Observation of $\psi(3686) \to \Xi(1530)^-\Xi(1530)^+$ and $\Xi(1530)^-$
Y. H. Zhang\textsuperscript{1,43}, Y. T. Zhang\textsuperscript{55,43}, Yang Zhang\textsuperscript{1}, Yao Zhang\textsuperscript{1}, Yi Zhang\textsuperscript{9,j}, Yu Zhang\textsuperscript{47}, Z. H. Zhang\textsuperscript{6}, Z. P. Zhang\textsuperscript{55}, Z. Y. Zhang\textsuperscript{60}, G. Zhao\textsuperscript{1,3}, J. W. Zhao\textsuperscript{1,43}, J. Y. Zhao\textsuperscript{1,47}, J. Z. Zhao\textsuperscript{1,43}, Lei Zhao\textsuperscript{55,43}, Ling Zhao\textsuperscript{1}, M. G. Zhao\textsuperscript{34}, Q. Zhao\textsuperscript{1}, S. J. Zhao\textsuperscript{63}, T. C. Zhao\textsuperscript{1}, Y. B. Zhao\textsuperscript{1,43}, Z. G. Zhao\textsuperscript{55,43}, A. Zhemchugov\textsuperscript{27,h}, B. Zheng\textsuperscript{56}, J. P. Zheng\textsuperscript{1,43}, Y. Zheng\textsuperscript{35}, Y. H. Zheng\textsuperscript{47}, B. Zhong\textsuperscript{32}, L. Zhou\textsuperscript{1,43}, L. P. Zhou\textsuperscript{1,47}, Q. Zhou\textsuperscript{1,47}, X. Zhou\textsuperscript{60}, X. K. Zhou\textsuperscript{47}, X. R. Zhou\textsuperscript{55,43}, Xiaoyu Zhou\textsuperscript{20}, Xu Zhou\textsuperscript{20}, A. N. Zhu\textsuperscript{1,47}, J. Zhu\textsuperscript{34}, J. Zhu\textsuperscript{44}, K. Zhu\textsuperscript{1}, K. J. Zhu\textsuperscript{1,43,47}, S. H. Zhu\textsuperscript{54}, W. J. Zhu\textsuperscript{44}, X. L. Zhu\textsuperscript{45}, Y. C. Zhu\textsuperscript{55,43}, Y. S. Zhu\textsuperscript{1,47}, Z. A. Zhu\textsuperscript{1,47}, J. Zhuang\textsuperscript{1,43}, B. S. Zou\textsuperscript{1}, J. H. Zou\textsuperscript{1}

(BESIII Collaboration)

1 Institute of High Energy Physics, Beijing 100049, People’s Republic of China
2 Beihang University, Beijing 100191, People’s Republic of China
3 Beijing Institute of Petrochemical Technology, Beijing 102617, People’s Republic of China
4 Bochum Ruhr-University, D-44780 Bochum, Germany
5 Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
6 Central China Normal University, Wuhan 430079, People’s Republic of China
7 China Center of Advanced Science and Technology, Beijing 100190, People’s Republic of China
8 COMSATS University Islamabad, Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan
9 Fudan University, Shanghai 200443, People’s Republic of China
10 G.I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia
11 GSI Helmholtzcentre for Heavy Ion Research GmbD, D-64291 Darmstadt, Germany
12 Guangxi Normal University, Guilin 541004, People’s Republic of China
13 Guangxi University, Nanning 530004, People’s Republic of China
14 Hangzhou Normal University, Hangzhou 310036, People’s Republic of China
15 Helmholtz Institute Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
16 Henan Normal University, Xinxiang 453007, People’s Republic of China
17 Henan University of Science and Technology, Luoyang 471003, People’s Republic of China
18 Huangshan College, Huangshan 245000, People’s Republic of China
19 Hunan Normal University, Changsha 410081, People’s Republic of China
20 Hunan University, Changsha 410082, People’s Republic of China
21 Indian Institute of Technology Madras, Chennai 600036, India
22 Indiana University, Bloomington, Indiana 47405, USA
23 (A)INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy; (B)INFN and University of Perugia, I-06100, Perugia, Italy
24 (A)INFN Sezione di Ferrara, I-44122, Ferrara, Italy; (B)University of Ferrara, I-44122, Ferrara, Italy
25 Institute of Physics and Technology, Peace Ave. 54B, Ulaanbaatar 13330, Mongolia
26 Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
27 Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
28 Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany
29 KVI-CART, University of Groningen, NL-9747 AA Groningen, The Netherlands
30 Lanzhou University, Lanzhou 730000, People’s Republic of China
31 Liaoning University, Shenyang 110036, People’s Republic of China
32 Nanjing Normal University, Nanjing 210023, People’s Republic of China
33 Nanjing University, Nanjing 210093, People’s Republic of China
34 Nankai University, Tianjin 300071, People’s Republic of China
35 Peking University, Beijing 100871, People’s Republic of China
36 Shandong Normal University, Jinan 250014, People’s Republic of China
37 Shandong University, Jinan 250100, People’s Republic of China
38 Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China
39 Shanxi University, Taiyuan 030006, People’s Republic of China
40 Sichuan University, Chengdu 610064, People’s Republic of China
41 Soochow University, Suzhou 215006, People’s Republic of China
42 Southeast University, Nanjing 211100, People’s Republic of China
43 State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People’s Republic of China
Using 448.1 × 10^6 ψ(3686) events collected with the BESIII detector at BEPCII, we employ a single-baryon tagging technique to make the first observation of ψ(3686) → Ξ(1530)^− Ξ(1530)^+ and Ξ(1530)^− Ξ(1530)^+ decays with a statistical significance of more than 10σ and 5.0σ, respectively. The branching fractions are measured to be \( B(ψ(3686) → Ξ(1530)^− Ξ(1530)^+) = (11.45 ± 0.40 ± 0.59) \times 10^{-5} \) and \( B(ψ(3686) → Ξ(1530)^− Ξ(1530)^+) = (0.70 ± 0.11 ± 0.04) \times 10^{-5} \). The angular distribution parameter for \( ψ(3686) → Ξ(1530)^− Ξ(1530)^+ \) is determined to be \( α = 0.40 ± 0.24 ± 0.06 \), which agrees with the theoretical predictions within 1σ. The first uncertainties are statistical, and the second systematic.

