

Supplementary Information for "Test of local realism via entangled $\Lambda\bar{\Lambda}$ system"

BESIII Collaboration*

Supplementary Note 1

Test of Bell inequality

The angular distribution of $p\bar{p}$ is shown in Supplementary Fig. 1. The points with total error bars, corresponding to signal, are obtained by subtracting the background and the weighted spin-entanglement background events in the amplitude model from the selected events, correcting by the efficiency, then normalizing by the total number of signal events. The dashed line shows the QM prediction with a slope of α_Λ^2 , we take $\alpha_\Lambda = 0.750 \pm 0.009 \pm 0.004$ [1]. The dotted line represents the QM prediction with Λ polarization determined by a hidden process, and its slope is $\alpha_\Lambda^2/3$. The shaded region represents the region that satisfies the Bell inequality of Eq. (3) in the main text. However, the measured angular distribution is outside this region, indicating a significant violation of the Bell inequality, while being consistent with the QM prediction for $\Lambda\bar{\Lambda}$ spin-entanglement events. To assess the significance of distinguishing the QM prediction from the Bell inequality, we fit the measured distribution using a linear combination of both the nearby boundary of the Bell inequality and the QM prediction (refer to Supplementary Fig. 1), with two parameters. The change in the χ^2 of the binned fit, with and without the QM prediction, is 69.2, corresponding to a change of one degree of freedom with consideration of systematic uncertainties. Therefore, the significance to exclude the Bell inequality region is 8.9σ .

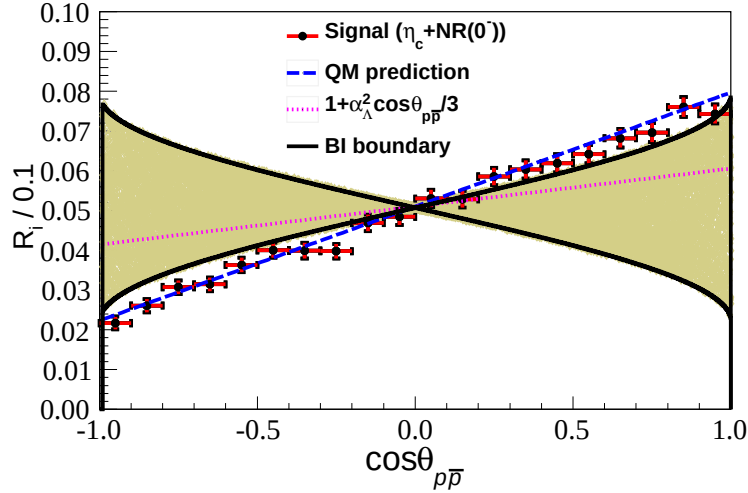
Test of Clauser–Horne–Shimony–Holt inequality

Another type of Bell inequality was proposed based on the Clauser–Horne–Shimony–Holt (CHSH) inequality. Utilizing the bilinear expression of the CHSH inequality in momentum space [2], one has

$$|\langle n_a n'_b \rangle + \langle n_a n'_d \rangle + \langle n_c n'_b \rangle - \langle n_c n'_d \rangle| \leq \frac{2\alpha_\Lambda^2}{9}, \quad (1)$$

Here, $\mathbf{n} = \mathbf{p}/|\mathbf{p}|$ and $\mathbf{n}' = \mathbf{p}'/|\mathbf{p}'|$, where $\mathbf{p}$ and $\mathbf{p}'$ represent the momenta of the proton and anti-proton in the rest frames of Λ and $\bar{\Lambda}$, respectively. The guide directions are denoted by a, b, c , and d , and momentum projections are defined as $\langle n_a n'_b \rangle = \langle \mathbf{n} \cdot \mathbf{a} \mathbf{n}' \cdot \mathbf{b} \rangle$, for example. In the case

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Supplementary Figure 1 | Normalized signal event distribution ($R_i = N_i/N_{\text{tot}}$) of $\cos \theta_{p\bar{p}}$. Here $N_i(N_{\text{tot}})$ is the number of events in i -th bin (total signal events). The points with total error bars are the signal, while the dashed line is the QM prediction, with a slope of α_Λ^2 . The dotted line represents the QM prediction with Λ polarization determined by a hidden process. The filled region indicates the domain that satisfies the Bell inequality (denoted by BI in this figure) in Eq. (3).

