

## Study of $J/\psi \rightarrow p\bar{p}$ , $\Lambda\bar{\Lambda}$ and Observation of $\eta_c \rightarrow \Lambda\bar{\Lambda}$ at Belle

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We study the baryonic charmonium decays of  $B$  mesons  $B^+ \rightarrow \eta_c K^+$  and  $B^+ \rightarrow J/\psi K^+$ , where the  $\eta_c$  and  $J/\psi$  subsequently decay into a  $p\bar{p}$  or  $\Lambda\bar{\Lambda}$  pair. We measure the  $J/\psi \rightarrow p\bar{p}$  and  $\Lambda\bar{\Lambda}$  anisotropy parameters  $\alpha_B = -0.60 \pm 0.13 \pm 0.14$  ( $p\bar{p}$ ),  $-0.44 \pm 0.51 \pm 0.31$  ( $\Lambda\bar{\Lambda}$ ) and compare to results from  $e^+e^- \rightarrow J/\psi$  formation experiments. We also report the first observation of  $\eta_c \rightarrow \Lambda\bar{\Lambda}$ . The measured branching fraction is  $\mathcal{B}(\eta_c \rightarrow \Lambda\bar{\Lambda}) = (0.87^{+0.24}_{-0.21}(\text{stat})^{+0.09}_{-0.14}(\text{syst}) \pm 0.27(\text{PDG})) \times 10^{-3}$ . This study is based on a  $357 \text{ fb}^{-1}$  data sample recorded on the  $Y(4S)$  resonance with the Belle detector at the KEKB asymmetric-energy  $e^+e^-$  collider.

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There have been many observations of baryonic three-body  $B$  decays in recent years [1–5]. An interesting feature of these observations is the presence of peaks near threshold in the mass spectra of the baryon-antibaryon pair. These enhancements are not likely to be resonance states, as the baryon angular distributions are not symmetric in their respective helicity frames [6]. Other visible structures in the mass spectra arise from charmonium decays. It is natural to compare the baryon angular distributions from charmonium decays with those in the region of the threshold enhancement. There is particular interest in  $J/\psi \rightarrow p\bar{p}$ , where the proton angular distribution has been studied by the DASP [7], DM2 [8], Mark I [9], Mark II [10], and BES [11–13] Collaborations.  $J/\psi$  mesons from the reaction  $e^+e^- \rightarrow J/\psi$  are produced predominantly in helicity  $\pm 1$  states. Therefore, the baryon angular distributions are proportional to  $1 + \alpha \cos^2\theta$ , where  $\theta$  is the baryon polar angle in the  $J/\psi$  helicity frame. Many theoretical predictions [14] exist for the value of  $\alpha$ .

Study of two-body baryonic decays of charmonia at a  $B$  factory has several different features as compared with an  $e^+e^-$  machine running at the  $J/\psi$  mass.  $J/\psi$  mesons from the two-body decay of  $B$  mesons accompanied by spin zero particles are in a pure helicity zero state. This provides a useful cross-check for previous measurements. The charmonia from  $B$  decays do not suffer from poor acceptance near the beam pipe, and events with  $|\cos\theta|$  near 1 can be detected. Such events are very effective for determining  $\alpha$ . Requiring that the  $J/\psi$  originate from a  $B$  decay eliminates  $e^+e^- \rightarrow q\bar{q} \rightarrow p\bar{p}$  background, where  $q$  stands for a  $u$  or  $d$  quark. For  $e^+e^- \rightarrow J/\psi \rightarrow p\bar{p}$ , this background cannot be separated from the signal on an event-by-event basis.

In the study of two-body baryonic decays of charmonia, we focus on the decay processes  $B^+ \rightarrow p\bar{p}K^+$  and  $B^+ \rightarrow$

$\Lambda\bar{\Lambda}K^+$  [15]. We report the first observation of  $\eta_c \rightarrow \Lambda\bar{\Lambda}$ . There is little information about  $\eta_c$  decays into baryon-antibaryon pairs except for  $\eta_c \rightarrow p\bar{p}$ . Measuring decay rates of the  $\eta_c$  to different baryon-antibaryon modes is a useful check for theoretical predictions [16] and can shed light on quark-diquark dynamics.

We use a  $357 \text{ fb}^{-1}$  data sample consisting of  $386 \times 10^6$   $B\bar{B}$  pairs collected by the Belle detector at the KEKB asymmetric-energy  $e^+e^-$  (3.5 on 8 GeV) collider [17]. The Belle detector is a large solid angle magnetic spectrometer that consists of a four layer silicon vertex detector (SVD), a 50 layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time of flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI (TI) crystals 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. The detector is described in detail elsewhere [18].

