

# Study of the Reactions $\bar{n}p \rightarrow 2\pi^+\pi^-$ , $2\pi^+\pi^-\pi^0$ , and $2\pi^+\pi^-2\pi^0$ Using $J/\psi \rightarrow p\pi^-\bar{n}$

M. Ablikim *et al.*<sup>\*</sup>  
(BESIII Collaboration)

 (Received 30 November 2025; revised 4 March 2026; accepted 19 May 2026; published 14 July 2026)

We report an experimental investigation of the reactions  $\bar{n}p \rightarrow 2\pi^+\pi^-$ ,  $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$ , and  $\bar{n}p \rightarrow 2\pi^+\pi^-2\pi^0$  using  $(10.087 \pm 0.044) \times 10^9$   $J/\psi$  events collected with the BESIII detector at the BEPCII storage ring. The antineutron ( $\bar{n}$ ) is produced in the decay  $J/\psi \rightarrow p\pi^-\bar{n}$  with studied momentum from 200 to 1174 MeV/ $c$ , while the target proton originates from the hydrogen nuclei in the cooling oil of the beam pipe. This novel method pioneers the study of  $\bar{n}$ -nucleon interactions at an  $e^+e^-$  collider, providing the first experimental data for  $\bar{n}$  momenta exceeding 800 MeV/ $c$ .

DOI: [10.1103/nm5t-qk3h](https://doi.org/10.1103/nm5t-qk3h)

Scattering experiments are fundamental tools for probing the internal structure of nucleons, with the choice of particle source playing a pivotal role. Antineutrons possess a sufficiently long lifetime to serve as a viable particle source. However, since their discovery [1], antineutrons have rarely been utilized due to the significant challenges associated with their production and control. Despite these difficulties, antineutron beams offer unique advantages, such as the absence of Coulomb corrections and the purity of the  $I = 1$  state in the  $\bar{n}p$  system, which simplifies the analysis of isospin-dependent effects [2].

To date, the most effective antineutron sources have been achieved at the BNL E-767 experiment [3], with momenta ranging from 100 to 500 MeV/ $c$ , and the CERN OBELIX experiment [4], with momenta ranging from 50 to 400 MeV/ $c$ . Both facilities produced antineutron sources through the charge-exchange process  $\bar{p}p \rightarrow n\bar{n}$ . Despite the experimental insights obtained, this method has notable drawbacks: the antineutron production rates remain low, and achieving precise control over their momenta and directions poses significant technical challenges. Significantly, experimental data for  $\bar{n}p$  annihilation cross sections are currently nonexistent for antineutron momenta exceeding 800 MeV/ $c$ . This higher-momentum region, extending up to 1174 MeV/ $c$  in this study, represents a critical transition zone where the relevant degrees of freedom shift from mesons and nucleons to quarks and gluons in quantum chromodynamics. Our work provides the first measurements in this previously unexplored energy regime, filling a long-standing experimental vacuum and marking the first

such observation at an  $e^+e^-$  collider. These results offer unique and essential benchmarks for the development of future  $N\bar{N}$  interaction models.

In this Letter, we use a novel source of antineutrons [5] from  $J/\psi$  decays to overcome traditional production challenges. The  $J/\psi$  meson, produced copiously in  $e^+e^-$  annihilation with a branching fraction of  $J/\psi \rightarrow p\pi^-\bar{n}$ ,  $(2.12 \pm 0.09) \times 10^{-3}$  [6], emerges as a promising new source of  $\bar{n}$ . By measuring  $p\pi^-$ , we can accurately determine the momentum of the  $\bar{n}$ . While previous BESIII studies [7–9] used two-body  $J/\psi$  decays for fixed-momentum hyperon ( $\Lambda$ ,  $\Sigma$ , and  $\Xi$ ) scattering, the three-body  $J/\psi \rightarrow p\pi^-\bar{n}$  decay here provides a continuous antineutron spectrum, enabling a cross-section scan over a wide momentum range. The interaction between the  $\bar{n}$  and protons in the target material, located within a small radius of the  $e^+e^-$  beam pipe, enables a precise study of the cross section and the properties of the final states. Following the single-tag (ST) and double-tag (DT) approach described in Refs. [9,10], we employ a similar analysis strategy to minimize systematic uncertainties associated with the branching fraction of  $J/\psi \rightarrow p\pi^-\bar{n}$ , the  $p\pi^-$  selection, and the total number of  $J/\psi$  events. Specifically, the ST selection involves reconstructing  $p\pi^-$  from  $J/\psi \rightarrow p\pi^-\bar{n}$ . The DT selection extends this by additionally reconstructing the final-state particles from the  $\bar{n}p$  interaction  $2\pi^+\pi^-i\pi^0$  ( $i = 0, 1, 2$ ), as discussed in detail later.

A total of  $(10.087 \pm 0.044) \times 10^9$   $J/\psi$  events collected by the BESIII detector at the center-of-mass energy 3.097 GeV are used in this analysis. The BESIII detector records symmetric  $e^+e^-$  collisions at the BEPCII collider [11]. Detailed information about the BESIII detector can be found in Ref. [12]. The BESIII detector surrounds the beam pipe, which consists of four layers: a gold ( $^{197}\text{Au}$ ) layer, a beryllium ( $^9\text{Be}$ ) layer, an oil layer ( $^{12}\text{C}$ ,  $^1\text{H}$ ) serving as a coolant, and another beryllium layer. The distances from the inner and outer surfaces of the oil layer to the beam direction

<sup>\*</sup>Full author list given at the end of the Letter.

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP<sup>3</sup>.

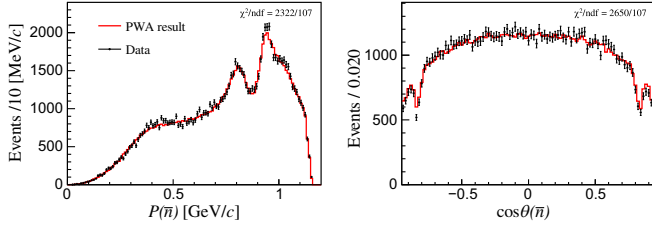


FIG. 1. The  $P(\bar{n})$  (left) and  $\cos\theta(\bar{n})$  (right) distributions for  $J/\psi \rightarrow p\pi^-\bar{n}$ . The black dots with error bars indicate data. The red histogram shows the PWA result.

are 3.23 and 3.31 cm, respectively. Since the proton in the  $^1\text{H}$  of the cooling oil is essentially at rest, whereas the protons in the  $^{197}\text{Au}/^{9}\text{Be}/^{12}\text{C}$  nuclei have Fermi motion, our focus is solely on the protons from the  $^1\text{H}$ . By utilizing these almost static protons in the cooling oil of the beam pipe, we can directly obtain information on the antineutron-proton interaction. This approach is similar to that adopted in Ref. [8], which studied the  $\Lambda p$  reaction by utilizing the proton from the cooling oil.

Simulated samples produced with a GEANT4-based [13] Monte Carlo (MC) package, which includes the geometric description [14] of the BESIII detector and the detector response, are used to optimize the event selection criteria and estimate the signal efficiency and backgrounds. The simulation models the beam-energy spread and initial-state radiation in the  $e^+e^-$  annihilation using the generator KKMC [15]. The inclusive MC sample includes the production of the  $J/\psi$  resonance and the continuum processes incorporated in KKMC. All particle decays are modeled with EVTGEN [16,17] using branching fractions either taken from the Particle Data Group [6], where available, or otherwise estimated with LUNDCHARM [18,19]. Final-state radiation from charged particles is incorporated using the PHOTOS package [20]. To estimate the detection efficiency, we generate  $1 \times 10^6$   $J/\psi \rightarrow p\pi^-\bar{n}$  ST MC events, and about  $2.3 \times 10^6$   $J/\psi \rightarrow p\pi^-\bar{n}$  with  $\bar{n}p \rightarrow 2\pi^+\pi^-i\pi^0$  events for each signal process as the DT MC samples. The  $\bar{n}p \rightarrow 2\pi^+\pi^-i\pi^0$  processes are simulated by assuming the proton to be at rest [8] and modeled with a uniform phase space distribution. In the signal MC simulation, the momentum and angular distributions of  $\bar{n}$  are generated according to a partial-wave analysis (PWA) conducted on  $J/\psi \rightarrow p\pi^-\bar{n}$ . The PWA utilizes a high-purity selected data sample of  $10^5$  events, and uses the open-source TF-PWA framework [21], employing the helicity amplitude formalism [22,23]. All known  $N^*$  resonances from the Particle Data Group are incorporated for  $p\pi^-$  and  $\bar{n}\pi^-$ , each modeled by relativistic Breit-Wigner functions, with masses and widths fixed to the world averages [6]. Figure 1 shows the distributions of the momentum and  $\cos\theta$  of the  $\bar{n}$ , with a  $z$  axis corresponding to the symmetry axis of the multilayer drift chamber. The good data-MC consistency validates the reliability of the PWA result.

The cross sections for each signal process are measured in five different  $\bar{n}$  momentum intervals, defined from 200 to 1174 MeV/c with a step size of 200 MeV/c.

In the ST selection, candidate events for  $J/\psi \rightarrow p\pi^-\bar{n}$  are reconstructed by identifying  $p\pi^-$  combinations. Charged tracks reconstructed in the main drift chamber are required to fall within the polar angle range  $|\cos\theta'| < 0.93$ , where  $\theta'$  is the angle relative to the  $z$  axis. Additionally, the distance of closest approach to the  $e^+e^-$  interaction point (IP) must be less than  $\pm 10$  cm along the  $z$  axis and less than 1 cm in the transverse plane. Particle identification (PID) for charged tracks is based on the combination of energy loss measurements ( $dE/dx$ ) in the main drift chamber and flight time from the time-of-flight system. These measurements are used to construct likelihoods  $\mathcal{L}(h)$  for each hadron  $h$  hypothesis ( $h = p, K, \pi$ ), and tracks are assigned the particle type corresponding to the highest likelihood. At least two charged tracks, identified as a proton and a pion ( $p\pi^-$ ), are required. No additional requirements are imposed on other charged tracks or neutral showers in the event. All valid  $p\pi^-$  combinations are subjected to a vertex fit to improve track momentum resolution, followed by a four-constraint kinematic fit. The four-constraint fit constrains the missing track's mass to that of the  $\bar{n}$  and enforces energy-momentum conservation. For events with multiple candidates, the combination with the smallest sum of  $\chi^2_{\text{vertex}} + \chi^2_{\text{kinematic}}$  is selected as the best candidate. This best combination is then required to satisfy  $\chi^2_{\text{vertex}} < 10$  and  $\chi^2_{\text{kinematic}} < 200$ . A relatively loose  $\chi^2_{\text{kinematic}}$  requirement is chosen to preserve a linear background shape in the distribution of the recoil mass  $\text{RM}(p\pi^-) = |p_{e^+e^-} - p_p - p_{\pi^-}|/c$ , where  $p_{e^+e^-}$ ,  $p_p$ , and  $p_{\pi^-}$  are the four-momenta of the  $e^+e^-$  initial-state, proton, and pion, respectively. The ST signal yield,  $N_{\text{ST}}$ , is then extracted by fitting this  $\text{RM}(p\pi^-)$  spectrum with a binned extended maximum likelihood fit. The  $\bar{n}$  signal region is defined as  $[0.92, 0.96]$  GeV/ $c^2$ . The signal is modeled using a double-Gaussian function, and the background is modeled with a first-order Chebyshev polynomial function. The fit result is shown in Fig. 2. This fitting procedure is also applied independently within each  $P(\bar{n})$  momentum interval. The ST selection efficiency,  $\epsilon_{\text{ST}}$ , is determined from a dedicated ST Monte Carlo sample using the same reconstruction and selection criteria. The resulting values for  $N_{\text{ST}}$  and  $\epsilon_{\text{ST}}$  are summarized in Table I.

