c^2 < M_{\gamma\gamma} < 155 \text{ MeV} / c^2 \) and \( 2 \gamma \) candidates to form \( J/\psi \) mesons. The leptons are required to be positively identified as electrons or muons. The invariant mass is required to lie in the ranges \(-0.150 \text{ GeV} / c^2 < M_{\mu\mu} < 0.036 \text{ GeV} / c^2 \) and \(-0.060 \text{ GeV} / c^2 < M_{\mu\mu} < 0.036 \text{ GeV} / c^2 \), where \( M_{\mu\mu} \) denotes the nominal \( J/\psi \) mass, and \( M_{\mu\mu} \) are the reconstructed invariant masses for \( e^-e^- \) and \( \mu^-\mu^- \), respectively.

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FIG. 1: Dominant diagram for the processes \( B_s^0 \rightarrow J/\psi \eta(0) \).
mass-constrained kinematic fits are applied to $J/\psi$, $\eta^{(l)}$ and $\pi^0$ candidates. We retain $B_s^0$ meson candidates with $|\Delta E| < 0.4$ GeV and $M_{bc} > 5.25$ GeV/$c^2$ for further analysis. If there are multiple candidates in a single event, we choose the candidate that minimizes the sum of the $\chi^2$’s of the mass-constrained fits.

To suppress the two-jet-like continuum background from $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$), we require the ratio of second to zeroth Fox-Wolfram moments [11] to be less than 0.4. This requirement is optimized by maximizing a figure-of-merit $N_S/\sqrt{N_S + N_B}$, where $N_S$ is the expected number of signal events and $N_B$ is the number of continuum events, in the $B^*\bar{B}^*$ signal region. The continuum background is modeled by a second-order polynomial in $\Delta E$ and an ARGUS function [12] in $M_{bc}$. We study the continuum background in a $J/\psi$ sideward defined as $2.5 \text{ GeV}/c^2 < M_{J/\psi} < 3.4 \text{ GeV}/c^2$, excluding the region $-0.200(-0.080) \text{ GeV}/c^2 < M_{J/\psi} < 0.048 \text{ GeV}/c^2$ for $J/\psi \rightarrow e^+e^- (\mu^+\mu^-)$ in data. The shapes for continuum backgrounds for each sub-channel are determined from fits to $J/\psi$ sideward data with a relaxed lepton identification requirement. The yields for continuum background are determined from the yields in $J/\psi$ sideward data with all selections other than the $J/\psi$ mass cut as in the nominal selection. Scale factors are determined from the ratio of the $J/\psi$ selection area to the $J/\psi$ sideward area by fitting Monte Carlo (MC) $J/\psi$ mass distributions. For continuum $J/\psi$ backgrounds that may not be well modeled in MC, we studied the off-resonance data and obtained the fractions of real $J/\psi$'s in continuum, which are applied as a correction to the continuum background yields.

The remaining background is from $B\bar{B}$ ($B = B^0, B_s^0, B_u^\pm$) events with one $B$ meson decays to a final state with $J/\psi$ (denoted $J/\psi X$). We use a MC sample generated at the $\Upsilon(5S)$ resonance that includes all known $B ightarrow J/\psi X$ processes to estimate this background, and find that the dominant contribution is from $B^0_s, B_u^\pm \rightarrow J/\psi +$ strange mesons. This background does not peak in either $\Delta E$ and $M_{bc}$ and is described by an exponential function in $\Delta E$ and an ARGUS function in $M_{bc}$, with shapes determined from MC. For the channel $J/\psi\eta' (\rho^0\gamma)$, the size of the $J/\psi X$ background is comparable to the expected yield in the $B^*_u B^*_d$ signal region, so we use a $\eta'$ sideward defined as $0.90 \text{ GeV}/c^2 < M_{\eta'} < 0.93 \text{ GeV}/c^2$ and $0.99 \text{ GeV}/c^2 < M_{\eta'} < 1.02 \text{ GeV}/c^2$ to study it. We fit the $\eta'$ sideward data to obtain the $J/\psi X$ background shape for the $J/\psi\eta' (\rho^0\gamma)$ channel, where the continuum contribution is fixed from the $J/\psi$ sideward.

We categorize events into two $\eta$ and three $\eta'$ sub-channels. For the $J/\psi\eta$ and $J/\psi\eta'$ modes, we perform a simultaneous unbinned maximum likelihood fit to the $\Delta E - M_{bc}$ distributions for each group of two $\eta$ or three $\eta'$ sub-channels, with the signal branching fraction as a common parameter while treating the signal and background shapes separately for the different $\eta^{(l)}$ sub-channels.

In the fit, the signal normalization for each $B_s^0$ production channel is parameterized as $N_{\text{sig}} = 2 \times N_{B_s^0 \rightarrow B_i} f_{B_i B_{s}} B(B^0 \rightarrow J/\psi \eta^{(l)}) B_i \bar{B}_i$. We use three fractions $f_{B_s B_u^+}, f_{B_s B_u^0}$, and $f_{B_u^0 B_{s}} = 1 - f_{B_s B_u^+} - f_{B_s B_u^0}$. In the $J/\psi\eta'$ mode, because of low statistics, we only include the $B_s^* B_{u}^*$ channel in the fit. The index $i$ denotes each $\eta^{(l)}$ sub-channel. The product $B_i = B(J/\psi \rightarrow l^+l^- B_i) (\eta^{(l)}/\lambda B_i (\eta^{(l)})$ is the total branching fraction to final states with a $J/\psi$ and an $\eta^{(l)}$, and $\epsilon_i$ is the MC reconstruction efficiency. The values of the weighted efficiencies $B_i \epsilon_i$ are listed in Table I. The signal shapes are from signal MC histograms while the means and widths of the distributions are corrected using a $B^+ \rightarrow J/\psi K^{+}(K^{+} \rightarrow K^+\pi^0)$ control sample from $\Upsilon(4S)$. The continuum back-
ground’s shapes and yields and the $J/\psi X$ background yields are fixed. The floating parameters for each fit are the branching fraction $B(B_s^0 \to J/\psi \eta^{(')})$ and the $J/\psi X$ background yields for each sub-channel.

The projections of the fit in the $B_s^+ B_s^-$ signal region are shown in Figures 2 and 3. The signal efficiencies, branching fractions, and significances including systematic uncertainties are listed in Table I. We calculate a total of 14.9 $\pm$ 4.1 $B_s^0 \to J/\psi \eta^{(')}$ events and 10.7 $\pm$ 4.6 $B_s^0 \to J/\psi \eta'\eta$ events in the $\Upsilon(5S) \to B_s^+ B_s^-$ channel.

The $B_s^0 \to J/\psi \eta^{(')}$ decay is observed for the first time and evidence for the $B_s^0 \to J/\psi \eta'\eta$ decay is found. The significance is defined by $S = \sqrt{2 \ln(L_{\text{max}}/L_0)}$, where $L_{\text{max}}(L_0)$ is the likelihood value at the maximum (with the signal branching fraction set to zero). The significance including systematic uncertainty is taken as the smallest value for each systematic variation described below.

The muon and pion identification efficiencies from MC are calibrated using the $J/\psi \to h^+h^-$ and $D^{*+} \to D^0\pi^+$ control samples in data, respectively. The total systematic error due to lepton identification is weighted to be 4.2(4.1)% for $J/\psi \eta^{(')}$ modes. The systematic error due to pion identification is 0.4(2.3)% for the $J/\psi \eta^{(')}$ modes.

The systematic errors due to the signal shape mean and width corrections and background parameters are determined by varying each parameter by its error, repeating the fit, and summing the shifts in branching fraction in quadrature. The beam energy has an error of $\pm 0.5$ MeV, whose systematic effect is evaluated by varying the mean value of $\Delta E$ and $M_{\text{true}}$ for the signal shapes simultaneously according to the uncertainty in the beam energy. All the systematic errors are summarized in Table II. The large systematic errors due to $f_s$ are quoted separately in the final results.

The ratio of the two branching fractions $R = B(B_s^0 \to J/\psi \eta')/B(B_s^0 \to J/\psi \eta)$ is also calculated. The statistical errors of the two modes are combined. The common systematic errors due to luminosity, cross-section and $f_s$ cancel. Correlated systematic errors due to calibration, beam energy, track reconstruction and particle identification are treated properly by varying the numerator and denominator simultaneously. Other systematic sources in the two branching fractions are treated independently.

In summary, we observe $B_s^0 \to J/\psi \eta^{(')}$ decay with a significance of 7.3$\sigma$ and find evidence for $B_s^0 \to J/\psi \eta^{(')}\eta$ with a significance of 3.8$\sigma$. We measure the branching fractions $B(B_s^0 \to J/\psi \eta) = (3.32 \pm 0.87(\text{stat.}) \pm 0.32(\text{syst.}) \pm 0.42(f_s)) \times 10^{-4}$ and $B(B_s^0 \to J/\psi \eta') = (3.1 \pm 1.2(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.38(f_s)) \times 10^{-4}$. The ratio of two branching fractions is measured as $R = B(B_s^0 \to J/\psi \eta')/B(B_s^0 \to J/\psi \eta) = 0.924^{+0.52}_{-0.44}(\text{stat.})^{+0.15}_{-0.26}(\text{syst.})$. The results are consistent with SU(3) expectations using the measured value of $B(B_s^0 \to J/\psi K^{(0)})$.

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| mode                  | $B_s$ | Significance | $B$     |
|-----------------------|-------|--------------|---------|
| $B_s^0 \to J/\psi \eta(\gamma\gamma)$ | 1.34% | 7.3$\sigma$  | $(3.32 \pm 0.87(\text{stat.})^{+0.32}_{-0.24}(\text{syst.}) \pm 0.42(f_s)) \times 10^{-4}$ |
| $B_s^0 \to J/\psi \eta'(\eta\pi\pi)$ | 0.45% |             |         |
| $B_s^0 \to J/\psi \eta(\eta\pi\pi)$   | 1.79% |             |         |
| $B_s^0 \to J/\psi \eta'(\eta\pi\pi)$ | 0.52% |             |         |
| $B_s^0 \to J/\psi \eta'(\rho\gamma\gamma)$ | 0.88% |             |         |
| Total $B_s^0 \to J/\psi \eta^{(')}$ | 1.40% | 3.8$\sigma$  | $(3.1 \pm 1.2(\text{stat.})^{+0.5}_{-0.6}(\text{syst.}) \pm 0.38(f_s)) \times 10^{-4}$ |

| Source                           | $B(J/\psi \eta)$ | $B(J/\psi \eta')$ | $B(J/\psi \eta')$ |
|----------------------------------|------------------|-------------------|-------------------|
| Signal shape calibration         | +5.8, −2.9       | +11.7, −16.8      |                   |
| Beam energy                      | +1.6, −0.0       | +4.8, −4.3        |                   |
| MC signal shape                  | +1.0, −2.0       | +2.6, −4.0        |                   |
| $f(B_s^{(s)} \to B_s^{(s)})$     | +0.7, −1.5       | +4.6, −4.0        |                   |
| Background parameters            | +0.9, −0.8       | +6.0, −5.5        |                   |
| Track reconstruction             | 2.5              | 4.2               |                   |
| Lepton identification            | 4.2              | 4.1               |                   |
| Pion identification              | 0.4              | 2.3               |                   |
| $\eta(\pi^0)$ → $\gamma \gamma$ | 4.1              | 2.8               |                   |
| $B(J/\psi \to \Upsilon(5S))$     | 0.72             | 0.72              |                   |
| $B(\eta^{(')} \to \text{final states})$ | 0.49 | 2.3               |                   |
| Luminosity                       | 1.3              | 1.3               |                   |
| $\sigma_{\text{b}}$             | 4.6              | 4.6               |                   |
| $f_s$                            | +13.4, −13.3     | +13.4, −13.3      |                   |
| Total                            | +16.8, −16.1     | +21.9, −24.8      |                   |
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