of maximal violation of the Bell inequality, the momentum correlation can be related to the decay amplitude by defining :

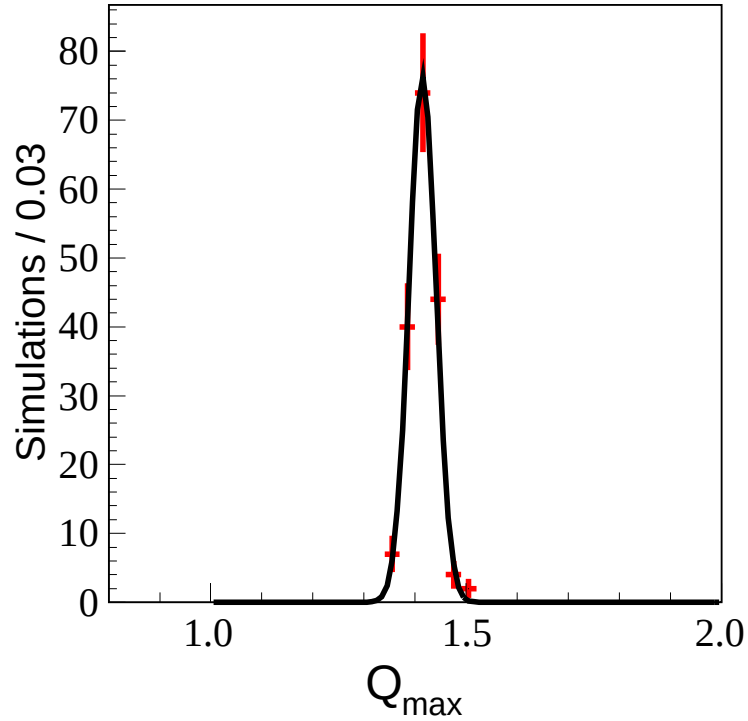
$$\begin{aligned}
 C_{ij} &\equiv \langle n_i n'_j \rangle \frac{9}{2\alpha_\Lambda^2} \quad (i, j = 1, 2, 3) \\
 &= \frac{9}{2\alpha_\Lambda^2 |\mathbf{p}|^2} \frac{\int d\Omega_\Lambda d\Omega_p d\Omega_{\bar{p}} p_i p'_j |\mathcal{M}_0|^2}{\int d\Omega_\Lambda d\Omega_p d\Omega_{\bar{p}} |\mathcal{M}_0|^2},
 \end{aligned} \tag{2}$$

where the indices i, j label the x, y, z components of a vector in Cartesian coordinates; $\mathcal{M}_0$ represents the amplitude for the sequential decay $\eta_c \rightarrow \Lambda \bar{\Lambda}$, $\Lambda \rightarrow p \pi^-$ and $\bar{\Lambda} \rightarrow \bar{p} \pi^+$. While C_{ij} depends on the QM measurement α_Λ^2 , it has been demonstrated that the correlation tensor can produce distinct maximum values of C_{ij} for predictions based on QM and local realism (LR), such as:

$$Q_{\max} = 2\sqrt{C_{11}^2 + C_{33}^2} = \begin{cases} 1 & \text{(LR)} \\ \sqrt{2} & \text{(QM)} \end{cases}. \tag{3}$$

The LR predicts a maximum value of $Q_{\max} = 1$, whereas QM can violate local realism with a maximum value of $\sqrt{2}$.

37 We tested the CHSH inequality by calculating the C_{ij} tensor (see Eq. 2) using the signal of
 38 TOY MC events. These events were generated based on the amplitude model with fixed parameters
 39 obtained from the amplitude analysis. The statistics of each TOY MC experiment were fixed to
 40 those obtained in the amplitude analysis. We then calculated the distribution of Q_{max} according to
 41 Eq. 3 as a function of the number of TOY MC experiments, as shown in Supplementary Fig. 2. The
 42 distribution was fitted with a Gaussian function, which provided a good description of the Q_{max}
 43 distribution. The mean (μ) and standard deviation (σ) of the Gaussian distribution were determined
 44 to be $\mu = 1.416 \pm 0.002$ and $\sigma = (2.771 \pm 0.001) \times 10^{-2}$, respectively. The p -value is calculated
 45 with $Q_{max} < 1$. Then the significance of vetoing LHVT was estimated to be larger than 10σ .

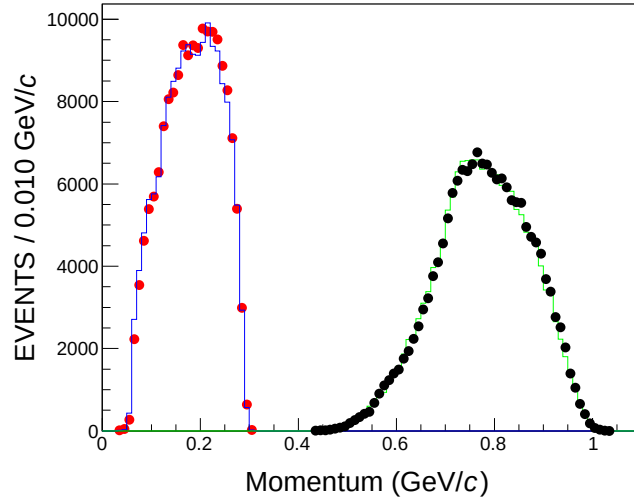


Supplementary Figure 2 | The distribution of Q_{max} is plotted as a function of the number of TOY MC simulations. The dots with error bars represent the TOY MC results, while the line represents the fitted results using a Gaussian distribution.

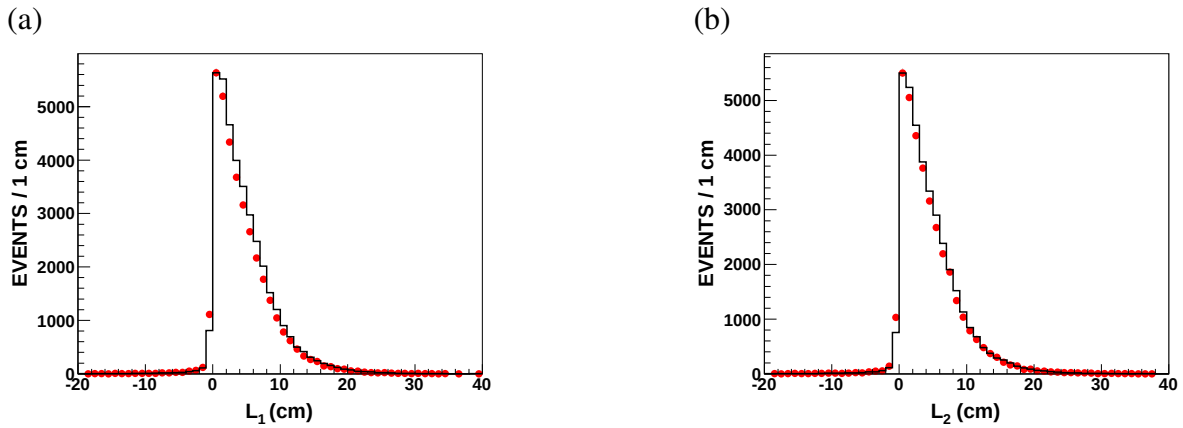
46 Supplementary Note 2

47 Selection Criteria

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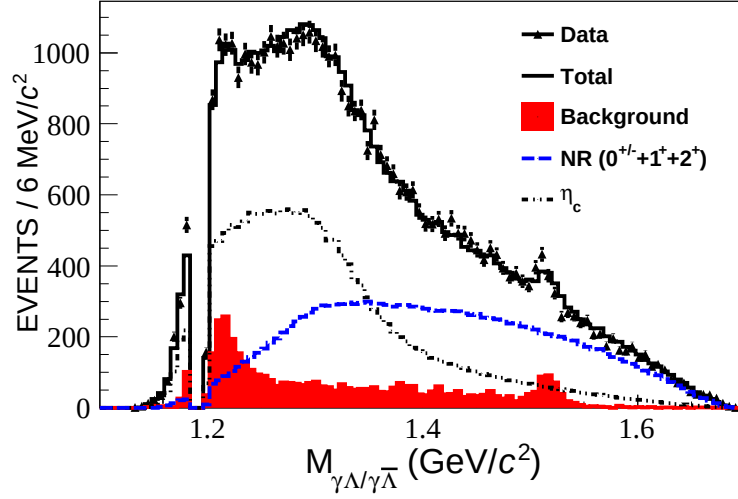
Supplementary Figure 3 | Comparison of the momentum distributions of pions and protons for the decay $J/\psi \rightarrow \gamma \eta_c \rightarrow \gamma \Lambda \bar{\Lambda} \rightarrow \gamma p \pi^- \bar{p} \pi^+$ with signal MC events. The black dots and green line denote data and MC events, respectively, corresponding to p ($\bar{p}$), and the red dots and blue line denote data and MC events corresponding to π^+ (π^-).