In DT, in addition to  $p\pi^-$ , the final-state particles of  $2\pi^+\pi^-i\pi^0$  with  $\pi^0 \rightarrow \gamma\gamma$  are reconstructed. The selected  $p\pi^-$  combination is further required to satisfy  $\chi^2_{\text{kinematic}} < 5$ . Because this results in a nonlinear background shape in the  $\text{RM}(p\pi^-)$  distribution, it is not used to determine the DT signal yield. Additionally, we require three charged tracks,  $2\pi^+\pi^-$ , to satisfy the same criteria as the  $\pi^-$  in ST. However, no requirement is imposed on the closest approach distance to IP, as  $2\pi^+\pi^-$  originates from the beam pipe. A vertex fit is conducted for  $2\pi^+\pi^-$ , where the

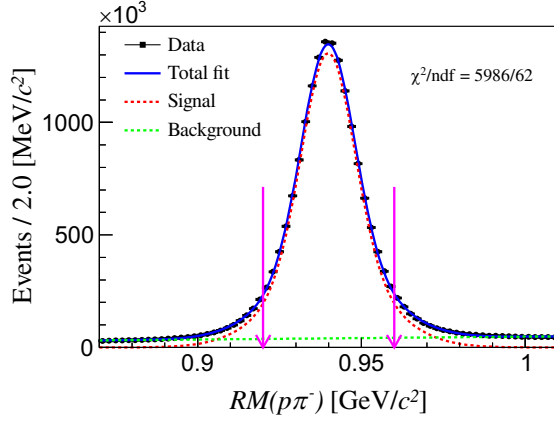


FIG. 2. The  $RM(p\pi^-)$  distribution with  $P(\bar{n}) \in [200, 1174]$  MeV/c. The black dots with error bars represent data. The blue solid line is the total fit. The dashed red line is the ST signal, and the dashed green line is the background. The pink arrows indicate the selected signal range.

vertex position is denoted as  $(x_1, y_1, z_1)$ , and  $\chi^2_{\text{vertex}}$  is required to be less than 5. The direction of the  $\bar{n}$  is determined from the  $p\pi^-$  kinematic fit, with its intersection point on the beam pipe denoted as  $(x_2, y_2, z_2)$ . The vector  $(x_1 - x_2, y_1 - y_2, z_1 - z_2)$  is defined to utilize the relative positions of these two vertices, with signal events expected to be close to (0,0,0). The requirements,  $|\sqrt{(x_1^2 + y_1^2)} - \sqrt{(x_2^2 + y_2^2)}| < 0.5$  cm and  $|z_1 - z_2| < 2.5$  cm, are applied. For  $\pi^0$  candidates, all photon pairs are looped through with their invariant mass required to be within (0.115, 0.150) GeV/c<sup>2</sup>. A one-constraint kinematic fit, constraining the photon-pair mass to the known  $\pi^0$  mass [6], is then applied to improve the momentum resolution. For the three signal processes, at least  $i$   $\pi^0$  candidate(s) must be identified. If there are additional  $\pi^0$  candidates, those with the minimal kinematic fit  $\chi^2$  are selected. For the  $i = 2$  case, the two selected  $\pi^0$  candidates must not share any photons.

To remove events from the reactions between  $\bar{n}$  and  $^{197}\text{Au}/^{9}\text{Be}/^{12}\text{C}$  nuclei, we define the momentum of the proton in the  $^1\text{H}$  of the cooling oil as  $P(p_{\text{oil}}) = |\vec{P}(2\pi^+\pi^-i\pi^0) - [\vec{P}(e^+e^-) - \vec{P}(p) - \vec{P}(\pi^-)]|$ ,

TABLE I. The sum of  $N_{\text{ST}}$  and  $\epsilon_{\text{ST}}$  of the full sample and in different  $P(\bar{n})$  intervals.

| $P(\bar{n})$ (MeV/c) | $N_{\text{ST}}(\times 10^3)$ | $\epsilon_{\text{ST}}(\%)$ |
|----------------------|------------------------------|----------------------------|
| [200, 1174]          | $14\,863.8 \pm 4.6$          | 66.65                      |
| [200, 400]           | $1312.6 \pm 1.3$             | 75.30                      |
| [400, 600]           | $2270.4 \pm 1.7$             | 73.35                      |
| [600, 800]           | $3268.7 \pm 2.1$             | 69.28                      |
| [800, 1000]          | $4863.1 \pm 2.8$             | 63.35                      |
| [1000, 1174]         | $3166.6 \pm 2.4$             | 61.50                      |

where  $\vec{P}$  represents the three-momentum of each particle in the lab frame. As shown in Fig. 3,  $P(p_{\text{oil}})$  is negligible for signal processes but hundreds of MeV/c for the background processes where protons originate from atomic nuclei with Fermi motion. To remove these background events, the requirements  $P(p_{\text{oil}}) < 0.035$ , 0.040, and 0.045 GeV/c are applied for  $i = 0, 1$ , and 2, respectively, optimized using a figure of merit,  $S/\sqrt{S+B}$ , where  $S$  in the numerator is the signal yield from the DT MC and  $S+B$  in the denominator is the number of events from the data sample.

For the signal process  $\bar{n}p \rightarrow 2\pi^+\pi^-i\pi^0$ , the energy of  $\bar{n}$  and a static  $p$  is equivalent to that of  $2\pi^+\pi^-i\pi^0$ . Therefore, we define  $\Delta E$  as the energy of  $2\pi^+\pi^-i\pi^0$  after subtracting the energy of  $\bar{n}$  and a static  $p$ . The number of DT events ( $N_{\text{DT}}$ ) is determined by fitting the  $\Delta E$  distribution in data, which includes both  $p\pi^-$  from the  $J/\psi$  decay and  $2\pi^+\pi^-i\pi^0$  from  $\bar{n}p$  interaction, as given by

$$N_{\text{DT}} = \mathcal{L}(\bar{n}) \sigma_i \mathcal{B}_{\pi^0 \rightarrow \gamma\gamma}^i \epsilon_{\text{DT}}, \quad (1)$$

where  $\sigma_i$  is the cross section of the processes  $\bar{n}p \rightarrow 2\pi^+\pi^-i\pi^0$ ,  $\mathcal{B}_{\pi^0 \rightarrow \gamma\gamma}^i$  is the branching fraction for  $\pi^0 \rightarrow \gamma\gamma$  [6] raised to the power  $i$ , and  $\epsilon_{\text{DT}}$  denotes the efficiency of the DT reconstruction. The “effective luminosity”  $\mathcal{L}(\bar{n})$  represents the integrated interaction opportunity between the incident  $\bar{n}$  and the  $^1\text{H}$  target [24]. It is determined by the number of produced  $\bar{n}$  from  $J/\psi \rightarrow p\pi^-\bar{n}$  decays and the target’s physical properties, calculated as

$$\mathcal{L}(\bar{n}) = \frac{N_{\text{ST}}}{\epsilon_{\text{ST}}} \frac{N_A \cdot \rho \cdot l}{M}, \quad (2)$$

where  $N_A$  is Avogadro’s number [25] and  $l = 0.106$  cm is the average path length of  $\bar{n}$  inside the oil layer, determined by averaging  $l/\sin\theta(\bar{n})$  over the  $\bar{n}$  angular distribution from PWA, with  $l$  denoting the oil layer thickness. The cooling oil has a density of  $\rho = 0.81$  g cm<sup>-3</sup> and a  $^{12}\text{C}:^1\text{H}$  mass fraction ratio of 84.9%: 15.1% [9]. Since the signal process specifically involves interactions with protons in the  $^1\text{H}$  component, an effective molar mass of  $M = 6.634$  g mol<sup>-1</sup> [26] is adopted for the  $^1\text{H}$  target in Eq. (2). Combining Eq. (1) and Eq. (2), the cross section  $\sigma_i$  is determined as

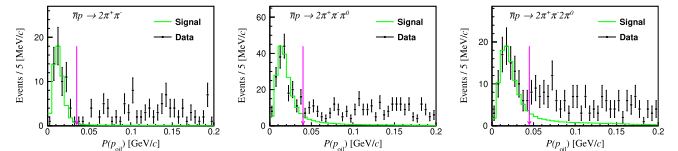


FIG. 3. Distributions of  $P(p_{\text{oil}})$  for  $\bar{n}p \rightarrow 2\pi^+\pi^-$  (left),  $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$  (middle), and  $\bar{n}p \rightarrow 2\pi^+\pi^-2\pi^0$  (right). The black dots with error bars represent the data, and the green lines are the signal MC. The pink arrows indicate the selected signal range.