PACS numbers: 13.25.Ft, 13.30.-a

The decays of the charmonium resonances, such as \( ψ(3686) \), into baryon anti-baryon pairs \( (B\bar{B}) \) have been extensively studied as a useful test of perturbative quantum chromodynamics (QCD) \([1, 2]\). They proceed via the annihilation of the \( c\bar{c} \) pair into three gluons for strong decays or a virtual photon for electromagnetic decays. Within the context of SU(3) flavor symmetry, decays of charmonium to \( B\bar{B} \) (i.e., \( B_1\bar{B}_1, B_8\bar{B}_8 \) and \( B_{10}\bar{B}_{10} \), where \( B_1 \) is for baryon singlet, \( B_8 \) is for baryon octet and \( B_{10} \) is for baryon decuplet) are allowed, but decays into octet-decuplet baryonic pairs \( (B_{10}\bar{B}_8) \) are forbidden \([3, 4]\). However, many experimental results on \( J/ψ → B_{10}\bar{B}_8 \) decay \([5, 6]\) indicate the pres-
ence of flavor SU(3) symmetry breaking. There is no previous experimental information on $\psi(3686) \to B_{16} \bar{B}_{16}$, such as $\psi(3686) \to \Xi(1530)^- \Xi^+$ decay.

Due to hadron helicity conservation [1, 7], the angular distributions for the process $e^+ e^- \to \psi(3686) \to B \bar{B}$ are given by

$$\frac{dN}{d\cos \theta_B} \propto 1 + \alpha \cos^2 \theta_B,$$

where $\theta_B$ is the angle between one of the baryons and the $e^+$ beam direction in the $e^+ e^-$ center-of-mass (CM) system, and the $\alpha$ is the angular distribution parameter, which is widely investigated in theory and experiment [8–10]. Many theoretical models, such as those considering quark mass effects [11], and electromagnetic effects [12], predict that the angular distribution parameter obeys $\alpha < 1$. The BES and BESIII collaborations measured the angular distribution of $J/\psi \to \Upsilon(0)^0, \Upsilon(1385)^0 \Xi(1385)$ and obtained a negative $\alpha$ value, but with poor precision [10, 13]. H. Chen et al. [14] noted that the angular distribution parameter for $J/\psi$ and $\psi(3686) \to B \bar{B}$ could be negative when re-scattering effects of $B \bar{B}$ in heavy quarkonium decays are taken into account. Additional measurements of the $\alpha$ parameter are of interest to confront the various theoretical approaches.

In other experiments, the angular distributions for charmonium decays to baryon pairs, such as $J/\psi$ and $\psi(3686) \to p\bar{p}, \Lambda \bar{\Lambda}, \Sigma^0 \Sigma^0, \Xi \Xi, \Sigma(1385) \Sigma(1385)$ [9, 15], were reported. Negative $\alpha$ values were found for the processes $J/\psi \to \Upsilon(0)^0, \Upsilon(1385)^0 \Xi(1385)$, while for other processes $\alpha$ was either measured to be positive, or not measured. The BESIII experiment has a large data sample at the $\psi(3686)$ resonance, which can be used to verify the theoretical models for the process like $\psi(3686) \to \Xi(1530)^- \Xi(1530)^+$, for which the $\alpha$ value is predicted to be 0.18 and 0.31 [11, 12].