Supplementary Figure 4 | The comparison of decay lengths of (a) Λ and (b) $\bar{\Lambda}$. The red dots denote data, and the black histograms denote the signal MC sample.

Supplementary Note 3

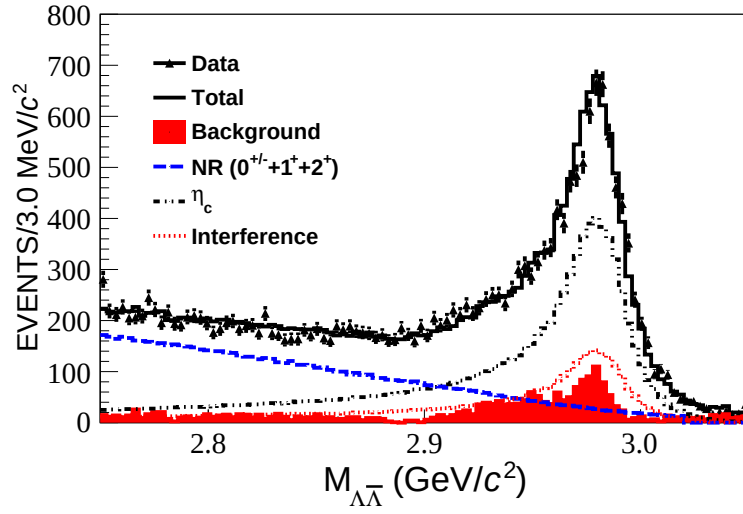
Amplitude analysis



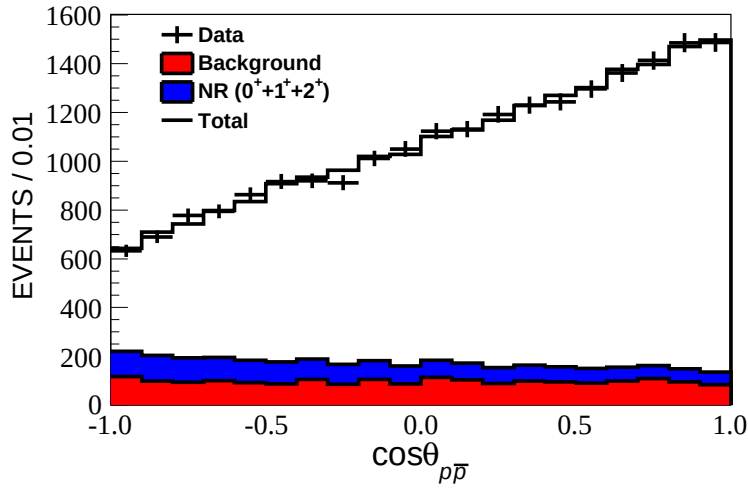
Supplementary Figure 5 | The invariant mass spectrum $M_{\gamma\Lambda/\gamma\bar{\Lambda}}$ (one event is filled twice by $M_{\gamma\Lambda}$ and $M_{\gamma\bar{\Lambda}}$). The triangles with error bars are data, the black histogram is the total fit result, the red shaded part is the background, the blue dash line is the NR state, and the black dash-dotted line is the signal η_c .

Supplementary Table 1| The yields of each component determined in the amplitude fit.

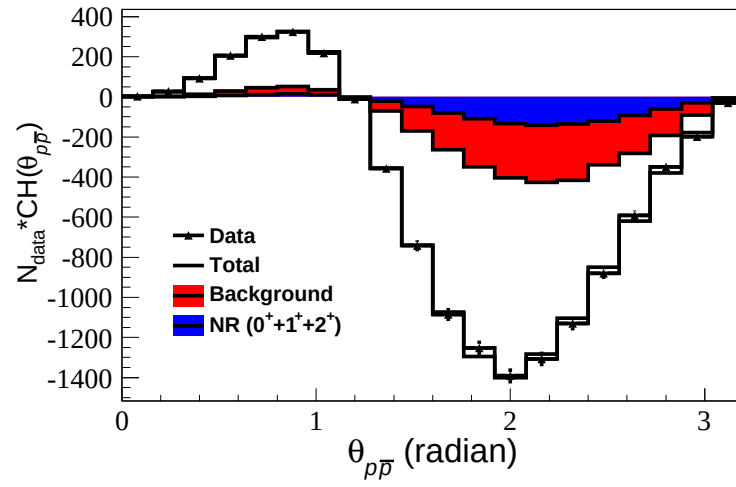
Components	$NR(0^+)$	$NR(1^+)$	$NR(2^+)$	$NR(0^-)$	η_c
Yields	892.4 ± 230.3	116.2 ± 52.8	478.5 ± 155.6	6139.7 ± 353.2	8576.6 ± 154.6



Supplementary Figure 6 | The invariant mass spectrum $M_{\Lambda\bar{\Lambda}}$. Along with the items described in Supplementary Fig. 5, the interference of the η_c with $NR(0^\pm, 1^+, 2^+)$ is shown.



Supplementary Figure 7 | The angular distribution $\cos\theta_{p\bar{p}}$. The triangles with error bars are data, the histogram is the total fit result, and the shaded areas are the background and non-resonant states.



Supplementary Figure 8 | The distribution of $CH(\theta_{p\bar{p}}) = \alpha_{\Lambda}^2 \left[\frac{3 \cos \theta_{p\bar{p}} - \cos(3\theta_{p\bar{p}})}{4} - \frac{1}{2} \right]$. The legend is the same as Supplementary Fig. 7.

Supplementary Note 4

Systematic uncertainties

The systematic uncertainties are listed as below.

1. Tracking efficiency. The tracking efficiencies of $p, \bar{p}$ and $\pi^\pm$ are obtained by studying the control sample $J/\psi \rightarrow \Lambda \bar{\Lambda} \rightarrow p \bar{p} \pi^+ \pi^-$. The event selection criteria of the control sample are the same as those applied in the data analysis. For events with a missing charged track, three charged tracks are identified using PID, and two of the tracks with opposite charge are required to be successfully fitted to a secondary Λ vertex. The tracking efficiency of reconstructing a charged track i in data and MC events is defined as: $\epsilon(i) = \frac{N_{\text{trk}=4}}{N_{\text{trk} \geq 3}}$. Here $N_{\text{trk}=4}$ is the number of events for which all four charged tracks are reconstructed, and $N_{\text{trk} \geq 3}$ is the number of events, in which all the other three charged tracks, in addition to the track i to be studied, are reconstructed. The ratio of the efficiency between data and MC events is $R_{\text{trk}}(i) = \frac{\epsilon_{\text{data}}(i)}{\epsilon_{\text{MC}}(i)}$. By comparing the control samples, the two-dimensional distributions of $R_{\text{trk}}(p_t, \cos \theta)$ for $p, \bar{p}$ and $\pi^\pm$ are determined, where p_t is the transverse momentum. In an alternative fit, the normalization factor $\mathcal{N}(\vec{\xi})$ is multiplied by $R_{\text{trk}}(i)$ for each charged track per event. The difference between the alternative and nominal fits is taken as the systematic uncertainty.
2. Photon detection efficiency. The photon detection efficiency is determined by studying the control sample $J/\psi \rightarrow \pi^+ \pi^- \pi^0$, as done in [3]. The photon selection criteria for the control sample are the same as those used in this analysis. The data selection process requires that each event must contain two oppositely charged tracks and at least one good photon. In cases where an event contains multiple good photons, every combination of $\gamma \pi^+ \pi^-$ is reconstructed. Subsequently, energy conservation is then utilized to pinpoint the region in the EMC where the second photon from $\pi^0 \rightarrow \gamma \gamma$ is expected to be located. The detection efficiency of photons is defined as $\epsilon_\gamma = \frac{N_{\gamma\gamma}}{N_\gamma}$, where $N_{\gamma\gamma}$ and N_γ represent the numbers of events in which two photons and one photon appear, respectively. The difference in photon detection efficiencies between data and MC events is determined to be 0.5% and 1.5%, corresponding to the barrel and end cap regions of the EMC, respectively. In an alternative fit, the normalization factor $\mathcal{N}(\vec{\xi})$ is calculated by multiplying a Gaussian dispersion factor $\text{Gaus}(1, \delta)$ for each MC event, where $\delta = 0.015$ or 0.005 depending on whether the photon is in the barrel or end cap. The difference between the alternative and nominal fits is taken as the systematic uncertainty.
3. Space-like separation criteria. The uncertainty in detection efficiency due to the space-like separation criteria is estimated by the control sample $J/\psi \rightarrow \Lambda \bar{\Lambda}$. The event selection criteria of the control sample are the same as those applied in the data analysis. Out of N events, N' events satisfy the requirements of the space-like separation criteria, and the

selection efficiency is defined as $\epsilon = N'/N$. The difference in selection efficiencies between data and MC events is 0.2%, which is negligible.

However, due to the resolution effect of the detector on the measured decay length of $\Lambda(\bar{\Lambda})$ particles, the space-like separation criteria L_1/L_2 is not uniquely determined. The deviation between the measured value and the true value is determined using MC simulation, where $\Delta(L_1/L_2)$ follows a Gaussian distribution with a mean of 0 and a standard deviation of 0.062 cm. To refine our analysis, we narrowed the window of the L_1/L_2 space-like separation by twice the standard deviation at both ends, and re-selected the data. The difference between the $p\bar{p}$ angular distribution and the CH inequality distribution, obtained by fitting this refined sample, is considered as the systematic uncertainties in comparison to the nominal fitting.

4. Kinematic fit. The systematic uncertainty of the 4C kinematic fit is obtained by applying track parameter corrections. The reason for the difference between the kinematic fit of the data and MC events is that the pull distributions of the helix parameters of charged tracks are not consistent. The momentum of the MC event is modified using the pull distribution of the helix parameters. In an alternative fit, we calculate the normalization factor $\mathcal{N}(\vec{\xi})$ with the modified MC events. The difference between the nominal and alternative fits is taken as the systematic uncertainty.
5. Background estimation. The number of background events estimated by MC samples for the two simultaneously fitted samples, collected in 2012 and other years, are $1,029 \pm 33$ and $3,290 \pm 63$. Their statistical fluctuations are used to estimate the uncertainty due to the background. The likelihood function of background events is calculated by multiplying a Gaussian weighting factor $\text{Gaus}(1, \delta n/n)$, where $\delta n/n$ is the relative error of the background. Thus $\ln \mathcal{L}(\vec{\xi}, \vec{\omega}_{\text{bg}}) = \text{Gaus}(1, \delta n/n) \sum_{i=1}^{N_{\text{bg}}} \ln \mathcal{P}_i(\vec{\xi}, \vec{\omega}_{\text{bg}})$ is used in an alternative fit.
6. η_c mass and width. In the nominal fit, the η_c mass and width are fixed to the world averages [4], i.e. $M_0 = (2983.9 \pm 0.4) \text{ MeV}/c^2$ and $\Gamma = (32.0 \pm 0.7) \text{ MeV}$. Their relative uncertainties are $\delta M_0/M_0 = 1.7 \times 10^{-4}$ and $\delta \Gamma/\Gamma = 2.2\%$. The uncertainties are estimated by smearing the η_c mass and width in the calculation of the likelihood function by a Gaussian distributions, $M_{\eta_c} \sim \text{Gaus}(M_0, \delta M_0/M_0)$ and $\Gamma_{\eta_c} \sim \text{Gaus}(\Gamma, \delta \Gamma/\Gamma)$.

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