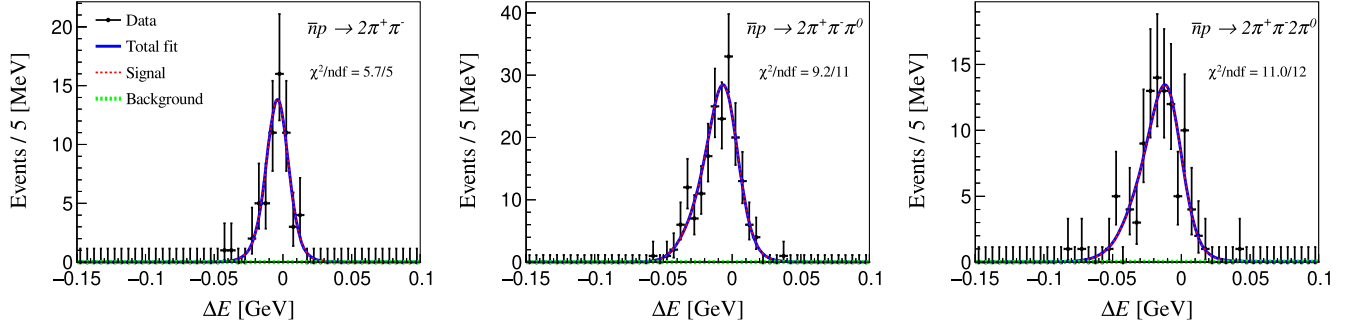


FIG. 4. The  $\Delta E$  distributions with  $P(\bar{n}) \in [200, 1174]$  MeV/ $c$ . The black dots with error bars represent the data. The blue solid lines are the total fits. The dashed red lines are the signals, and the dashed green lines are the backgrounds.

$$\sigma_i = \frac{M}{N_{A\rho l}} \frac{N_{\text{DT}}}{\epsilon_{\text{DT}} N_{\text{ST}}/\epsilon_{\text{ST}}} \frac{1}{\mathcal{B}_{\pi^0 \rightarrow \gamma\gamma}^i}. \quad (3)$$

Figure 4 shows the  $\Delta E$  distributions from data after the final event selection. Clear enhancements around 0 GeV/ $c$ , corresponding to the reactions  $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$ , are observed. Inclusive and signal MC studies confirm that peaking backgrounds and cross feeds among different  $\pi^0$  multiplicities are negligible due to kinematic constraints. An unbinned extended maximum likelihood fit is performed to the  $\Delta E$  distribution to determine the signal yield. We use the MC-determined shape convolved with a Gaussian function with free parameters to describe the signal shape. The background is described by a first-order Chebyshev polynomial function. In the fit, the signal yield and the parameters of the Gaussian and polynomial functions are free to vary. The fit results are shown in Fig. 4. The central values of  $\Delta E$  are negatively shifted mainly due to energy leakage during  $\pi^0$  reconstruction. The same method was used to extract the cross sections in the different  $P(\bar{n})$  intervals. Because of limited statistics, the Gaussian parameters are fixed to those obtained from the fit using the full  $\bar{n}$  momentum range [200, 1174] MeV/ $c$  to ensure fit stability across all bins. All the  $N_{\text{DT}}$  and  $\epsilon_{\text{DT}}$  values, and the PWA-weighted average momentum  $\langle P \rangle$  to better characterize each momentum range, are shown in Table II.

Furthermore, we examine the invariant mass distributions of the final-state pions in two-body and three-body combinations of the events, as shown in Fig. 5. All possible combinations are included for each event. We observe clear signals from  $\rho$  and  $\omega$  intermediate states, indicating significant contributions from these vector mesons.

Further studies with higher statistics and advanced techniques, including PWA to disentangle the  $S$ -wave and  $P$ -wave contributions, would be crucial for quantifying the role of these intermediate states in mediating the antineutron-proton interaction.

The cross section for each signal process is determined using Eq. (3). In this calculation, the DT reconstruction efficiency,  $\epsilon_{\text{DT}}$ , cannot be directly extracted from the DT MC samples because their  $\cos\theta(\bar{n})$  distribution is inherited from  $J/\psi \rightarrow p\pi^-\bar{n}$  and differs from that of  $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$ . For large values of  $|\cos\theta(\bar{n})|$ , the increased  $\bar{n}$  penetration distance within the beam pipe enhances the likelihood of  $\bar{n}p$  scattering. To account for this, we derive  $\epsilon_{\text{DT}}[\cos\theta(\bar{n})]$  from DT MC and reweight it to match the actual  $\cos\theta(\bar{n})$  distribution of the  $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$  process. After reweighting, the  $\epsilon_{\text{DT}}$  values decrease to 86%–96% of their uncorrected values, reflecting the greater difficulty in reconstructing tracks when  $\bar{n}$  has a large absolute value of  $\cos\theta$ . The final values of  $\epsilon_{\text{DT}}$ , along with the corresponding cross sections, are presented in Table II.

TABLE II. Summary of the measured  $N_{\text{DT}}$ ,  $\epsilon_{\text{DT}}$  (in %),  $\sigma_i$ , and  $\langle P \rangle$  for  $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$  in full and different  $P(\bar{n})$  intervals. For  $\sigma_i$ , the first uncertainties are statistical, and the second systematic.

| $P(\bar{n})/\langle P \rangle$ (MeV/ $c$ ) | $\bar{n}p \rightarrow 2\pi^+\pi^-$ |                        |                                   | $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$ |                        |                                    | $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$ |                        |                                    |
|--------------------------------------------|------------------------------------|------------------------|-----------------------------------|-----------------------------------------|------------------------|------------------------------------|-----------------------------------------|------------------------|------------------------------------|
|                                            | $N_{\text{DT}}$                    | $\epsilon_{\text{DT}}$ | $\sigma_0$ (mb)                   | $N_{\text{DT}}$                         | $\epsilon_{\text{DT}}$ | $\sigma_1$ (mb)                    | $N_{\text{DT}}$                         | $\epsilon_{\text{DT}}$ | $\sigma_2$ (mb)                    |
| [200, 1174]/765                            | 59.0 $\pm$ 7.7                     | 12.7                   | 2.7 $\pm$ 0.3 $\pm$ 0.3           | 182.0 $\pm$ 13.5                        | 9.8                    | 10.8 $\pm$ 0.8 $\pm$ 0.9           | 97.7 $\pm$ 10.0                         | 4.6                    | 12.6 $\pm$ 1.3 $\pm$ 1.0           |
| [200, 400]/320                             | 3.0 $\pm$ 2.1 $\pm$ 1.4            | 3.9                    | 5.6 $\pm$ 3.9 $\pm$ 2.7 $\pm$ 0.5 | 16.0 $\pm$ 4.3 $\pm$ 3.7                | 7.2                    | 16.7 $\pm$ 4.5 $\pm$ 3.9 $\pm$ 1.3 | 11.0 $\pm$ 3.7 $\pm$ 3.0                | 4.2                    | 19.9 $\pm$ 6.6 $\pm$ 5.4 $\pm$ 1.6 |
| [400, 600]/503                             | 12.0 $\pm$ 3.8 $\pm$ 3.2           | 9.7                    | 5.1 $\pm$ 1.6 $\pm$ 1.4 $\pm$ 0.5 | 30.9 $\pm$ 6.0 $\pm$ 5.4                | 9.7                    | 13.4 $\pm$ 2.6 $\pm$ 2.3 $\pm$ 1.1 | 14.5 $\pm$ 4.3 $\pm$ 3.6                | 4.7                    | 13.1 $\pm$ 3.9 $\pm$ 3.3 $\pm$ 1.1 |
| [600, 800]/710                             | 11.0 $\pm$ 3.7 $\pm$ 3.0           | 13.2                   | 2.3 $\pm$ 0.8 $\pm$ 0.6 $\pm$ 0.2 | 42.2 $\pm$ 6.9 $\pm$ 6.3                | 10.4                   | 11.2 $\pm$ 1.8 $\pm$ 1.7 $\pm$ 0.9 | 22.6 $\pm$ 5.2 $\pm$ 4.6                | 4.7                    | 13.5 $\pm$ 3.1 $\pm$ 2.8 $\pm$ 1.1 |
| [800, 1000]/907                            | 21.0 $\pm$ 4.9 $\pm$ 4.3           | 14.2                   | 2.5 $\pm$ 0.6 $\pm$ 0.5 $\pm$ 0.3 | 64.0 $\pm$ 7.7 $\pm$ 7.1                | 10.0                   | 10.8 $\pm$ 1.4 $\pm$ 1.3 $\pm$ 0.9 | 29.1 $\pm$ 5.8 $\pm$ 5.1                | 4.5                    | 11.0 $\pm$ 2.2 $\pm$ 1.9 $\pm$ 0.9 |
| [1000, 1174]/1063                          | 10.4 $\pm$ 4.0 $\pm$ 3.2           | 15.1                   | 1.7 $\pm$ 0.7 $\pm$ 0.5 $\pm$ 0.2 | 28.0 $\pm$ 5.6 $\pm$ 5.0                | 10.1                   | 7.0 $\pm$ 1.4 $\pm$ 1.3 $\pm$ 0.6  | 19.0 $\pm$ 4.7 $\pm$ 4.0                | 4.6                    | 10.6 $\pm$ 2.6 $\pm$ 2.3 $\pm$ 0.9 |

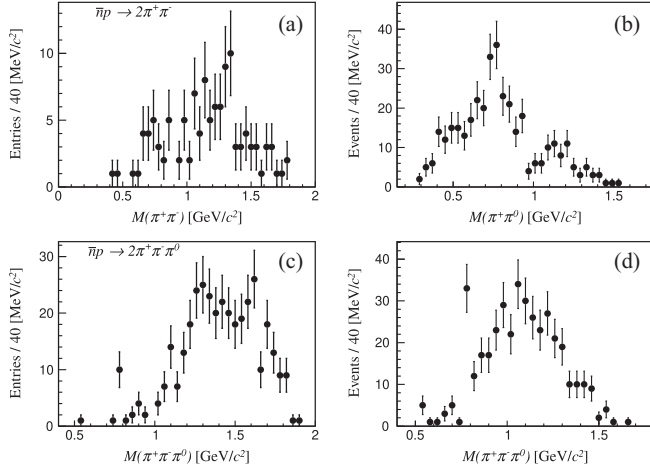


FIG. 5. Invariant mass distributions for (a)  $M(\pi^+\pi^-)$  in  $\bar{n}p \rightarrow 2\pi^+\pi^-$ , (b)  $M(\pi^+\pi^0)$  in  $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$  and (c)  $M(\pi^+\pi^-\pi^0)$  in  $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$ , and (d)  $M(\pi^+\pi^-\pi^0)$  in  $\bar{n}p \rightarrow 2\pi^+\pi^-2\pi^0$  for data.