In this paper, the observation of $\psi(3686) \to \Xi(1530)^- \Xi(1530)^+$ and $\Xi(1530)^- \Xi^+$ decays is presented based on 448.1 $\times 10^6 \psi(3686)$ events [16] collected with the BESIII detector at the BEPCII in 2009 and 2012. Selection of $\psi(3686) \to \Xi(1530)^- \Xi(1530)^+$ and $\Xi(1530)^- \Xi^+$ events via full reconstruction suffers from low efficiency. To achieve a higher efficiency, we first reconstruct a $\Xi(1530)^-$, referred to as a $\Xi(1530)^-$ tag, and then search for a recoiling $\Xi(1530)^+$ or $\Xi^+$ signal (unless otherwise noted, charge conjugation (c.c.) is implied throughout the paper).

To determine the detection efficiencies for $\psi(3686) \to \Xi(1530)^- \Xi(1530)^+$ and $\Xi(1530)^- \Xi^+$, 100,000 simulated events are generated for each reconstructed mode. For the $\Xi(1530)^- \Xi(1530)^+$ final state, the angular distribution is generated with the $\alpha$ value measured in this analysis, while for $\Xi(1530)^- \Xi^+$ we use $\alpha = 1$ based on theory [17]. The $\Xi(1530)^-$ decays to the $\pi^0(0^-)\Xi^- (0^-)$ modes, with $\Xi^0(0^-) \to \pi^0(0^-)\Lambda, \Lambda \to p\pi^-$ and $n^0 \to \gamma\gamma$, are simulated using EVTGEN [18], and the response of the BESIII detector is modeled with Monte Carlo (MC) simulations using a framework based on GEANT4 [19]. A detailed description of the BESIII detector is given in Ref. [20]. To study the potential backgrounds, an inclusive MC sample of $350 \times 10^6 \psi(3686)$ decays is generated, where the production of the $\psi(3686)$ resonance is simulated with the KKMC generator [21], the subsequent decays are processed via EVTGEN [18] according to the measured branching fractions provided by the Particle Data Group (PDG) [22], and the remaining unmeasured decay modes are generated with LUNDCHARM [23]. Data collected at the CM energy of 3.65 GeV (off-peak data sample, 44 pb$^{-1}$) [16] is used to estimate the contamination from the continuum processes $e^+ e^- \to \Xi(1530)^- \Xi(1530)^+$ and $\Xi(1530)^- \Xi^+$.

Charged tracks are reconstructed in the main drift chamber (MDC) within an angular range of $|\cos \theta| < 0.93$, where $\theta$ is the polar angle with respect to the $e^+$ beam direction. Information on the specific energy deposition ($dE/dx$) in the MDC and from the time-of-flight (TOF) counters are combined to form particle identification (PID) confidence levels (CLs) for pion, kaon, and proton hypotheses. Each track is assigned to the particle type with the highest CL. At least two negatively-charged pions and one proton are required. Photons are reconstructed from isolated showers in the electromagnetic calorimeter (EMC). Energy deposited in the nearby TOF counters is included to improve the reconstruction efficiency and energy resolution. Photon energies are required to be greater than 25 MeV in the EMC barrel region ($|\cos \theta| < 0.80$) or greater than 50 MeV in the EMC end caps ($0.86 < |\cos \theta| < 0.92$). Showers in between these angular regions are poorly reconstructed and are excluded. The EMC shower timing is required to be within the range [0, 700] ns, relative to the event start time, to suppress electronic noise and energy deposits unrelated to the analyzed event. The number of good photon candidates, $N_\gamma$, must satisfy $2 \leq N_\gamma \leq 15$.

In order to reconstruct $\pi^0$ candidates, a one-constraint (1C) kinematic fit is applied to all $\gamma\gamma$ combinations, constraining the two-photon invariant mass to the nominal $\pi^0$ mass [22]. To suppress non-$\pi^0$ backgrounds, only combinations with $\chi^2_{1C} < 20$ are retained. The $\Lambda$ candidates are reconstructed from $p\pi^-$ pairs with an invariant mass within 5 MeV/$c^2$ of the nominal $\Lambda$ mass. This interval is determined by optimizing the figure of merit $FOM = \frac{S}{\sqrt{S+B}}$, where $S$ is the number of signal events and $B$ is the number of background events, based on the MC simulation. A secondary vertex fit [24] is performed on all $p\pi^-$ combinations; those with $\chi^2 < 500$ are kept for further analysis. To further suppress the background, the decay length of the $\Lambda$ is required to be positive. In the case of multiple candidates, the one with an unconstrained mass closest to the nominal mass is retained as used in Refs. [13, 25, 26]. The $\Xi$ candidates are reconstructed by considering all $\pi\Lambda$ combinations within 10 MeV/$c^2$ of the nominal $\Xi$ mass. For $\Xi^-$ candidates, a secondary vertex-constrained fit is used, while for both charged and neutral $\Xi$, only the candidate closest to the nominal mass is retained when there is more than one per event. The decay length of the $\Xi^-$ is required to be positive to further suppress the back-
grounds. The $\Xi(1530)^-$ candidates are reconstructed in the $\pi^0\Xi^-$ and $\pi^-\Xi^0$ modes and the candidate closest to the nominal mass is retained when there is more than one per event.