The event selection criteria are based on information obtained from the tracking system (SVD + CDC) and the hadron identification system (CDC + ACC + TOF). We follow the same procedure as in Ref. [3] to select proton and kaon candidates.  $\Lambda$  candidates are reconstructed via the  $p\pi^-$  channel using the method described in Ref. [19].

To identify the reconstructed  $B$  meson candidates, we use the beam energy constrained mass  $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2}$  and the energy difference  $\Delta E = E_B - E_{\text{beam}}$ , where  $E_{\text{beam}}$  is the beam energy, and  $p_B$  and  $E_B$  are the momentum and energy of the reconstructed  $B$  meson in the rest frame of the  $Y(4S)$ . The signal region is defined as  $5.2 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$  and

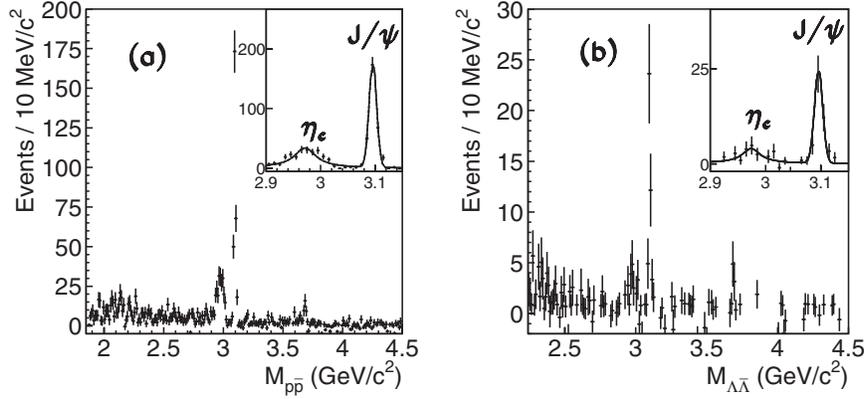


FIG. 1. (a)  $B$  signal yield versus  $M_{p\bar{p}}$  and (b)  $B$  signal yield versus  $M_{\Lambda\bar{\Lambda}}$ . The inset shows the  $\eta_c$ - $J/\psi$  mass region. The curves represent the unbinned likelihood fits to the data.

$-0.1 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$ . The signal peaks at  $M_{bc} = 5.279 \text{ GeV}/c^2$  and  $\Delta E = 0$ .

The dominant background arises from continuum  $e^+e^- \rightarrow q\bar{q}$  processes. The background from  $b \rightarrow c$  and from  $B$  decays into charmless final states is negligible. In the  $Y(4S)$  rest frame, continuum events are jetlike while  $B\bar{B}$  events are more spherical. The reconstructed momenta of final state particles are used to form several event shape variables (e.g., thrust angle, Fox-Wolfram moments, etc.) in order to categorize each event. We follow the scheme described in Ref. [20] that combines seven event shape variables into a Fisher discriminant to suppress continuum background.

Probability density functions (PDFs) for the Fisher discriminant and the cosine of the angle between the  $B$  flight direction and the beam direction in the  $Y(4S)$  rest frame are combined to form the signal likelihood  $\mathcal{L}_s$  and the background likelihood  $\mathcal{L}_b$ . The signal PDFs are determined from GEANT-based Monte Carlo (MC) simulation, and the background PDFs are obtained from sideband data with  $M_{bc} < 5.26 \text{ GeV}/c^2$ . We require the likelihood ratio  $\mathcal{R} = \mathcal{L}_s/(\mathcal{L}_s + \mathcal{L}_b)$  to be greater than 0.4 for both  $p\bar{p}K^+$  and  $\Lambda\bar{\Lambda}K^+$  modes. These selection criteria suppress approximately 69% (66%) of the background while retaining 92% (91%) of the signal for the  $p\bar{p}K^+$  ( $\Lambda\bar{\Lambda}K^+$ ) mode. If there are multiple  $B$  candidates in an event, we select the one with the best  $\chi^2$  value from the  $B$  decay vertex fit. Multiple  $B$  candidates are found in less than 2% (5%) of events for the  $p\bar{p}K^+$  ( $\Lambda\bar{\Lambda}K^+$ ) mode.