The systematic uncertainty of the cross-section measurement is determined over the full momentum range and applied to the submomentum intervals of  $\bar{n}$ . The systematic uncertainty related to the number of ST events is evaluated in the  $\text{RM}(p\pi^-)$  fit by varying the signal shape using the signal MC shape convolved with a Gaussian function with free parameters. The background shape is varied using a second-order Chebyshev polynomial function, and the fit range is changed by  $\pm 0.01$  GeV/ $c^2$ , resulting in a systematic uncertainty of 2.1%. The systematic uncertainty due to the tracking or PID is 1% per charged track [7]. For a single  $\pi^0$  reconstruction, the systematic uncertainty is estimated to be 1% [27]. Since the  $\chi^2_{\text{kinematic}}$  requirement is loose ( $< 200$ ) in ST but much more stringent ( $< 5$ ) in DT, we adjust the  $\chi^2_{\text{kinematic}}$  requirement in DT by  $\pm 10\%$ . The maximum deviation from the nominal  $\sigma_i$  values is assigned as the systematic uncertainty. The systematic uncertainty from the angular distribution of  $\bar{n}$  is 2.2%, determined by the difference in  $l$  values from the PWA and phase space  $J/\psi \rightarrow p\pi^-\bar{n}$  angular distributions. To address the uncertainty arising from the reweighting of MC efficiency, we adjust the counts per bin during reweighting by adding or subtracting 20% to observe the change in efficiency. The larger change is taken as the systematic uncertainty. By varying the  $2\pi^+\pi^-$  vertex requirement by  $\pm 10\%$ , the most significant  $\sigma_i$  deviation is taken as the uncertainty. For the  $\bar{n}p$  scattering position, we adjust the requirements on  $|\sqrt{(x_1^2 + y_1^2)} - \sqrt{(x_2^2 + y_2^2)}|$  and  $|z_1 - z_2|$  by  $\pm 10\%$ , and take the larger difference as the systematic uncertainty. By modifying the  $P(p_{\text{oil}})$  requirement by  $\pm 10\%$ , the larger difference is taken as the systematic uncertainty. Similar to the uncertainty in the  $\text{RM}(p\pi^-)$  fit, the uncertainty in the  $\Delta E$  fit also includes three parts: the signal shape using a Gaussian function with free

TABLE III. The systematic uncertainties in the cross-section measurements (in %). The term “neg.” indicates negligible.

| Source                                | $i = 0$ | $i = 1$ | $i = 2$ |
|---------------------------------------|---------|---------|---------|
| Number of ST events                   | 2.1     | 2.1     | 2.1     |
| $2\pi^+\pi^-$ tracking                | 3.0     | 3.0     | 3.0     |
| $2\pi^+\pi^-$ PID                     | 3.0     | 3.0     | 3.0     |
| $\pi^0$ reconstruction                |         | 1.0     | 2.0     |
| $p\pi^-$ kinematic fit $\chi^2$ cut   | 3.6     | 1.5     | 0.6     |
| Angular distribution of $\bar{n}$     | 2.2     | 2.2     | 2.2     |
| Reweight MC efficiency                | 0.2     | 0.2     | 0.2     |
| $2\pi^+\pi^-$ vertex fit $\chi^2$ cut | 4.5     | 2.7     | 3.4     |
| $\bar{n}p$ scattering position        | 1.3     | 0.5     | 1.2     |
| $P(p_{\text{oil}})$ requirement       | 1.0     | 3.1     | 3.7     |
| $\Delta E$ fit strategy               | 0.2     | 0.9     | 1.4     |
| IP position                           | Neg.    | Neg.    | Neg.    |
| Intermediate states                   | 2.6     | 2.6     | 1.8     |
| Total                                 | 8.4     | 7.5     | 8.0     |

parameters, which also accounts for potential bias from the fixed parameters in  $P(\bar{n})$  intervals, the background shape using a second-order Chebyshev polynomial function, and the fit range varying by  $\pm 0.01$  GeV. To assess the uncertainty arising from the position of the IP, the coordinate origin is adjusted from (0,0,0) to (0.2,0.2,0.2) cm. The difference in the  $l$  value is less than 0.1% and is negligible. We check the  $\cos\theta$  and momentum distributions of the final particles  $2\pi^+\pi^-i\pi^0$  from data and signal MC sample, and correct the MC efficiency based on data. The differences observed before and after this efficiency correction are taken as the systematic uncertainties. A summary of the systematic uncertainties is presented in Table III. The total systematic uncertainty is obtained by adding all the individual components in quadrature. The systematic uncertainties on the cross-section measurements are shown in Table II.

In summary, based on a sample of  $(10.087 \pm 0.044) \times 10^9$   $J/\psi$  events collected with the BESIII detector at the BEPCII storage ring, we report the first measurements of the reactions  $\bar{n}p \rightarrow 2\pi^+\pi^-$ ,  $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$ , and  $\bar{n}p \rightarrow 2\pi^+\pi^-2\pi^0$ , where the  $\bar{n}$  is produced via the decay  $J/\psi \rightarrow p\pi^-\bar{n}$  and the  $p$  is sourced from hydrogen nuclei in the cooling oil of the beam pipe. The cross sections for these reactions are measured in five intervals of  $P(\bar{n})$ : [200, 400], [400, 600], [600, 800], [800, 1000], and [1000, 1174] MeV/ $c$ , within the overall range of [200, 1174] MeV/ $c$ , providing the first experimental data for the momentum range exceeding 800 MeV/ $c$ . As shown in Fig. 6, our interval cross-section results are compared with previous measurements from the OBELIX experiment [2] for  $i = 0, 1, 2$  in the range [50, 400] MeV/ $c$  and a bubble chamber experiment [28] for  $i = 0, 1$  in the range [500, 800] MeV/ $c$ . Direct comparisons are limited by

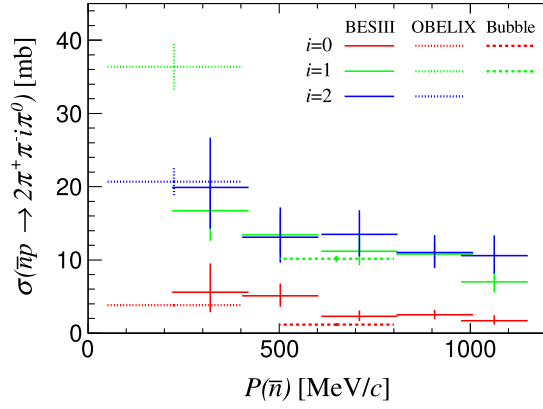


FIG. 6. Cross sections for  $\bar{n}p \rightarrow 2\pi^+\pi^-\pi^0$  (red for  $i = 0$ , green for  $i = 1$ , and blue for  $i = 2$ ). BESIII results are shown as solid lines with crosses in  $P(\bar{n})$  intervals with the center of the bin indicated  $\langle P \rangle$ . Vertical error bars show combined statistical and systematic uncertainties, and horizontal error bars indicate the  $P(\bar{n})$  bin widths. Results from OBELIX and the bubble chamber experiment are shown as dotted and dashed lines, respectively, for comparison.

variations in the  $\bar{n}$  momentum distributions across experiments. In the absence of direct theoretical predictions, we compare the relative channel strengths with the charge-conjugate  $\bar{p}n \rightarrow 2\pi^-\pi^+\pi^0$  annihilation at rest in liquid deuterium [29], where branching fractions of  $(1.57 \pm 0.21)\%$ ,  $(21.8 \pm 2.2)\%$ , and  $(6.3 \pm 1.1)\%$  are reported for  $i = 0, 1, 2$ , respectively. Interestingly, while the  $i = 1$  channel dominates in  $\bar{p}n$  annihilation at rest and in the lower-momentum OBELIX data, our measurements at higher momenta show that the  $\sigma_2$  is comparable to or exceeds  $\sigma_1$  across most of the measured momentum range. This enhancement of multipion final states at higher energies provides new insights into the dynamics of nucleon-antinucleon annihilation. Moreover, intermediate  $\rho$  and  $\omega$  resonances are clearly observed in the invariant mass distributions of the  $\pi\pi$  and  $\pi\pi\pi$  subsystems, indicating the significant role of vector mesons in these annihilation processes. The reported results represent the first measurement of antineutron-nucleon inelastic scattering at an electron-positron collider, demonstrating the feasibility of using this configuration to study such reactions. This research opens a path for future investigations at the proposed super tau-charm factory [30,31], where the abundant  $J/\psi$  sample can provide an excellent source of antineutrons and long-lived (anti)baryons for high-precision studies in nuclear and particle physics.

**Acknowledgments**—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 R&D Program of China under Contracts No. 2023YFA1606000 and No. 2023YFA1606704; National Natural Science Foundation of China (NSFC)

under Contracts No. 11635010, No. 11935015, No. 11935016, No. 11935018, No. 12025502, No. 12035009, No. 12035013, No. 12061131003, No. 12192260, No. 12192261, No. 12192262, No. 12192263, No. 12192264, No. 12192265, No. 12221005, No. 12225509, No. 12235017, No. 12361141819; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the Strategic Priority Research Program of Chinese Academy of Sciences under Contract No. XDA0480600; CAS under Contract No. YSBR-101; 100 Talents Program of CAS; Program of Science and Technology Development Plan of Jilin Province of China under Contract No. 20230101021JC; The Institute of Nuclear and Particle Physics (INPAC) and Shanghai Key Laboratory for Particle Physics and Cosmology; ERC under Contract No. 758462; German Research Foundation DFG under Contract No. FOR5327; Istituto Nazionale di Fisica Nucleare, Italy; Knut and Alice Wallenberg Foundation under Contracts No. 2021.0174 and No. 2021.0299; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Research Foundation of Korea under Contract No. NRF-2022R1A2C1092335; National Science and Technology fund of Mongolia; Polish National Science Centre under Contract No. 2024/53/B/ST2/00975; STFC (United Kingdom); Swedish Research Council under Contract No. 2019.04595; U.S. Department of Energy under Contract No. DE-FG02-05ER41374.

**Data availability**—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

- [1] B. Cork, G. R. Lambertson, O. Piccioni, and W. A. Wenzel, Antineutrons produced from antiprotons in charge-exchange collisions, *Phys. Rev.* **104**, 1193 (1956).
- [2] T. Bressani and A. Filippi, Antineutron physics, *Phys. Rep.* **383**, 213 (2003).
- [3] T. Armstrong *et al.* (Brookhaven-Houston-Pennsylvania State-Rice Collaboration), Measurement of antineutron-proton total and annihilation cross sections from 100 to 500 MeV/c, *Phys. Rev. D* **36**, 659 (1987).
- [4] M. Agnello *et al.*, The antineutron beam at OBELIX, *Nucl. Instrum. Methods Phys. Res., Sect. A* **399**, 11 (1997).
- [5] C. Z. Yuan and M. Karliner, Cornucopia of antineutrons and hyperons from a super  $J/\psi$  factory for next-generation nuclear and particle physics high-precision experiments, *Phys. Rev. Lett.* **127**, 012003 (2021).
- [6] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [7] M. Ablikim *et al.* (BESIII Collaboration), First study of reaction  $\Xi^0 n \rightarrow \Xi^- p$  using  $\Xi^0$ -nucleus scattering at an