The anti-baryon candidates $\bar{\Xi}^+$ and $\Xi(1530)^+$ are inferred by the mass recoiling against the selected $\pi\Xi$ system,

$$M_{\pi\Xi}^{\text{recoil}} = \sqrt{(E_{\text{CM}} - E_{\pi\Xi})^2 - |\vec{p}_{\pi\Xi}|^2},$$

where $E_{\pi\Xi}$ and $\vec{p}_{\pi\Xi}$ are the energy and momentum of the selected $\pi\Xi$ system, and $E_{\text{CM}}$ is the CM energy. Figure 1 shows the scatter plot of $M_{\pi\Xi}^{\text{recoil}}$ versus $M_{\pi\Xi}^{\text{recoil}}$. To determine signal yields, the mass of the $\pi\Xi$ is required to be within 15 MeV/$c^2$ of the nominal mass of $\Xi(1530)^-$.

Our inclusive MC sample reveals that the main background for $\psi(3686) \to \Xi(1530)^-\Xi(1530)^+$ and $\Xi(1530)^-\Xi(1530)^+$ decays comes from $\psi(3686) \to \pi^+\pi^-\Xi^0\Xi^0$ with $J/\psi \to \Xi^+\Xi^-$; it is distributed smoothly in the signal region of $M_{\pi\Xi}^{\text{recoil}}$. Only a few events in the off-peak data sample survive and do not form any obvious peaking structures in the $\Xi(1530)$ signal region of the corresponding $M_{\pi\Xi}^{\text{recoil}}$ distribution. Taking into account the normalization of the luminosity and CM energy dependence of the cross section, the contribution from continuum processes is expected to be small and is neglected in the further analysis. There are transition $\pi^0$s with similar momenta in both the baryon and anti-baryon decay chains within the signal events. Incorrect use of these in the $\Xi^0$ or $\Xi(1530)^-$ reconstruction leads to a wrong combination background (WCB).

The signal yields for the two decays $\psi(3686) \to \Xi(1530)^-\Xi(1530)^+$ and $\Xi(1530)^-\Xi(1530)^+$ are determined by performing an extended maximum likelihood fit to the $M_{\pi\Xi}^{\text{recoil}}$ spectrum. In the fit, the signal shapes for the two decays are represented by the simulated MC shape convolved with a Gaussian function to take into account the mass resolution difference between the data and the MC simulation, where the parameters of the Gaussian function are left free but are shared by the two decay modes. The WCB is described by the simulated MC shape, and the corresponding numbers of events are fixed according to the MC simulation. The other remaining backgrounds (Other-Bkg) are found to distribute smoothly in the $M_{\pi\Xi}^{\text{recoil}}$ spectrum and are therefore described by a third-order Chebychev function. Figure 2 shows the $M_{\pi\Xi}^{\text{recoil}}$ distributions for the $\Xi(1530)^-$ and $\Xi(1530)^+$ tags, respectively, with $\Xi$ and $\Xi(1530)$ peaks evident in each. Including systematic uncertainties, the significance for $\psi(3686) \to \Xi(1530)^-\Xi(1530)^+$ is calculated to be more than 5.0$\sigma$ for the $\Xi(1530)^-\Xi^+$ and its c.c. mode combined. The individual significances are calculated from the change in log likelihood and degrees of freedom with and without the signal in the fit.