We use an unbinned extended maximum likelihood fit to estimate the  $B$  signal yield. For the signal PDF, we use a Gaussian in  $M_{bc}$  and a double Gaussian in  $\Delta E$ . We fix the parameters of these functions to the values determined from MC simulation [21]. Background shapes are fixed from fitting to the sideband events in the region  $3.14 \text{ GeV}/c^2 < M_{p\bar{p}} < 3.34 \text{ GeV}/c^2$ . The  $M_{bc}$  background is modeled using a parametrization used by the ARGUS Collaboration [22]. The  $\Delta E$  background shape is modeled by a first order polynomial.

We determine  $B$  signal yields in  $10 \text{ MeV}/c^2$ -wide  $M_{p\bar{p}}$  ( $M_{\Lambda\bar{\Lambda}}$ ) mass bins from the kinematic threshold to  $4.5 \text{ GeV}/c^2$ ; the result is shown in Fig. 1(a) [Fig. 1(b)]. There are clear  $\eta_c$  and  $J/\psi$  peaks [and a possible  $\psi(2S)$  signal] in the mass spectrum. We use a relativistic Breit-Wigner function for the  $\eta_c$  peak, a Gaussian for the  $J/\psi$  peak, and a linear function for the nonresonant background. The Breit-Wigner function is convolved with the detector response function, which is taken from the  $J/\psi$  peak. A maximum likelihood fit to the data is shown in the inset. We obtain an  $\eta_c$  mass of  $M_{\eta_c} = 2971 \pm 3_{-1}^{+2} \text{ MeV}/c^2$  ( $2974 \pm 7_{-1}^{+2} \text{ MeV}/c^2$ ) and a width of  $\Gamma(\eta_c) = 48_{-7}^{+8} \pm 5 \text{ MeV}/c^2$  ( $40 \pm 19 \pm 5 \text{ MeV}/c^2$ ) for the  $\eta_c \rightarrow p\bar{p}$  ( $\eta_c \rightarrow \Lambda\bar{\Lambda}$ ) mode. The systematic errors are determined from the differences of  $J/\psi$  peaks between data and the Particle Data Group (PDG) [23] value and by varying different fit shapes for  $\eta_c$  signal and background, assuming no interference effect between them. The width is larger than the PDG average but is consistent with recent BABAR [5,24] and previous Belle [25] measurements.

We define the  $J/\psi$  signal region as  $3.075 \text{ GeV}/c^2 < M_{p\bar{p}} < 3.117 \text{ GeV}/c^2$  and use events in this signal region to study the proton angular distribution in the helicity frame of the  $J/\psi$ . The helicity angle  $\theta_X$  is defined as the angle between the proton flight direction and the direction opposite to the flight of the kaon in the  $J/\psi$  rest frame. The angular distribution of  $J/\psi$  in the helicity zero state is parametrized as  $P(\alpha_B, \cos\theta_X) = (1 + \alpha_B \cos^2\theta_X)/(2 + 2\alpha_B/3)$ , with  $\alpha_B = -2\alpha/(\alpha + 1)$  [26]. Here  $\alpha$  is the anisotropy parameter determined from the angular distribution of  $J/\psi$  in helicity  $= \pm 1$  states produced in  $e^+e^- \rightarrow J/\psi$ . Previous measurements [7–13] give an average of  $\alpha = 0.66 \pm 0.05$  for  $p\bar{p}$  and  $\alpha = 0.65 \pm 0.11$  for  $\Lambda\bar{\Lambda}$ ; these values correspond to  $\alpha_B = -0.80 \pm 0.04$  for  $p\bar{p}$  and  $\alpha_B = -0.79 \pm 0.08$  for  $\Lambda\bar{\Lambda}$ .

For analysis of the angular distribution, we define a likelihood  $L$ ,

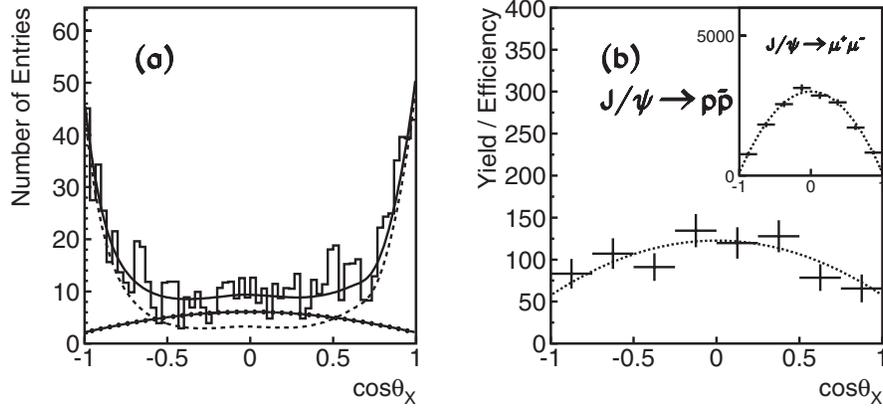


FIG. 2. (a) Likelihood fit and (b)  $\chi^2$  fit results of the  $J/\psi \rightarrow p\bar{p}$  helicity angle distribution. In the maximum likelihood fit plot, the solid, dotted solid, and dashed lines represent the combined fit result, fitted signal, and fitted background, respectively. In the  $\chi^2$  fit plot, the inset shows the fit result for  $B$  signal yield of  $B^+ \rightarrow J/\psi K^+$ ,  $J/\psi \rightarrow \mu^+ \mu^-$ .

$$\frac{e^{-(N_s+N_b)}}{N!} \prod_{i=1}^N [N_s P_s(M_{bc_i}, \Delta E_i) \epsilon(\cos\theta_{X_i}) P(\alpha_B, \cos\theta_{X_i}) + N_b P_b(M_{bc_i}, \Delta E_i, \cos\theta_{X_i})],$$

where  $\alpha_B$  is a fit parameter in addition to  $N_s$  and  $N_b$ ,  $\epsilon(\cos\theta_X)$  is the efficiency function, and  $\epsilon P$  is normalized to 1. The efficiency  $\epsilon(\cos\theta_X)$  obtained from the signal MC simulation is flat as a function of  $\cos\theta_X$ . From a study of a signal MC simulation, we find that there is no correlation between  $M_{bc}$ ,  $\Delta E$ , and  $\theta_X$ . The background PDF as a function of  $M_{bc}$ ,  $\Delta E$ , and  $\cos\theta_X$  is determined from  $M_{p\bar{p}}$  sideband data. Figure 2(a) shows the result of the fit to the  $J/\psi \rightarrow p\bar{p}$  candidates in the entire  $M_{bc}$ ,  $\Delta E$  region. We determine  $\alpha_B$  to be  $-0.60 \pm 0.13$ . As a cross-check, we use a  $\chi^2$  method and fit the efficiency corrected  $B$  signal yields in bins of  $\cos\theta_X$  to a  $1 + \alpha_B \cos^2\theta_X$  parametrization. The results of the fit are shown in Fig. 2(b). We obtain  $\alpha_B = -0.53 \pm 0.15$ , with  $\chi^2/\text{d.o.f.} = 0.9$ , consistent with the result of the unbinned fit. We measure the angular distribution of  $J/\psi \rightarrow \mu^+ \mu^-$  decays from  $B^+ \rightarrow J/\psi K^+$  to verify the fitting procedure. The result is shown in the inset in Fig. 2(b). The fitted value agrees with the expectation for massless fermions.

We determine the systematic error in  $\alpha_B$  by varying the value of various selection cuts and parameters of PDFs to

check for trends in the value of  $\alpha_B$ . These trends are parametrized by a linear function. We then quote the change in  $\alpha_B$  along the line between the selected point and the far end of the tested region as a systematic error. Note that this is a conservative estimate, since statistical fluctuations also contribute to changes in  $\alpha_B$ . We assign a systematic error of 0.08 for the  $\mathcal{R}$  selection, 0.06 for proton or kaon selection, and 0.02 for fitting PDFs. Other systematic errors are negligible. The observed difference between the maximum likelihood method and the  $\chi^2$  method is also included in the systematic error. The total systematic uncertainty in  $\alpha_B$  is 0.13.

There are several complicating factors in the analysis of  $B^+ \rightarrow \Lambda \bar{\Lambda} K^+$  decays relative to  $B^+ \rightarrow p\bar{p} K^+$  decays. The efficiency for detecting slow pion from  $\Lambda$  decays is small. As a result, the  $\Lambda$  reconstruction efficiency is nonuniform as a function of the polar angle ( $\cos\theta_p$ ) of the secondary proton in the  $\Lambda$  helicity frame and is correlated with  $\cos\theta_X$ , where  $\theta_X$  refers to the  $\Lambda$  polar angle in the  $J/\psi$  helicity frame. The likelihood function is similar to the previous one except that the angular part contains two more varia-

TABLE I. Measured branching fractions for  $J/\psi$ ,  $\eta_c \rightarrow p\bar{p}$ ,  $\Lambda \bar{\Lambda}$ .

Modes	Yield	Efficiency (%)	Branching fraction product ( $10^{-6}$ )	$\mathcal{B}(J/\psi, \eta_c \rightarrow p\bar{p}, \Lambda \bar{\Lambda})(10^{-3})$
$B^+ \rightarrow \eta_c K^+$ , $\eta_c \rightarrow p\bar{p}$	$195_{-15}^{+16}$	$35.8_{-0.3}^{+0.3}$	$1.42_{-0.11-0.20}^{+0.11+0.16}$	$1.58 \pm 0.12_{-0.22}^{+0.18} \pm 0.47^a$
$B^+ \rightarrow \eta_c K^+$ , $\eta_c \rightarrow \Lambda \bar{\Lambda}$	$19.5_{-4.5}^{+5.2}$	$5.3_{-0.1}^{+0.1}$	$0.95_{-0.22-0.11}^{+0.25+0.08}$	$0.87_{-0.21-0.14}^{+0.24+0.09} \pm 0.27^b$
$B^+ \rightarrow J/\psi K^+$ , $J/\psi \rightarrow p\bar{p}$	$317_{-18}^{+19}$	$37.3_{-0.4}^{+0.4}$	$2.21_{-0.13}^{+0.13} \pm 0.10$	$2.21 \pm 0.13 \pm 0.31 \pm 0.10^c$
$B^+ \rightarrow J/\psi K^+$ , $J/\psi \rightarrow \Lambda \bar{\Lambda}$	$45.9_{-6.7}^{+7.7}$	$5.9_{-0.3}^{+0.3}$	$2.00_{-0.29}^{+0.34} \pm 0.34$	$2.00_{-0.29}^{+0.34} \pm 0.34 \pm 0.08^c$

<sup>a</sup> $\mathcal{B}(B^+ \rightarrow \eta_c K^+) = 0.9 \pm 0.27 \times 10^{-3}$  [23].

<sup>b</sup>We use  $\mathcal{B}(B^+ \rightarrow \eta_c K^+, \eta_c \rightarrow \Lambda \bar{\Lambda})/\mathcal{B}(B^+ \rightarrow \eta_c K^+, \eta_c \rightarrow p\bar{p}) = 0.67_{-0.16}^{+0.19} \pm 0.12$  measured in this Letter and  $\mathcal{B}(\eta_c \rightarrow p\bar{p}) = 1.3 \pm 0.4 \times 10^{-3}$  [23].

<sup>c</sup> $\mathcal{B}(B^+ \rightarrow J/\psi K^+) = 1.00 \pm 0.04 \times 10^{-3}$  [23].

bles,  $\cos\theta_p$  and  $\cos\theta_{\bar{p}}$ . The efficiency function  $\epsilon(\cos\theta_X, \cos\theta_p, \cos\theta_{\bar{p}})$  is obtained from a signal MC sample with  $4 \times 10^6$  events. The background PDF is determined from  $M_{\Lambda\bar{\Lambda}}$  sideband data in the region  $3.14 \text{ GeV}/c^2 < M_{\Lambda\bar{\Lambda}} < 3.54 \text{ GeV}/c^2$ . The value of  $\alpha_B$  obtained from the maximum likelihood fit is  $-0.44 \pm 0.51 \pm 0.31$ , where the systematic error is determined from the same procedure as that used for  $J/\psi \rightarrow p\bar{p}$  decays.

We define an  $\eta_c$  signal region as  $2.94 \text{ GeV}/c^2 < M_{\Lambda\bar{\Lambda}} < 3.02 \text{ GeV}/c^2$ . Signal peaks are visible in the  $M_{bc}$  and  $\Delta E$  distributions. The fitted  $B$  signal yield, efficiency, and obtained branching fraction are shown in Table I. The maximum likelihood fit for  $B^+ \rightarrow \eta_c K^+$ ,  $\eta_c \rightarrow \Lambda\bar{\Lambda}$  gives a yield of  $19.5^{+5.1}_{-4.4}$  with a statistical significance of 7.9 standard deviations. The significance is defined as  $\sqrt{-2\ln(L_0/L_{\max})}$ , where  $L_0$  and  $L_{\max}$  are the likelihood values returned by the fit with the signal yield fixed to zero and at its best fit value, respectively. The fit yield is consistent with the yield ( $18.2 \pm 4.8$ ) obtained from the first fit shown in Fig. 1(b). As a cross-check, the obtained  $\mathcal{B}(J/\psi \rightarrow p\bar{p}, \Lambda\bar{\Lambda})$  are in good agreement with the world average and with the latest BES result [13]. We also determine the branching fraction ratios:  $\mathcal{B}(\eta_c \rightarrow \Lambda\bar{\Lambda})/\mathcal{B}(\eta_c \rightarrow p\bar{p}) = 0.67^{+0.19}_{-0.16} \pm 0.12$  and  $\mathcal{B}(J/\psi \rightarrow \Lambda\bar{\Lambda})/\mathcal{B}(J/\psi \rightarrow p\bar{p}) = 0.90^{+0.15}_{-0.14} \pm 0.10$ , where common systematic errors in the numerator and denominator cancel.

Systematic uncertainties are studied using high statistics control samples. For proton identification, we use a  $\Lambda \rightarrow p\pi^-$  sample, while for  $K/\pi$  identification, we use a  $D^{*+} \rightarrow D^0\pi^+$ ,  $D^0 \rightarrow K^-\pi^+$  sample. The tracking efficiency is studied with fully and partially reconstructed  $D^*$  samples. The modeling of the requirement on the likelihood ratio  $\mathcal{R}$  for background suppression is studied with a topologically similar control sample  $B^+ \rightarrow J/\psi K^+$ ,  $J/\psi \rightarrow \mu^+\mu^-$ . For  $\Lambda$  reconstruction, we have an additional uncertainty on the efficiency for detecting tracks away from the IP. The size of this uncertainty is determined from the difference between  $\Lambda$  decay-time distributions in data and MC simulation. Based on these studies, we assign a 1% error for each track, 2% for each proton identification, 1% for each kaon or pion identification, an additional 3% for  $\Lambda$  reconstruction, and 3% for the  $\mathcal{R}$  selection.

The systematic uncertainty in the fit yield is studied by varying the parameters of the signal and background PDFs and is approximately 5%. The MC statistical uncertainty and modeling contributes a 5% error. The error on the number of  $B\bar{B}$  pairs is determined to be 1%, where the branching fractions of  $Y(4S)$  to neutral and charged  $B\bar{B}$  pairs are assumed to be equal. The noncharmonium feed-down background below the  $\eta_c$  mass region is estimated to be 8% and 12% for the  $p\bar{p}$  and  $\Lambda\bar{\Lambda}$  modes, respectively.

The correlated errors are added linearly and combined quadratically with the uncorrelated errors in the

systematic error calculation. The total systematic uncertainties are 14% and 17% for the  $p\bar{p}K^+$  and  $\Lambda\bar{\Lambda}K^+$  modes, respectively.

In summary, using  $386 \times 10^6 B\bar{B}$  events, we measure the branching fractions of  $J/\psi \rightarrow p\bar{p}$ ,  $\eta_c \rightarrow p\bar{p}$ ,  $J/\psi \rightarrow \Lambda\bar{\Lambda}$ , and  $\eta_c \rightarrow \Lambda\bar{\Lambda}$  from  $B^+ \rightarrow p\bar{p}K^+$  and  $B^+ \rightarrow \Lambda\bar{\Lambda}K^+$  decays. We measure the parameter  $\alpha_B$  for baryonic  $J/\psi$  decays. The parameters  $\alpha_B$  are  $-0.60 \pm 0.13 \pm 0.14$  and  $-0.44 \pm 0.51 \pm 0.31$  for  $J/\psi \rightarrow p\bar{p}$  and  $J/\psi \rightarrow \Lambda\bar{\Lambda}$ , respectively. This gives an  $\alpha$  value for  $J/\psi \rightarrow p\bar{p}$  of  $0.43 \pm 0.13 \pm 0.14$ , which is smaller than, but still consistent with, the current world average  $0.66 \pm 0.05$ . We also report the first observation of  $\eta_c \rightarrow \Lambda\bar{\Lambda}$  decays with  $\mathcal{B}(\eta_c \rightarrow \Lambda\bar{\Lambda}) = (0.87^{+0.24}_{-0.21} +^{0.09}_{-0.14} \pm 0.27) \times 10^{-3}$ . The observed ratio  $\mathcal{B}(\eta_c \rightarrow \Lambda\bar{\Lambda})/\mathcal{B}(\eta_c \rightarrow p\bar{p})$  is  $0.67^{+0.19}_{-0.16} \pm 0.12$ , which is consistent with theoretical expectation [16].

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