- electron-positron collider, *Phys. Rev. Lett.* **130**, 251902 (2023).
- [8] M. Ablikim *et al.* (BESIII Collaboration), First study of antihyperon-nucleon scattering  $\bar{\Lambda}p \rightarrow \bar{\Lambda}p$  and measurement of  $\Lambda p \rightarrow \Lambda p$  cross section, *Phys. Rev. Lett.* **132**, 231902 (2024).
- [9] M. Ablikim *et al.* (BESIII Collaboration), First measurement of  $\Lambda N$  inelastic scattering with  $\Lambda$  from  $e^+e^- \rightarrow j/\psi \rightarrow \Lambda\bar{\Lambda}$ , *Phys. Rev. C* **109**, L052201 (2024).
- [10] J. Dai, H. B. Li, H. Miao, and J. Zhang, Prospects to study hyperon-nucleon interactions at BESIII, *Chin. Phys. C* **48**, 073003 (2024).
- [11] C. H. Yu *et al.*, BEPCII performance and beam dynamics studies on luminosity, in *Proceedings of IPAC2016, Busan, Korea* (JACoW, 2016), 10.18429/JACoW-IPAC2016-TUYA01.
- [12] M. Ablikim *et al.* (BESIII Collaboration), Design and construction of the BESIII detector, *Nucl. Instrum. Methods Phys. Res., Sect. A* **614**, 345 (2010).
- [13] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4—a simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [14] K. X. Huang *et al.*, Method for detector description transformation to Unity and application in BESIII, *Nucl. Sci. Tech.* **33**, 142 (2022).
- [15] S. Jadach, B. F. L. Ward, and Z. Was, Coherent exclusive exponentiation for precision Monte Carlo calculations, *Phys. Rev. D* **63**, 113009 (2001).
- [16] D. J. Lange, The EvtGen particle decay simulation package, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [17] R. G. Ping, Event generators at BESIII, *Chin. Phys. C* **32**, 599 (2008).
- [18] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, Event generator for  $J/\psi$  and  $\psi(2S)$  decay, *Phys. Rev. D* **62**, 034003 (2000).
- [19] R. L. Yang, R. G. Ping, and H. Chen, Tuning and validation of the Lundcharm model with  $J/\psi$  decays, *Chin. Phys. Lett.* **31**, 061301 (2014).
- [20] E. Barberio, B. van Eijk, and Z. Was, PHOTOS—a universal Monte Carlo for QED radiative corrections in decays, *Comput. Phys. Commun.* **66**, 115 (1991).
- [21] Yi Jiang (BESIII Collaboration), Amplitude analysis tools at BESIII, Oral Talk in Hadron2023, Genova, Italy (2023), Source code: <https://github.com/jiangyi15/tf-pwa>.
- [22] J. D. Richman, An Experimenter's Guide to the Helicity Formalism, Report No. CALT-68-1148 (1984).
- [23] S. U. Chung, SPIN FORMALISMS <http://10.5170/CERN-1971-008> (1971).
- [24] J. Rowley *et al.* (CLAS Collaboration), Improved  $\Lambda p$  elastic scattering cross sections between 0.9 and 2.0 GeV/c as a main ingredient of the neutron star equation of state, *Phys. Rev. Lett.* **127**, 272303 (2021).
- [25] Bureau International des Poids et Mesures (BIPM), The International System of Units (SI).
- [26] NIST Chemistry webbook, <https://webbook.nist.gov/chemistry/>.
- [27] M. Ablikim *et al.* (BESIII Collaboration), Observation of  $D^+ \rightarrow \eta\eta\pi^+$  and improved measurement of  $D^{0(+)} \rightarrow \eta\pi^+\pi^{-(0)}$ , *Phys. Rev. D* **101**, 052009 (2020).
- [28] S. Banerjee *et al.* (Bombay-Chandigarh-Jammu-Tokyo), Studies of  $\bar{p}p \rightarrow \bar{n}n$  and  $\bar{n}p$  annihilation at incident momenta of 700 and 760 MeV/c, *Z. Phys. C* **28**, 163 (1985).
- [29] E. Klempt, C. Batty, and J. M. Richard, The antinucleon-nucleon interaction at low energy: annihilation dynamics, *Phys. Rep.* **413**, 197 (2005).
- [30] A. E. Bondar *et al.* (Charm-Tau Factory Collaboration), Project of a Super Charm-Tau factory at the Budker Institute of Nuclear Physics in Novosibirsk, *Phys. At. Nucl.* **76**, 1072 (2013).
- [31] M. Achasov *et al.*, STCF conceptual design report (Volume 1), *Front. Phys.* **19**, 14701 (2024).

M. Ablikim<sup>1</sup>, M. N. Achasov<sup>4,c</sup>, P. Adlarson<sup>81</sup>, X. C. Ai<sup>86</sup>, R. Aliberti<sup>39</sup>, A. Amoroso<sup>80a,80c</sup>, Q. An<sup>77,64,b</sup>, Y. Bai<sup>62</sup>, O. Bakina<sup>40</sup>, Y. Ban<sup>50,d</sup>, H.-R. Bao<sup>70</sup>, X. L. Bao<sup>49</sup>, V. Batozskaya<sup>1,48</sup>, K. Begzsuren<sup>35</sup>, N. Berger<sup>39</sup>, M. Berlowski<sup>48</sup>, M. B. Bertani<sup>30a</sup>, D. Bettoni<sup>31a</sup>, F. Bianchi<sup>80a,80c</sup>, E. Bianco<sup>80a,80c</sup>, A. Bortone<sup>80a,80c</sup>, I. Boyko<sup>40</sup>, R. A. Briere<sup>5</sup>, A. Brueggemann<sup>74</sup>, H. Cai<sup>82</sup>, M. H. Cai<sup>42,e,f</sup>, X. Cai<sup>1,64</sup>, A. Calcaterra<sup>30a</sup>, G. F. Cao<sup>1,70</sup>, N. Cao<sup>1,70</sup>, S. A. Cetin<sup>68a</sup>, X. Y. Chai<sup>50,d</sup>, J. F. Chang<sup>1,64</sup>, T. T. Chang<sup>47</sup>, G. R. Che<sup>47</sup>, Y. Z. Che<sup>1,64,70</sup>, C. H. Chen<sup>10</sup>, Chao Chen<sup>60</sup>, G. Chen<sup>1</sup>, H. S. Chen<sup>1,70</sup>, H. Y. Chen<sup>21</sup>, M. L. Chen<sup>1,64,70</sup>, S. J. Chen<sup>46</sup>, S. M. Chen<sup>67</sup>, T. Chen<sup>1,70</sup>, W. Chen<sup>49</sup>, X. R. Chen<sup>34,70</sup>, X. T. Chen<sup>1,70</sup>, X. Y. Chen<sup>12,g</sup>, Y. B. Chen<sup>1,64</sup>, Y. Q. Chen<sup>16</sup>, Z. K. Chen<sup>65</sup>, J. Cheng<sup>49</sup>, L. N. Cheng<sup>47</sup>, S. K. Choi<sup>11</sup>, X. Chu<sup>12,g</sup>, G. Cibinetto<sup>31a</sup>, F. Cossio<sup>80c</sup>, J. Cotte-Meldrum<sup>69</sup>, H. L. Dai<sup>1,64</sup>, J. P. Dai<sup>84</sup>, X. C. Dai<sup>67</sup>, A. Dbeyssi<sup>19</sup>, R. E. de Boer<sup>3</sup>, D. Dedovich<sup>40</sup>, C. Q. Deng<sup>78</sup>, Z. Y. Deng<sup>1</sup>, A. Denig<sup>39</sup>, I. Denisenko<sup>40</sup>, M. Destefanis<sup>80a,80c</sup>, F. De Mori<sup>80a,80c</sup>, X. X. Ding<sup>50,d</sup>, Y. Ding<sup>44</sup>, Y. X. Ding<sup>32</sup>, J. Dong<sup>1,64</sup>, L. Y. Dong<sup>1,70</sup>, M. Y. Dong<sup>1,64,70</sup>, X. Dong<sup>82</sup>, M. C. Du<sup>1</sup>, S. X. Du<sup>86</sup>, S. X. Du<sup>12,g</sup>, X. L. Du<sup>86</sup>, Y. Y. Duan<sup>60</sup>, Z. H. Duan<sup>46</sup>, P. Egorov<sup>40,h</sup>, G. F. Fan<sup>46</sup>, J. J. Fan<sup>20</sup>, Y. H. Fan<sup>49</sup>, J. Fang<sup>1,64</sup>, J. Fang<sup>65</sup>, S. S. Fang<sup>1,70</sup>, W. X. Fang<sup>1</sup>, Y. Q. Fang<sup>1,64,b</sup>, L. Fava<sup>80b,80c</sup>, F. Feldbauer<sup>3</sup>, G. Felici<sup>30a</sup>, C. Q. Feng<sup>77,64</sup>, J. H. Feng<sup>16</sup>, L. Feng<sup>42,e,f</sup>, Q. X. Feng<sup>42,e,f</sup>, Y. T. Feng<sup>77,64</sup>, M. Fritsch<sup>3</sup>, C. D. Fu<sup>1</sup>, J. L. Fu<sup>70</sup>, Y. W. Fu<sup>1,70</sup>, H. Gao<sup>70</sup>, Y. Gao<sup>77,64</sup>, Y. N. Gao<sup>50,d</sup>, Y. N. Gao<sup>20</sup>, Y. Y. Gao<sup>32</sup>, Z. Gao<sup>47</sup>, S. Garbolino<sup>80c</sup>, I. Garzia<sup>31a,31b</sup>, L. Ge<sup>62</sup>, P. T. Ge<sup>20</sup>, Z. W. Ge<sup>46</sup>, C. Geng<sup>65</sup>, E. M. Gersabeck<sup>73</sup>, A. Gilman<sup>75</sup>, K. Goetzen<sup>13</sup>