The branching fraction is calculated as

$$B[\psi(3686) \to X] = \frac{N_{\text{obs}}}{N_{\psi(3686)}} \cdot \frac{1}{\sum_{i} |B_{i}|},$$

where $X$ stands for $\Xi(1530)^-\Xi(1530)^+$ or $\Xi(1530)^-\Xi^+$. $N_{\text{obs}}$ is the number of extracted signal events, $N_{\psi(3686)}$ is the total number of $\psi(3686)$ events [16], $i$ runs over the $\pi^-\Xi^0$ and $\pi^0\Xi^-$ modes, $\epsilon_i$ denotes the detection efficiency obtained with the measured $\alpha$ value for both modes, $B_i$ denotes the product of branching fractions of $\Xi(1530) \to \pi\Xi$ and $\Xi \to \pi\Lambda$. Table I summarizes the numerical results for the various modes studied. The angular distribution parameter for $\psi(3686) \to \Xi(1530)^-\Xi(1530)^+$ decay is determined by performing a least squares fit to the $\cos \theta_B$ distribution in the range from $-0.8$ to $0.8$ by Eq. (1), divided into 8 equidistant intervals; this is done separately for $\Xi(1530)^-$ and $\Xi(1530)^+$ tags. The signal yield in each $\cos \theta_B$ bin is obtained with the aforementioned fit method in the $M_{\pi\Xi}^{\text{recoil}}$ range of 1.4 GeV/$c^2$ to 1.7 GeV/$c^2$. The distributions of the efficiency-corrected signal yields together with the fit curves are shown in Fig. 3. The $\alpha$ values obtained are summarized in Table I.

Systematic uncertainties on the branching fractions measurements are mainly due to differences of detection efficiency between data and the MC simulation. The uncertainties associated with the efficiencies of tracking and PID for the pion from the mother particle $\Xi(1530)^-$ in the $\pi^-\Xi^0$ decay mode, are investigated with the control sample $J/\psi \to \rho\pi\pi$. The uncertainty due to the 1C kinematic fit for the $\pi^0$ reconstruction is estimated with the control sample $J/\psi \to \rho\pi$. The uncertainties related to the $\Xi^0$ and $\Xi^-$ reconstruction efficiency combined with tracking, PID, and the $\Lambda$ reconstruction efficiencies are estimated using the control sample $\psi(3686) \to \Xi^0\Xi^0$ and $\Xi^-\Xi^+$. A detailed description of our methods can be found in Ref. [13, 27]. The uncertainties due to the requirements for mass window and decay length of $\Xi$, $\Lambda$ are estimated with the control sample $J/\psi \to \Xi^0\Xi^0$ and $\Xi^-\Xi^+$. The uncertainty related to the mass window of $\Xi(1530)^-$ is estimated by varying the half-width of 15 MeV/$c^2$ by $\pm 1$ MeV/$c^2$. The largest difference of the efficiency between data and MC simulation is taken as the systematic uncertainty. The uncertainty due to the signal shape is estimated by changing the nominal signal function to the Breit-Wigner function; the difference of the signal yields is taken as the systematic uncertainty. The parameters of the Gaussian signal function for the $\Xi(1530)^-\Xi^+$ final state are fixed in the fit; uncertainties are estimated by varying the nominal values by 1$\sigma$. The uncertainty due to the $M_{\pi\Xi}^{\text{recoil}}$ fitting range is estimated by varying the mass range by $\pm 10$ MeV/$c^2$. 

FIG. 1. Distributions of $M_{\pi\Xi}^{\text{recoil}}$ versus $M_{\pi\Xi}^{\text{recoil}}$ for $\pi^-\Xi^0$ mode (Left) and $\pi^+\Xi^-$ mode (Right). The dashed lines denote the $\Xi(1530)$ signal region.
due to the modeling of the angular distribution of the baryon
the fit. The uncertainty related with the detection efficiency
with and without the corresponding component included in
order Chebychev function. The uncertainty due to the WCB
shape are estimated by alternate fits using a second or a fourth-
cos
TABLE I. The number of the extracted events ($N_{\text{obs}}$), efficiencies ($\epsilon_1$ is for $\pi^-\Xi^0$ mode, $\epsilon_2$ is for $\pi^0\Xi^-$ mode), statistical significance ($S$), the angular distribution parameter ($\alpha$) and branching fractions ($B$), where $B^{\text{com}}$ and $\alpha^{\text{com}}$ denote the combined branching fraction and angular distribution parameters. The first uncertainties are statistical, and the second systematic.