J. Gollub<sup>3</sup>, J. D. Gong<sup>38</sup>, L. Gong<sup>44</sup>, W. X. Gong<sup>1,64</sup>, W. Gradl<sup>39</sup>, S. Gramigna<sup>31a,31b</sup>, M. Greco<sup>80a,80c</sup>, M. D. Gu<sup>55</sup>, M. H. Gu<sup>1,64</sup>, C. Y. Guan<sup>1,70</sup>, A. Q. Guo<sup>34</sup>, J. N. Guo<sup>12,g</sup>, L. B. Guo<sup>45</sup>, M. J. Guo<sup>54</sup>, R. P. Guo<sup>53</sup>, X. Guo<sup>54</sup>, Y. P. Guo<sup>12,g</sup>, A. Guskov<sup>40,h</sup>, J. Gutierrez<sup>29</sup>, T. T. Han<sup>1</sup>, F. Hanisch<sup>3</sup>, K. D. Hao<sup>77,64</sup>, X. Q. Hao<sup>20</sup>, F. A. Harris<sup>71</sup>, C. Z. He<sup>50,d</sup>, K. L. He<sup>1,70</sup>, F. H. Heinsius<sup>3</sup>, C. H. Heinz<sup>39</sup>, Y. K. Heng<sup>1,64,70</sup>, C. Herold<sup>66</sup>, P. C. Hong<sup>38</sup>, G. Y. Hou<sup>1,70</sup>, X. T. Hou<sup>1,70</sup>, Y. R. Hou<sup>70</sup>, Z. L. Hou<sup>1</sup>, H. M. Hu<sup>1,70</sup>, J. F. Hu<sup>61,i</sup>, Q. P. Hu<sup>77,64</sup>, S. L. Hu<sup>12,g</sup>, T. Hu<sup>1,64,70</sup>, Y. Hu<sup>1</sup>, Z. M. Hu<sup>65</sup>, G. S. Huang<sup>77,64</sup>, K. X. Huang<sup>65</sup>, L. Q. Huang<sup>34,70</sup>, P. Huang<sup>46</sup>, X. T. Huang<sup>54</sup>, Y. P. Huang<sup>1</sup>, Y. S. Huang<sup>65</sup>, T. Hussain<sup>79</sup>, N. Hüsken<sup>39</sup>, N. in der Wiesche<sup>74</sup>, J. Jackson<sup>29</sup>, Q. Ji<sup>1</sup>, Q. P. Ji<sup>20</sup>, W. Ji<sup>1,70</sup>, X. B. Ji<sup>1,70</sup>, X. L. Ji<sup>1,64</sup>, X. Q. Jia<sup>54</sup>, Z. K. Jia<sup>77,64</sup>, D. Jiang<sup>1,70</sup>, H. B. Jiang<sup>82</sup>, P. C. Jiang<sup>50,d</sup>, S. J. Jiang<sup>10</sup>, X. S. Jiang<sup>1,64,70</sup>, J. B. Jiao<sup>54</sup>, J. K. Jiao<sup>38</sup>, Z. Jiao<sup>25</sup>, L. C. L. Jin<sup>1</sup>, S. Jin<sup>46</sup>, Y. Jin<sup>72</sup>, M. Q. Jing<sup>1,70</sup>, X. M. Jing<sup>70</sup>, T. Johansson<sup>81</sup>, S. Kabana<sup>36</sup>, X. L. Kang<sup>10</sup>, X. S. Kang<sup>44</sup>, B. C. Ke<sup>86</sup>, V. Khachatryan<sup>29</sup>, A. Khoukaz<sup>74</sup>, O. B. Kolcu<sup>68a</sup>, B. Kopf<sup>3</sup>, L. Kröger<sup>74</sup>, M. Kuessner<sup>3</sup>, X. Kui<sup>1,70</sup>, N. Kumar<sup>28</sup>, A. Kupsc<sup>48,81</sup>, W. Kühn<sup>41</sup>, Q. Lan<sup>78</sup>, W. N. Lan<sup>20</sup>, T. T. Lei<sup>77,64</sup>, M. Lellmann<sup>39</sup>, T. Lenz<sup>39</sup>, C. Li<sup>51</sup>, C. Li<sup>47</sup>, C. H. Li<sup>45</sup>, C. K. Li<sup>21</sup>, D. M. Li<sup>86</sup>, F. Li<sup>1,64</sup>, G. Li<sup>1</sup>, H. B. Li<sup>1,70</sup>, H. J. Li<sup>20</sup>, H. L. Li<sup>86</sup>, H. N. Li<sup>61,i</sup>, Hui Li<sup>47</sup>, J. R. Li<sup>67</sup>, J. S. Li<sup>65</sup>, J. W. Li<sup>54</sup>, K. Li<sup>1</sup>, K. L. Li<sup>42,e,f</sup>, L. J. Li<sup>1,70</sup>, Lei Li<sup>52</sup>, M. H. Li<sup>47</sup>, M. R. Li<sup>1,70</sup>, P. L. Li<sup>70</sup>, P. R. Li<sup>42,e,f</sup>, Q. M. Li<sup>1,70</sup>, Q. X. Li<sup>54</sup>, R. Li<sup>18,34</sup>, S. X. Li<sup>12</sup>, Shanshan Li<sup>27,j</sup>, T. Li<sup>54</sup>, T. Y. Li<sup>47</sup>, W. D. Li<sup>1,70</sup>, W. G. Li<sup>1,b</sup>, X. Li<sup>1,70</sup>, X. H. Li<sup>77,64</sup>, X. K. Li<sup>50,d</sup>, X. L. Li<sup>54</sup>, X. Y. Li<sup>1,9</sup>, X. Z. Li<sup>65</sup>, Y. Li<sup>20</sup>, Y. G. Li<sup>70</sup>, Y. P. Li<sup>38</sup>, Z. H. Li<sup>42</sup>, Z. J. Li<sup>65</sup>, Z. X. Li<sup>47</sup>, Z. Y. Li<sup>84</sup>, C. Liang<sup>46</sup>, H. Liang<sup>77,64</sup>, Y. F. Liang<sup>59</sup>, Y. T. Liang<sup>34,70</sup>, G. R. Liao<sup>14</sup>, L. B. Liao<sup>65</sup>, M. H. Liao<sup>65</sup>, Y. P. Liao<sup>1,70</sup>, J. Libby<sup>28</sup>, A. Limphirat<sup>66</sup>, D. X. Lin<sup>34,70</sup>, L. Q. Lin<sup>43</sup>, T. Lin<sup>1</sup>, B. J. Liu<sup>1</sup>, B. X. Liu<sup>82</sup>, C. X. Liu<sup>1</sup>, F. Liu<sup>1</sup>, F. H. Liu<sup>58</sup>, Feng Liu<sup>6</sup>, G. M. Liu<sup>61,i</sup>, H. Liu<sup>42,e,f</sup>, H. B. Liu<sup>15</sup>, H. M. Liu<sup>1,70</sup>, Huihui Liu<sup>22</sup>, J. B. Liu<sup>77,64</sup>, J. J. Liu<sup>21</sup>, K. Liu<sup>42,e,f</sup>, K. Liu<sup>78</sup>, K. Y. Liu<sup>44</sup>, Ke Liu<sup>23</sup>, L. Liu<sup>42</sup>, L. C. Liu<sup>47</sup>, Lu Liu<sup>47</sup>, M. H. Liu<sup>38</sup>, P. L. Liu<sup>1</sup>, Q. Liu<sup>70</sup>, S. B. Liu<sup>77,64</sup>, W. M. Liu<sup>77,64</sup>, W. T. Liu<sup>43</sup>, X. Liu<sup>42,e,f</sup>, X. K. Liu<sup>42,e,f</sup>, X. L. Liu<sup>12,g</sup>, X. Y. Liu<sup>82</sup>, Y. Liu<sup>42,e,f</sup>, Y. Liu<sup>86</sup>, Y. B. Liu<sup>47</sup>, Z. A. Liu<sup>1,64,70</sup>, Z. D. Liu<sup>10</sup>, Z. Q. Liu<sup>54</sup>, Z. Y. Liu<sup>42</sup>, X. C. Lou<sup>1,64,70</sup>, H. J. Lu<sup>25</sup>, J. G. Lu<sup>1,64</sup>, X. L. Lu<sup>16</sup>, Y. Lu<sup>7</sup>, Y. H. Lu<sup>1,70</sup>, Y. P. Lu<sup>1,64</sup>, Z. H. Lu<sup>1,70</sup>, C. L. Luo<sup>45</sup>, J. R. Luo<sup>65</sup>, J. S. Luo<sup>1,70</sup>, M. X. Luo<sup>85</sup>, T. Luo<sup>12,g</sup>, X. L. Luo<sup>1,64</sup>, Z. Y. Lv<sup>23</sup>, X. R. Lyu<sup>70,k</sup>, Y. F. Lyu<sup>47</sup>, Y. H. Lyu<sup>86</sup>, F. C. Ma<sup>44</sup>, H. L. Ma<sup>1</sup>, Heng Ma<sup>27,j</sup>, J. L. Ma<sup>1,70</sup>, L. L. Ma<sup>54</sup>, L. R. Ma<sup>72</sup>, Q. M. Ma<sup>1</sup>, R. Q. Ma<sup>1,70</sup>, R. Y. Ma<sup>20</sup>, T. Ma<sup>77,64</sup>, X. T. Ma<sup>1,70</sup>, X. Y. Ma<sup>1,64</sup>, Y. M. Ma<sup>34</sup>, F. E. Maas<sup>19</sup>, I. MacKay<sup>75</sup>, M. Maggiora<sup>80a,80c</sup>, S. Malde<sup>75</sup>, Q. A. Malik<sup>79</sup>, H. X. Mao<sup>42,e,f</sup>, Y. J. Mao<sup>50,d</sup>, Z. P. Mao<sup>1</sup>, S. Marcello<sup>80a,80c</sup>, A. Marshall<sup>69</sup>, F. M. Melendi<sup>31a,31b</sup>, Y. H. Meng<sup>70</sup>, Z. X. Meng<sup>72</sup>, G. Mezzadri<sup>31a</sup>, H. Miao<sup>1,70</sup>, T. J. Min<sup>46</sup>, R. E. Mitchell<sup>29</sup>, X. H. Mo<sup>1,64,70</sup>, B. Moses<sup>29</sup>, N. Yu. Muchnoi<sup>4,c</sup>, J. Muskalla<sup>39</sup>, Y. Nefedov<sup>40</sup>, F. Nerling<sup>19,l</sup>, H. Neuwirth<sup>74</sup>, Z. Ning<sup>1,64</sup>, S. Nisar<sup>33</sup>, Q. L. Niu<sup>42,e,f</sup>, W. D. Niu<sup>12,g</sup>, Y. Niu<sup>54</sup>, C. Normand<sup>69</sup>, S. L. Olsen<sup>11,70</sup>, Q. Ouyang<sup>1,64,70</sup>, S. Pacetti<sup>30b,30c</sup>, X. Pan<sup>60</sup>, Y. Pan<sup>62</sup>, A. Pathak<sup>11</sup>, Y. P. Pei<sup>77,64</sup>, M. Pelizaeus<sup>3</sup>, H. P. Peng<sup>77,64</sup>, X. J. Peng<sup>42,e,f</sup>, Y. Y. Peng<sup>42,e,f</sup>, K. Peters<sup>13,l</sup>, K. Petridis<sup>69</sup>, J. L. Ping<sup>45</sup>, R. G. Ping<sup>1,70</sup>, S. Plura<sup>39</sup>, V. Prasad<sup>38</sup>, F. Z. Qi<sup>1</sup>, H. R. Qi<sup>67</sup>, M. Qi<sup>46</sup>, S. Qian<sup>1,64</sup>, W. B. Qian<sup>70</sup>, C. F. Qiao<sup>70</sup>, J. H. Qiao<sup>20</sup>, J. J. Qin<sup>78</sup>, J. L. Qin<sup>60</sup>, L. Q. Qin<sup>14</sup>, L. Y. Qin<sup>77,64</sup>, P. B. Qin<sup>78</sup>, X. P. Qin<sup>43</sup>, X. S. Qin<sup>54</sup>, Z. H. Qin<sup>1,64</sup>, J. F. Qiu<sup>1</sup>, Z. H. Qu<sup>78</sup>, J. Rademacker<sup>69</sup>, C. F. Redmer<sup>39</sup>, A. Rivetti<sup>80c</sup>, M. Rolo<sup>80c</sup>, G. Rong<sup>1,70</sup>, S. S. Rong<sup>1,70</sup>, F. Rosini<sup>30b,30c</sup>, Ch. Rosner<sup>19</sup>, M. Q. Ruan<sup>1,64</sup>, N. Salone<sup>48,m</sup>, A. Sarantsev<sup>40,n</sup>, Y. Schelhaas<sup>39</sup>, K. Schoenning<sup>81</sup>, M. Scodeggio<sup>31a</sup>, W. Shan<sup>26</sup>, X. Y. Shan<sup>77,64</sup>, Z. J. Shang<sup>42,e,f</sup>, J. F. Shangguan<sup>17</sup>, L. G. Shao<sup>1,70</sup>, M. Shao<sup>77,64</sup>, C. P. Shen<sup>12,g</sup>, H. F. Shen<sup>1,9</sup>, W. H. Shen<sup>70</sup>, X. Y. Shen<sup>1,70</sup>, B. A. Shi<sup>70</sup>, H. Shi<sup>77,64</sup>, J. L. Shi<sup>8,o</sup>, J. Y. Shi<sup>1</sup>, S. Y. Shi<sup>78</sup>, X. Shi<sup>1,64</sup>, H. L. Song<sup>77,64</sup>, J. J. Song<sup>20</sup>, M. H. Song<sup>42</sup>, T. Z. Song<sup>65</sup>, W. M. Song<sup>38</sup>, Y. X. Song<sup>50,d,p</sup>, Zirong Song<sup>27,j</sup>, S. Sosio<sup>80a,80c</sup>, S. Spataro<sup>80a,80c</sup>, S. Stansilaus<sup>75</sup>, F. Stierler<sup>39</sup>, M. Stolte<sup>3</sup>, S. S. Su<sup>44</sup>, G. B. Sun<sup>82</sup>, G. X. Sun<sup>1</sup>, H. Sun<sup>70</sup>, H. K. Sun<sup>1</sup>, J. F. Sun<sup>20</sup>, K. Sun<sup>67</sup>, L. Sun<sup>82</sup>, R. Sun<sup>77</sup>, S. S. Sun<sup>1,70</sup>, T. Sun<sup>56,q</sup>, W. Y. Sun<sup>55</sup>, Y. C. Sun<sup>82</sup>, Y. H. Sun<sup>32</sup>, Y. J. Sun<sup>77,64</sup>, Y. Z. Sun<sup>1</sup>, Z. Q. Sun<sup>1,70</sup>, Z. T. Sun<sup>54</sup>, C. J. Tang<sup>59</sup>, G. Y. Tang<sup>1</sup>, J. Tang<sup>65</sup>, J. J. Tang<sup>77,64</sup>, L. F. Tang<sup>43</sup>, Y. A. Tang<sup>82</sup>, L. Y. Tao<sup>78</sup>, M. Tat<sup>75</sup>, J. X. Teng<sup>77,64</sup>, J. Y. Tian<sup>77,64</sup>, W. H. Tian<sup>65</sup>, Y. Tian<sup>34</sup>, Z. F. Tian<sup>82</sup>, I. Uman<sup>68b</sup>, E. van der Smagt<sup>3</sup>, B. Wang<sup>1</sup>, B. Wang<sup>65</sup>, Bo Wang<sup>77,64</sup>, C. Wang<sup>42,e,f</sup>, C. Wang<sup>20</sup>, Cong Wang<sup>23</sup>, D. Y. Wang<sup>50,d</sup>, H. J. Wang<sup>42,e,f</sup>, H. R. Wang<sup>83</sup>, J. Wang<sup>10</sup>, J. J. Wang<sup>82</sup>, J. P. Wang<sup>37</sup>, K. Wang<sup>1,64</sup>, L. L. Wang<sup>1</sup>, L. W. Wang<sup>38</sup>, M. Wang<sup>54</sup>, M. Wang<sup>77,64</sup>, N. Y. Wang<sup>70</sup>, S. Wang<sup>42,e,f</sup>, Shun Wang<sup>63</sup>, T. Wang<sup>12,g</sup>, T. J. Wang<sup>47</sup>, W. Wang<sup>65</sup>, W. P. Wang<sup>39</sup>, X. Wang<sup>50,d</sup>, X. F. Wang<sup>42,e,f</sup>, X. L. Wang<sup>12,g</sup>, X. N. Wang<sup>1,70</sup>, Xin Wang<sup>27,j</sup>, Y. Wang<sup>1</sup>, Y. D. Wang<sup>49</sup>, Y. F. Wang<sup>1,9,70</sup>

Y. H. Wang<sup>42,e,f</sup> Y. J. Wang<sup>77,64</sup> Y. L. Wang<sup>20</sup> Y. N. Wang<sup>49</sup> Y. N. Wang<sup>82</sup> Yaqian Wang<sup>18</sup> Yi Wang<sup>67</sup>  
 Yuan Wang<sup>18,34</sup> Z. Wang<sup>1,64</sup> Z. Wang<sup>47</sup> Z. L. Wang<sup>2</sup> Z. Q. Wang<sup>12,g</sup> Z. Y. Wang<sup>1,70</sup> Ziyi Wang<sup>70</sup> D. Wei<sup>47</sup>  
 D. H. Wei<sup>14</sup> H. R. Wei<sup>47</sup> F. Weidner<sup>74</sup> S. P. Wen<sup>1</sup> U. Wiedner<sup>3</sup> G. Wilkinson<sup>75</sup> M. Wolke<sup>81</sup> J. F. Wu<sup>1,9</sup>  
 L. H. Wu<sup>1</sup> L. J. Wu<sup>20</sup> Lianjie Wu<sup>20</sup> S. G. Wu<sup>1,70</sup> S. M. Wu<sup>70</sup> X. W. Wu<sup>78</sup> Y. J. Wu<sup>34</sup> Z. Wu<sup>1,64</sup>  
 L. Xia<sup>77,64</sup> B. H. Xiang<sup>1,70</sup> D. Xiao<sup>42,e,f</sup> G. Y. Xiao<sup>46</sup> H. Xiao<sup>78</sup> Y. L. Xiao<sup>12,g</sup> Z. J. Xiao<sup>45</sup> C. Xie<sup>46</sup>  
 K. J. Xie<sup>1,70</sup> Y. Xie<sup>54</sup> Y. G. Xie<sup>1,64</sup> Y. H. Xie<sup>6</sup> Z. P. Xie<sup>77,64</sup> T. Y. Xing<sup>1,70</sup> C. J. Xu<sup>65</sup> G. F. Xu<sup>1</sup> H. Y. Xu<sup>2</sup>  
 M. Xu<sup>77,64</sup> Q. J. Xu<sup>17</sup> Q. N. Xu<sup>32</sup> T. D. Xu<sup>78</sup> X. P. Xu<sup>60</sup> Y. Xu<sup>12,g</sup> Y. C. Xu<sup>83</sup> Z. S. Xu<sup>70</sup> F. Yan<sup>24</sup>  
 L. Yan<sup>12,g</sup> W. B. Yan<sup>77,64</sup> W. C. Yan<sup>86</sup> W. H. Yan<sup>6</sup> W. P. Yan<sup>20</sup> X. Q. Yan<sup>12,g</sup> Y. Y. Yan<sup>66</sup> H. J. Yang<sup>56,q</sup>  
 H. L. Yang<sup>38</sup> H. X. Yang<sup>1</sup> J. H. Yang<sup>46</sup> R. J. Yang<sup>20</sup> Y. Yang<sup>12,g</sup> Y. H. Yang<sup>46</sup> Y. Q. Yang<sup>10</sup> Y. Z. Yang<sup>20</sup>  
 Z. P. Yao<sup>54</sup> M. Ye<sup>1,64</sup> M. H. Ye<sup>9,b</sup> Z. J. Ye<sup>61,i</sup> Junhao Yin<sup>47</sup> Z. Y. You<sup>65</sup> B. X. Yu<sup>1,64,70</sup> C. X. Yu<sup>47</sup>  
 G. Yu<sup>13</sup> J. S. Yu<sup>27,j</sup> L. W. Yu<sup>12,g</sup> T. Yu<sup>78</sup> X. D. Yu<sup>50,d</sup> Y. C. Yu<sup>86</sup> Y. C. Yu<sup>42</sup> C. Z. Yuan<sup>1,70</sup> H. Yuan<sup>1,70</sup>  
 J. Yuan<sup>38</sup> J. Yuan<sup>49</sup> L. Yuan<sup>2</sup> M. K. Yuan<sup>12,g</sup> S. H. Yuan<sup>78</sup> Y. Yuan<sup>1,70</sup> C. X. Yue<sup>43</sup> Ying Yue<sup>20</sup>  
 A. A. Zafar<sup>79</sup> F. R. Zeng<sup>54</sup> S. H. Zeng<sup>69</sup> X. Zeng<sup>12,g</sup> Y. J. Zeng<sup>65</sup> Y. J. Zeng<sup>1,70</sup> Y. C. Zhai<sup>54</sup> Y. H. Zhan<sup>65</sup>  
 S. N. Zhang<sup>75</sup> B. L. Zhang<sup>1,70</sup> B. X. Zhang<sup>1,b</sup> D. H. Zhang<sup>47</sup> G. Y. Zhang<sup>20</sup> G. Y. Zhang<sup>1,70</sup> H. Zhang<sup>77,64</sup>  
 H. Zhang<sup>86</sup> H. C. Zhang<sup>1,64,70</sup> H. H. Zhang<sup>65</sup> H. Q. Zhang<sup>1,64,70</sup> H. R. Zhang<sup>77,64</sup> H. Y. Zhang<sup>1,64</sup> J. Zhang<sup>65</sup>  
 J. J. Zhang<sup>57</sup> J. L. Zhang<sup>21</sup> J. Q. Zhang<sup>45</sup> J. S. Zhang<sup>12,g</sup> J. W. Zhang<sup>1,64,70</sup> J. X. Zhang<sup>42,e,f</sup> J. Y. Zhang<sup>1</sup>  
 J. Z. Zhang<sup>1,70</sup> Jianyu Zhang<sup>70</sup> L. M. Zhang<sup>67</sup> Lei Zhang<sup>46</sup> N. Zhang<sup>38</sup> P. Zhang<sup>1,9</sup> Q. Zhang<sup>20</sup>  
 Q. Y. Zhang<sup>38</sup> R. Y. Zhang<sup>42,e,f</sup> S. H. Zhang<sup>1,70</sup> Shulei Zhang<sup>27,j</sup> X. M. Zhang<sup>1</sup> X. Y. Zhang<sup>54</sup> Y. Zhang<sup>1</sup>  
 Y. Zhang<sup>78</sup> Y. T. Zhang<sup>86</sup> Y. H. Zhang<sup>1,64</sup> Y. P. Zhang<sup>77,64</sup> Z. D. Zhang<sup>1</sup> Z. H. Zhang<sup>1</sup> Z. L. Zhang<sup>38</sup>  
 Z. L. Zhang<sup>60</sup> Z. X. Zhang<sup>20</sup> Z. Y. Zhang<sup>82</sup> Z. Y. Zhang<sup>47</sup> Z. Y. Zhang<sup>49</sup> Zh. Zh. Zhang<sup>20</sup> G. Zhao<sup>1</sup>  
 J. Y. Zhao<sup>1,70</sup> J. Z. Zhao<sup>1,64</sup> L. Zhao<sup>1</sup> L. Zhao<sup>77,64</sup> M. G. Zhao<sup>47</sup> S. J. Zhao<sup>86</sup> Y. B. Zhao<sup>1,64</sup> Y. L. Zhao<sup>60</sup>  
 Y. P. Zhao<sup>49</sup> Y. X. Zhao<sup>34,70</sup> Z. G. Zhao<sup>77,64</sup> A. Zhemchugov<sup>40,h</sup> B. Zheng<sup>78</sup> B. M. Zheng<sup>38</sup> J. P. Zheng<sup>1,64</sup>  
 W. J. Zheng<sup>1,70</sup> X. R. Zheng<sup>20</sup> Y. H. Zheng<sup>70,k</sup> B. Zhong<sup>45</sup> C. Zhong<sup>20</sup> H. Zhou<sup>39,54,r</sup> J. Q. Zhou<sup>38</sup>  
 S. Zhou<sup>6</sup> X. Zhou<sup>82</sup> X. K. Zhou<sup>6</sup> X. R. Zhou<sup>77,64</sup> X. Y. Zhou<sup>43</sup> Y. X. Zhou<sup>83</sup> Y. Z. Zhou<sup>12,g</sup> A. N. Zhu<sup>70</sup>  
 J. Zhu<sup>47</sup> K. Zhu<sup>1</sup> K. J. Zhu<sup>1,64,70</sup> K. S. Zhu<sup>12,g</sup> L. X. Zhu<sup>70</sup> Lin Zhu<sup>20</sup> S. H. Zhu<sup>76</sup> T. J. Zhu<sup>12,g</sup>  
 W. D. Zhu<sup>12,g</sup> W. J. Zhu<sup>1</sup> W. Z. Zhu<sup>20</sup> Y. C. Zhu<sup>77,64</sup> Z. A. Zhu<sup>1,70</sup> X. Y. Zhuang<sup>47</sup> and J. H. Zou<sup>1</sup>