| Tag mode | $\psi(3686) \to \Xi(1530)^-$ | $\Xi(1530)^+$ | $\psi(3686) \to \Xi(1530)^-\Xi^+$ | $\Xi(1530)^+$
|----------|----------------|----------------|---------------------------------|----------------|
| $N_{\text{obs}}$ | 2664 $\pm$ 114 | 2403 $\pm$ 132 | 152 $\pm$ 37 | 247 $\pm$ 48 |
| $\epsilon_1$($\%$) | 7.85 $\pm$ 0.09 | 7.16 $\pm$ 0.08 | 8.89 $\pm$ 0.09 | 8.42 $\pm$ 0.09 |
| $\epsilon_2$($\%$) | 8.91 $\pm$ 0.09 | 8.17 $\pm$ 0.09 | 10.58 $\pm$ 0.10 | 9.82 $\pm$ 0.10 |
| $S(\sigma)$ | 23.0 | 18.2 | 4.4 | 5.3 |
| $\alpha$ | 0.43 $\pm$ 0.30 $\pm$ 0.09 | 0.36 $\pm$ 0.35 $\pm$ 0.08 | ... | ... |
| $B(10^{-5})$ | 11.51 $\pm$ 0.49 $\pm$ 0.92 | 11.36 $\pm$ 0.62 $\pm$ 1.14 | 0.57 $\pm$ 0.14 $\pm$ 0.05 | 0.93 $\pm$ 0.18 $\pm$ 0.10 |
| $\alpha^{\text{com}}$ | 0.40 $\pm$ 0.24 $\pm$ 0.06 | ... | ... | ... |
| $B^{\text{com}}(10^{-5})$ | 11.45 $\pm$ 0.40 $\pm$ 0.59 | 0.70 $\pm$ 0.11 $\pm$ 0.04 |

FIG. 3. Distributions of $\cos \theta_B$ for the $\Xi(1530)^-$ tag (Left) and the $\Xi(1530)^+$ tag (Right). The dots with error bars indicate the efficiency corrected data, and the curves show the fit results.

The uncertainties due to the assumed polynomial background shape are estimated by alternate fits using a second or a fourth-order Chebychev function. The uncertainty due to the WCB is estimated by comparing the signal yields between the fits with and without the corresponding component included in the fit. The uncertainty related with the detection efficiency due to the modeling of the angular distribution of the baryon pairs, represented by the parameter $\alpha$, is estimated for the $\Xi(1530)^-\Xi(1530)^+$ mode by varying the measured $\alpha$ values by 1$\sigma$ in the MC simulation. For the $\Xi(1530)^-\Xi^+$ mode, $\alpha$ is set to zero. The uncertainties due to the branching fractions of the intermediate states, $\Xi \to \pi \Lambda$ and $\Lambda \to p \pi$ are taken to be 0.1% and 0.8% according to the PDG [22]. The uncertainty of the branching fraction of $\Xi(1530)^-\Xi^+$ mode, $\alpha$ is taken conservatively according to the branching fraction of $\Xi(1530)^-\Xi^+$ mode. The uncertainties due to the total number of $\psi(3686)$ events ($N_{\psi(3686)}$) are determined with inclusive hadronic $\psi(3686)$ decays [16]. The various systematic uncertainties on the branching fraction measurements are summarized in Table II. The total systematic uncertainty is obtained by summing the individual contributions in quadrature.

Systematic issues for the measurement of the $\alpha$ include the determinations of signal yields in $\cos \theta_B$ intervals and the $\cos \theta_B$ fitting procedure. Signal yield systematic uncertainties arise from the fit range, the background shape, signal shape and WCB. These are evaluated with a method similar.
to the one described above; the resulting differences with respect to the nominal \( \alpha \) values are taken systematic uncertainties. The \( \cos \theta_B \) fitting uncertainties are estimated by re-fitting the \( \cos \theta_B \) distribution with a different binning and fit range. We divide \( \cos \theta_B \) into five intervals of eight, and the change in \( \alpha \) is taken as the systematic uncertainty. We also repeat the fit after altering the \( \cos \theta_B \) range to \([-0.9, 0.9]\) or \([-0.7, 0.7]\), with the same bin size as the nominal fit. The largest changes of \( \alpha \) with respect to the nominal fit are taken as systematic uncertainties. All the systematic uncertainties for the \( \alpha \) measurement are summarized in Table III, where the total systematic uncertainty is the quadratic sum of the contributions.

### Table II. Systematic uncertainties (in %) and their sources for each measured decay mode.

| Source                          | \( \Xi(1530)^-\Xi(1530)^+ \) | \( \Xi(1530)^-\Xi(1530)^+ \) | \( \Xi(1530)^-\Xi(1530)^+ \) | \( \Xi(1530)^-\Xi(1530)^+ \) |
|---------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Tracking for pion               | 1.0                           | 1.0                           | 1.0                           | 1.0                           |
| PID for pion                    | 1.0                           | 1.0                           | 1.0                           | 1.0                           |
| \( \pi^0 \) reconstruction      | 1.0                           | 1.0                           | 1.0                           | 1.0                           |
| \( \Xi^- \) reconstruction      | 3.0                           | 6.0                           | 3.0                           | 6.0                           |
| Mass window of \( \Lambda \)    | 0.1                           | 0.3                           | 0.1                           | 0.3                           |
| Decay length of \( \Lambda \)   | 0.2                           | 0.1                           | 0.2                           | 0.1                           |
| \( \Xi^0 \) mass window         | 1.4                           | 1.8                           | 1.4                           | 1.8                           |
| \( \Xi^- \) mass window         | 1.0                           | 1.0                           | 1.0                           | 1.0                           |
| \( \Xi(1530)^- \) mass window   | 1.0                           | 1.0                           | 1.0                           | 1.0                           |
| Signal shape                    | 2.0                           | 2.2                           | 1.0                           | 1.0                           |
| Parameterization                | 1.0                           | 1.0                           | ...                           | ...                           |
| Fitting range                   | 1.8                           | 2.0                           | 0.5                           | 4.9                           |
| Background shape                | 1.7                           | 1.3                           | 4.5                           | 2.0                           |
| Wrong combinations              | 3.3                           | 2.0                           | 1.0                           | 1.0                           |
| Angular distribution            | 1.0                           | 1.0                           | 2.3                           | 2.5                           |
| \( B(\Lambda \rightarrow p\pi) \) | 0.8                           | 0.8                           | 0.8                           | 0.8                           |
| \( B(\Xi(1530) \rightarrow \pi\Xi) \) | 4.0                           | 4.0                           | 4.0                           | 4.0                           |
| \( N(\psi(3686)) \)            | 0.7                           | 0.7                           | 0.7                           | 0.7                           |
| Total                           | 8.0                           | 10.0                          | 9.6                           | 11.1                          |

Combined branching fractions and \( \alpha \) values are calculated according to the unconstrained averaging introduced in the PDG [22]. Note that the single-baryon recoil mass method leads to some double-counting of the \( \Xi(1530)^-\Xi(1530)^+ \) final-state; MC studies indicate this occurs at a rate of about 10%. This is taken into account when combining branching fractions and angular distribution parameters. The systematic uncertainties are weighted to properly account for common and uncommon systematic uncertainties using \( \frac{1}{2} \sum_{i,j(i \neq j)} \sigma_i \sigma_j \), where \( \sigma \) (\( \sigma' \)) is the systematic uncertainty with (without) common sources, and \( i,j \) run over the baryon and anti-baryon tags.

In summary, using 448.1 million \( \psi(3686) \) events collected with the BESIII detector at the BEPCII, we present the observation of \( \psi(3686) \rightarrow \Xi(1530)^-\Xi(1530)^+ \) and \( \Xi(1530)^-\Xi^+ \) decays with the statistical significances of more than 10\( \sigma \) and 5.0\( \sigma \), respectively, based on a single baryon tag strategy. The branching fractions for \( \psi(3686) \rightarrow \Xi(1530)^-\Xi(1530)^+ \) and \( \Xi(1530)^-\Xi^+ \) are measured to be \((11.45 \pm 0.40 \pm 0.59) \times 10^{-5}\) and \((0.70 \pm 0.11 \pm 0.04) \times 10^{-5}\), where the first (second) uncertainty is statistical (systematic). The corresponding results are summarized in Table I. The observation of the decay \( \psi(3686) \rightarrow \Xi(1530)^-\Xi^+ \) indicates that the SU(3) flavor symmetry is still broken in the \( \psi(3686) \) case, which further validates the generality of SU(3) flavor symmetry breaking. The measured angular distribution parameter \( \alpha \) for \( \psi(3686) \rightarrow \Xi(1530)^-\Xi(1530)^+ \) decay agrees with the theoretical prediction [11, 12] with our current errors. This offers support, within our limited statistics, for these models which include quark mass and electromagnetic effects.

### Table III. Systematic uncertainties (absolute) on the measurement of \( \alpha \) value for \( \psi(3686) \rightarrow \Xi(1530)^-\Xi(1530)^+ \) decay.

| Source                          | \( \Xi(1530)^-\Xi(1530)^+ \) | \( \Xi(1530)^-\Xi(1530)^+ \) |
|---------------------------------|-------------------------------|-------------------------------|
| \( M_{\text{ex}} \) fitting range | 0.05                          | 0.02                          |
| Background shape                | 0.03                          | 0.02                          |
| Signal shape                    | 0.06                          | 0.04                          |
| Wrong combinations              | 0.01                          | 0.04                          |
| \( \cos \theta_B \) binning     | 0.02                          | 0.01                          |
| \( \cos \theta_B \) fitting range | 0.03                          | 0.04                          |
| Total                           | 0.09                          | 0.08                          |

**ACKNOWLEDGEMENT**

The BESIII collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Key Basic Research Program of China under Contract No. 2015CB856700; Postdoctoral Natural Science Foundation of China under Contract Nos. 2018M630206, 2017M622347; National Natural Science Foundation of China (NSFC) under Contracts Nos. 11335008, 11425524, 11521505, 11605042, 11625523, 11635010, 11735014, 11875115; Chinese Academy of Science Focused Science Grant; National 1000 Talents Program of China; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts Nos. U1532257, U1532258, U1732263; CAS Key Research Program of Frontier Sciences under Contracts Nos. QYZDJ-SSW-SLH003, QYZDJ-SSW-SLH040; 100 Talents Program of CAS; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; German Research Foundation DFG under Contract No. Collaborative Research Center CRC 1044, FOR 2359; Istituto Nazionale di Fisica Nucleare, Italy; Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) under Contract No. 530-4CDP03; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Science and Technology fund; The Swedish Research Council; U. S. Department of Energy under Contracts Nos. DE-FG02-05ER41374, DE-SC-0010118, DE-SC-0012069; University of Groningen (RuG) and the Helmholtzzentrum fuer Schwerionenforschung
GmbH (GSI), Darmstadt; Post-doctoral research start-up fees
of Henan Province under Contract No. 2017SBH005; Ph.D
research start-up fees of Henan Normal University under Con-
tract No. qd16164; Program for Innovative Research T e

[1] S. J. Brodsky and G. P. Lepage, Phys. Rev. D 24, 2848 (1981).
[2] J. Bolz and P. Kroll, Eur. Phys. J. C 2, 545 (1998); R. G. Ping,
H. C. Chiang and B. S. Zou, Phys. Rev. D 66, 054020 (2002).
[3] D. M. Asner et al., Int. J. Mod. Phys. A 24, S1 (2009).
[4] L. Köpke and N. Wermes, Phys. Rept. 174, 67 (1989);
H. Kowalski and T. F. Walsh, Phys. Rev. D 14, 852 (1976).
[5] M. W. Eaton et al., Int. J. Mod. Phys. A 24, S1 (2009).
[6] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 87,
052007 (2013).
[7] A. Pais, Phys. Rev. Lett. 26, 51 (1971); P. Kessler, Nucl. Phys.
B 15, 253 (1970).
[8] F. Murgia and M. Melis, Phys. Rev. D 51, 3487 (1995);
A. Buzzo et al. (Fermilab E835 Collaboration), Phys. Lett. B
610, 177 (2005).
[9] J. Z. Bai et al. (BES Collaboration), Phys. Lett. B 591, 42
(2004).
[10] M. Ablikim et al. (BES Collaboration), Phys. Lett. B 632, 181
(2006).
[11] C. Carimalo, Int. J. Mod. Phys. A 2, 249 (1987).
[12] M. Claudson, S. L. Glashow and M. B. Wise, Phys. Rev. D
25, 1345 (1982).
[13] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 93,
072003 (2016); M. Ablikim et al. (BESIII Collaboration), Phys.
Lett. B 770, 217 (2017).
[14] H. Chen and R. G. Ping, Phys. Lett. B 644, 54 (2007).
[15] M. Ablikim et al. (BES Collaboration), Phys. Lett. B 648, 149
(2007); M. Ablikim et al. (BES Collaboration), Chin. Phys.
C 36, 1031 (2012); M. Ablikim et al. (BESIII Collaboration),
Phys. Rev. D 95, 052003 (2017); M. Ablikim et al. (BESIII
Collaboration), Phys. Rev. D 98, 032006 (2018); M. Ablikim et
al. (BESIII Collaboration), Nature Phys. 15, 631 (2019).
[16] M. Ablikim et al. (BESIII Collaboration), Chin. Phys. C 42,
023001 (2018).
[17] C. Y. Pang and R. G. Ping, Chin. Phys. Lett. 24, 1441 (2007).
[18] R. G. Ping et al., Chin. Phys. C 32, 599 (2008); D. J. Lange,
Nucl. Instrum. Meth. A 462, 152 (2001).
[19] S. Agostinelli et al. (GEANT4 Collaboration), Nucl. Instrum.
Meth. A 506, 250 (2003); J. Allison et al., IEEE Trans. Nucl.
Sci. 53, 270 (2006).
[20] M. Ablikim et al. (BESIII Collaboration), Nucl. Instrum. Meth.
A 614, 345 (2010).
[21] S. Jadach, B. F. L. Ward and Z. Was, Comput. Phys. Commun.
130, 260 (2000); S. Jadach, B. F. L. Ward and Z. Was, Phys.
Rev. D 63, 113009 (2001).
[22] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98,
030001 (2018).
[23] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang and Y. S. Zhu,
Phys. Rev. D 62, 034003 (2000).
[24] M. Xu et al., Chin. Phys. C 33, 428 (2009).
[25] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 95,
052003 (2017).
[26] M. Ablikim et al. (BESIII Collaboration), Phys. Lett. B 770,
217 (2017).
[27] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 87,
032007 (2013).