(BESIII Collaboration)

<sup>1</sup>*Institute of High Energy Physics, Beijing 100049, People's Republic of China*
<sup>2</sup>*Beihang University, Beijing 100191, People's Republic of China*
<sup>3</sup>*Bochum Ruhr-University, D-44780 Bochum, Germany*
<sup>4</sup>*Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia*
<sup>5</sup>*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
<sup>6</sup>*Central China Normal University, Wuhan 430079, People's Republic of China*
<sup>7</sup>*Central South University, Changsha 410083, People's Republic of China*
<sup>8</sup>*Chengdu University of Technology, Chengdu 610059, People's Republic of China*
<sup>9</sup>*China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China*
<sup>10</sup>*China University of Geosciences, Wuhan 430074, People's Republic of China*
<sup>11</sup>*Chung-Ang University, Seoul, 06974, Republic of Korea*
<sup>12</sup>*Fudan University, Shanghai 200433, People's Republic of China*
<sup>13</sup>*GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany*
<sup>14</sup>*Guangxi Normal University, Guilin 541004, People's Republic of China*
<sup>15</sup>*Guangxi University, Nanning 530004, People's Republic of China*
<sup>16</sup>*Guangxi University of Science and Technology, Liuzhou 545006, People's Republic of China*
<sup>17</sup>*Hangzhou Normal University, Hangzhou 310036, People's Republic of China*
<sup>18</sup>*Hebei University, Baoding 071002, People's Republic of China*
<sup>19</sup>*Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany*
<sup>20</sup>*Henan Normal University, Xinxiang 453007, People's Republic of China*
<sup>21</sup>*Henan University, Kaifeng 475004, People's Republic of China*
<sup>22</sup>*Henan University of Science and Technology, Luoyang 471003, People's Republic of China*
<sup>23</sup>*Henan University of Technology, Zhengzhou 450001, People's Republic of China*
<sup>24</sup>*Hengyang Normal University, Hengyang 421001, People's Republic of China*

- <sup>25</sup>Huangshan College, Huangshan 245000, People's Republic of China
- <sup>26</sup>Hunan Normal University, Changsha 410081, People's Republic of China
- <sup>27</sup>Hunan University, Changsha 410082, People's Republic of China
- <sup>28</sup>Indian Institute of Technology Madras, Chennai 600036, India
- <sup>29</sup>Indiana University, Bloomington, Indiana 47405, USA
- <sup>30a</sup>INFN Laboratori Nazionali di Frascati, INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy
- <sup>30b</sup>INFN Sezione di Perugia, I-06100, Perugia, Italy
- <sup>30c</sup>University of Perugia, I-06100, Perugia, Italy
- <sup>31a</sup>INFN Sezione di Ferrara, INFN Sezione di Ferrara, I-44122, Ferrara, Italy
- <sup>31b</sup>University of Ferrara, I-44122, Ferrara, Italy
- <sup>32</sup>Inner Mongolia University, Hohhot 010021, People's Republic of China
- <sup>33</sup>Institute of Business Administration, Karachi, Pakistan
- <sup>34</sup>Institute of Modern Physics, Lanzhou 730000, People's Republic of China
- <sup>35</sup>Institute of Physics and Technology, Mongolian Academy of Sciences, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia
- <sup>36</sup>Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile
- <sup>37</sup>Jiangsu Ocean University, Lianyungang 222000, People's Republic of China
- <sup>38</sup>Jilin University, Changchun 130012, People's Republic of China
- <sup>39</sup>Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
- <sup>40</sup>Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
- <sup>41</sup>Justus-Liebig-Universität Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany
- <sup>42</sup>Lanzhou University, Lanzhou 730000, People's Republic of China
- <sup>43</sup>Liaoning Normal University, Dalian 116029, People's Republic of China
- <sup>44</sup>Liaoning University, Shenyang 110036, People's Republic of China
- <sup>45</sup>Nanjing Normal University, Nanjing 210023, People's Republic of China
- <sup>46</sup>Nanjing University, Nanjing 210093, People's Republic of China
- <sup>47</sup>Nankai University, Tianjin 300071, People's Republic of China
- <sup>48</sup>National Centre for Nuclear Research, Warsaw 02-093, Poland
- <sup>49</sup>North China Electric Power University, Beijing 102206, People's Republic of China
- <sup>50</sup>Peking University, Beijing 100871, People's Republic of China
- <sup>51</sup>Qufu Normal University, Qufu 273165, People's Republic of China
- <sup>52</sup>Renmin University of China, Beijing 100872, People's Republic of China
- <sup>53</sup>Shandong Normal University, Jinan 250014, People's Republic of China
- <sup>54</sup>Shandong University, Jinan 250100, People's Republic of China
- <sup>55</sup>Shandong University of Technology, Zibo 255000, People's Republic of China
- <sup>56</sup>Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
- <sup>57</sup>Shanxi Normal University, Linfen 041004, People's Republic of China
- <sup>58</sup>Shanxi University, Taiyuan 030006, People's Republic of China
- <sup>59</sup>Sichuan University, Chengdu 610064, People's Republic of China
- <sup>60</sup>Soochow University, Suzhou 215006, People's Republic of China
- <sup>61</sup>South China Normal University, Guangzhou 510006, People's Republic of China
- <sup>62</sup>Southeast University, Nanjing 211100, People's Republic of China
- <sup>63</sup>Southwest University of Science and Technology, Mianyang 621010, People's Republic of China
- <sup>64</sup>State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China
- <sup>65</sup>Sun Yat-Sen University, Guangzhou 510275, People's Republic of China
- <sup>66</sup>Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
- <sup>67</sup>Tsinghua University, Beijing 100084, People's Republic of China
- <sup>68a</sup>Turkish Accelerator Center Particle Factory Group, Istinye University, 34010, Istanbul, Turkey
- <sup>68b</sup>Near East University, Nicosia, North Cyprus, 99138, Mersin 10, Turkey
- <sup>69</sup>University of Bristol, H H Wills Physics Laboratory, Tyndall Avenue, Bristol BS8 1TL, United Kingdom
- <sup>70</sup>University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
- <sup>71</sup>University of Hawaii, Honolulu, Hawaii 96822, USA
- <sup>72</sup>University of Jinan, Jinan 250022, People's Republic of China
- <sup>73</sup>University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom
- <sup>74</sup>University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany
- <sup>75</sup>University of Oxford, Keble Road, Oxford OX13RH, United Kingdom
- <sup>76</sup>University of Science and Technology Liaoning, Anshan 114051, People's Republic of China
- <sup>77</sup>University of Science and Technology of China, Hefei 230026, People's Republic of China
- <sup>78</sup>University of South China, Hengyang 421001, People's Republic of China
- <sup>79</sup>University of the Punjab, Lahore-54590, Pakistan
- <sup>80a</sup>University of Turin and INFN, University of Turin, I-10125, Turin, Italy

<sup>80b</sup>*University of Eastern Piedmont, I-15121, Alessandria, Italy*

<sup>80c</sup>*INFN, I-10125, Turin, Italy*

<sup>81</sup>*Uppsala University, Box 516, SE-75120 Uppsala, Sweden*

<sup>82</sup>*Wuhan University, Wuhan 430072, People's Republic of China*

<sup>83</sup>*Yantai University, Yantai 264005, People's Republic of China*

<sup>84</sup>*Yunnan University, Kunming 650500, People's Republic of China*

<sup>85</sup>*Zhejiang University, Hangzhou 310027, People's Republic of China*

<sup>86</sup>*Zhengzhou University, Zhengzhou 450001, People's Republic of China*

<sup>b</sup>Deceased.

<sup>c</sup>Also at the Novosibirsk State University, Novosibirsk, 630090, Russia.

<sup>d</sup>Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China.

<sup>e</sup>Also at MOE Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, People's Republic of China.

<sup>f</sup>Also at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, People's Republic of China.

<sup>g</sup>Also at Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, People's Republic of China.

<sup>h</sup>Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.

<sup>i</sup>Also at Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, People's Republic of China.

<sup>j</sup>Also at School of Physics and Electronics, Hunan University, Changsha 410082, People's Republic of China.

<sup>k</sup>Also at Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, People's Republic of China.

<sup>l</sup>Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.

<sup>m</sup>Currently at Silesian University in Katowice, Chorzow, 41-500, Poland.

<sup>n</sup>Also at the NRC "Kurchatov Institute", PNPI, 188300, Gatchina, Russia.

<sup>o</sup>Also at Applied Nuclear Technology in Geosciences Key Laboratory of Sichuan Province, Chengdu University of Technology, Chengdu 610059, People's Republic of China.

<sup>p</sup>Also at Ecole Polytechnique Federale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland.

<sup>q</sup>Also at Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology; Institute of Nuclear and Particle Physics, Shanghai 200240, People's Republic of China.

<sup>r</sup>Also at Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany.