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Observation of $e^+e^- \to \eta\psi(2S)$ at center-of-mass energies from 4.236 to 4.600 GeV

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Abstract: Using a total of 5.25 fb^{-1} of e^+e^- collision data with center-of-mass energies from 4.236 to 4.600 GeV, we report the first observation of the process $e^+e^- \to \eta\psi(2S)$ with a statistical significance of 4.9 standard deviations. The data sets were collected by the BESIII detector operating at the BEPCII storage ring. We measure the yield of events integrated over center-of-mass energies and also present the energy dependence of the measured cross section.

Keywords: e^+-e^- Experiments, Exotics, Particle and resonance production, Quarkonium

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Contents

1 Introduction

The recent observation of a number of unexpected vector charmonium-like states ($J^{PC} = 1^{--}$) above open-charm threshold has stimulated theoretical and experimental studies of the conventional and exotic states in this energy region [1–7]. These vector states, originally called the $Y(4260)$ [8–12], the $Y(4360)$ [13–15], and the $Y(4660)$ [14, 15], observed by the BaBar, Belle, and CLEO experiments, can be produced via the initial state radiation (ISR) process, and are often observed in final states with two pions and a charmonium state, like the J/ψ or $\psi(2S)$. They differ from the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ states which are observed in the e^+e^- inclusive hadronic cross section [16] and match potential model calculations of the charmonium spectrum [17]. The Y states have many theoretical interpretations, including compact tetraquarks, molecules, hybrids, hadrocharmonia [1–7], and so on, but they are still not well understood.

In recent years two resonant structures around 4.22 and 4.32 GeV$/c^2$ were observed in a fit to the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ measured by the BESIII experiment [18]. The lower mass structure, the $Y(4220)$, is interpreted as the main component of the well-known $Y(4260)$ structure [8–12], and the higher mass structure, the $Y(4320)$, could be the $Y(4360)$ resonance [13–15, 19] observed in the process $e^+e^- \to \pi^+\pi^-\psi(2S)$. A series of cross-section measurements of $e^+e^- \to \pi^+\pi^- h_c$ [20], $e^+e^- \to \omega\chi_{c0}$ [21], and $e^+e^- \to \pi^+ D^0 D^{*-}$ together with the charge-conjugate (*c.c.*) mode [22] has been reported by BESIII, and the parameters of the $Y(4220)$ resonance in these processes are consistent with those measured in the $e^+e^- \to \pi^+\pi^- J/\psi$ process [18].

Searching for new decay modes of Y states produced in e^+e^- annihilation and measuring the line shapes of the production cross sections will shed light on the nature of the Y states. Besides the $\pi\pi$ hadronic transitions, other hadronic transitions (via η, η') of these Y states to lower mass charmonium states such as the J/ψ or $\psi(2S)$ also provide further insight into their internal structure. The CLEO-c [23], Belle [24], and BESIII [25–27] experiments measured the cross section of $e^+e^- \to \eta J/\psi$, and BESIII observed the decays $Y(4220) \to \eta J/\psi$ and $Y(4390) \to \eta J/\psi$ [27] for the first time. The authors of ref. [28] reproduced the measured $e^+e^- \to \eta J/\psi$ line shape and predicted the production cross section of the analogous process $e^+e^- \to \eta' J/\psi$ at $\mathcal{O}(\alpha_s^4)$ accuracy in the framework of non-relativistic Quantum Chromodynamics (NRQCD). However, the measured cross section of $e^+e^- \to \eta' J/\psi$ [29, 30] by BESIII is significantly smaller than the theoretical prediction [28].

To provide more information for the study of the vector charmonium-like states, the cross section of $e^+e^- \to \eta\psi(2S)$ can also be compared with those of the processes $e^+e^- \to \eta J/\psi$ and $e^+e^- \to \eta' J/\psi$. The CLEO-c experiment searched for the process $e^+e^- \to \eta\psi(2S)$ with data at center-of-mass (c.m.) energy $\sqrt{s} = 4.260$ GeV, and reported an upper limit on the Born cross section, $\sigma[e^+e^- \to \eta\psi(2S)] < 25$ pb, at a 90% confidence level (C.L.) [23]. This is the only available experimental study of this process.

In this article, we present a study of $e^+e^- \to \eta\psi(2S)$ at 14 c.m. energies from 4.236 to 4.600 GeV, using data collected with the BESIII detector [31] operating at the BEPCII collider [32]. The total integrated luminosity is $5.25\,\mathrm{fb}^{-1}$. The c.m. energies were measured using $e^+e^- \to \mu^+\mu^-$ events with an uncertainty of 0.8 MeV [33] and the integrated luminosities were measured using Bhabha scattering events to an uncertainty of 1.0% [34, 35]. The $\psi(2S)$ is reconstructed using the decay chain $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \ell^+\ell^-$ ($\ell = e$, μ), and the η using $\eta \to \gamma\gamma$.

2 BESIII detector and Monte Carlo simulation

The cylindrical core of the BESIII detector consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate chamber muon identifier modules interleaved with steel. The acceptance of charged particles and photons is 93% over 4π solid angle. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for the electrons from Bhabha scattering events. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution of the TOF barrel part is 68 ps, while that of the end cap part is 110 ps. The end cap TOF system was upgraded in 2015 with multi-gap resistive plate chamber technology, providing a time resolution of 60 ps [36, 37].

To optimize the signal event selection criteria, estimate the background contributions and determine the detection efficiency, simulated samples are produced with the GEANT4-based [38] Monte Carlo (MC) package which includes the geometric description of the BESIII detector and the detector response. The signal MC events of $e^+e^- \to \eta\psi(2S)$ with the corresponding η and $\psi(2S)$ decay modes are generated using HELAMP and EVTGEN [39, 40] at each c.m. energy. The beam energy spread and ISR in the e^+e^- annihilations are modelled with the generator KKMC [41, 42] and the final state radiations (FSR) from charged final-state particles are incorporated with the PHOTOS package [43]. The possible background contributions are also studied with KKMC [41, 42] at each c.m. energy. The decay modes are modelled with EVTGEN using branching fractions taken from the PDG [16].

3 Event selection

Candidate events with four charged tracks with zero net charge and at least two photons are selected. The charged tracks are required to be well reconstructed in the MDC with a polar angle θ satisfying $|\cos\theta| < 0.93$; and their distances of the closest approach to the interaction point in $x-y$ plane and z direction have to be less than 1 cm and 10 cm, respectively. Since the $\pi^\pm$ and $\ell^\pm$ are kinematically well separated, charged particles with momenta less than 0.8 GeV/c in the laboratory frame are assumed to be $\pi^\pm$, whereas the ones with momenta larger than 1.0 GeV/c are assumed to be $\ell^\pm$. To separate electron from muon candidates, the EMC deposited energy is used. The energy deposits of electron candidates and muon candidates are required to be larger than 1.0 GeV and less than 0.4 GeV, respectively. Photon candidates are reconstructed from showers in EMC crystals. The reconstructed energies for the clusters in the barrel ($|\cos\theta| < 0.80$) and the end caps ($0.86 < |\cos\theta| < 0.92$) of the EMC are required to be higher than 25 and 50 MeV, respectively. To eliminate showers associated with charged particles, the angle between the photon and any charged track in the EMC must be at least 10 degrees. To suppress the electronic noise and energy deposits unrelated to the event, the time of the EMC shower is required to be $0 \leqslant t \leqslant 700$ ns with respect to the start of the event. To improve the mass resolution and suppress background contributions, we require charged tracks to originate from a common vertex. In addition, a four-constraint (4C) kinematic fit is performed under the hypothesis of $e^+e^- \to \gamma\gamma\pi^+\pi^-\ell^+\ell^-$ to constrain the sum of four momenta of the final state particles to that of the initial colliding beams. The χ^2 of the kinematic fit, χ^2_{4C}, is required to be less than 40. If there are more than two photons in an event, the combination of $\gamma\gamma\pi^+\pi^-\ell^+\ell^-$ with the least χ^2_{4C} is retained for further study.

To identify signal candidates that involve the J/ψ resonance, we select events with a $\ell^+\ell^-$ invariant mass within a window of three detector resolutions from the J/ψ nominal mass [16], $3064.6 < M(\ell^+\ell^-) < 3140.8\,\text{MeV}/c^2$, referred to as the J/ψ mass window. To remove the background from process $e^+e^- \to \eta' J/\psi$ with $\eta' \to \pi^+\pi^-\eta$, the invariant mass of $\pi^+\pi^-\gamma\gamma$ is required to be larger than 1 GeV/c^2. Two-dimensional (2D) distributions for $\gamma\gamma$ and $\pi^+\pi^- J/\psi$ invariant masses, $M(\gamma\gamma)$ versus $M(\pi^+\pi^- J/\psi)$, and the corresponding one-dimensional (1D) projections for data, signal MC samples, background contributions at $\sqrt{s} = 4.258\,\text{GeV}$ are presented in figures 1(a-e). The distributions for the sum of 14 energy points are shown in figures 1(f-j). To select the signal candidates, the $\gamma\gamma$ combination is required to be within three detector resolutions from the known η mass [16], $507.1 < M(\gamma\gamma) < 579.1\,\text{MeV}/c^2$, and the $\pi^+\pi^- J/\psi$ combination is required to be within three detector resolutions from the known $\psi(2S)$ mass [16], $3680.3 < M(\pi^+\pi^- J/\psi) <$

Decay mode (Branching fraction)		
$e^+e^- \to \pi^+\pi^-\psi(2S)$,	$\psi(2S) \to J/\psi\eta$ (3.37%),	$\eta \to \gamma\gamma$ (39.41%)
$e^+e^- \to \pi^+\pi^-\psi(2S)$,	$\psi(2S) \to \gamma\chi_{c0}$ (9.79%),	$\chi_{c0} \to \gamma J/\psi$ (1.4%)
$e^+e^- \to \pi^+\pi^-\psi(2S)$,	$\psi(2S) \to \gamma\chi_{c1}$ (9.75%),	$\chi_{c1} \to \gamma J/\psi$ (34.3%)
$e^+e^- \to \pi^+\pi^-\psi(2S)$,	$\psi(2S) \to \gamma\chi_{c2}$ (9.52%),	$\chi_{c2} \to \gamma J/\psi$ (19.0%)
$e^+e^- \to \pi^0\pi^0\psi(2S)$,	$\psi(2S) \to \pi^+\pi^-J/\psi$ (34.68%)	
$e^+e^- \to \omega\chi_{c0}$,	$\omega \to \pi^+\pi^-\pi^0$ (89.3%),	$\chi_{c0} \to \gamma J/\psi$ (1.4%)
$e^+e^- \to \omega\chi_{c1}$,	$\omega \to \pi^+\pi^-\pi^0$ (89.3%),	$\chi_{c1} \to \gamma J/\psi$ (34.3%)
$e^+e^- \to \omega\chi_{c2}$,	$\omega \to \pi^+\pi^-\pi^0$ (89.3%),	$\chi_{c2} \to \gamma J/\psi$ (19.0%)
$e^+e^- \to \gamma X(3872)$,	$X(3872) \to \omega J/\psi$ (2.3%),	$\omega \to \pi^+\pi^-\pi^0$ (89.3%)
$e^+e^- \to \phi\chi_{c1}$,	$\phi \to \pi^+\pi^-\pi^0$ (15.24%),	$\chi_{c1} \to \gamma J/\psi$ (34.3%)
$e^+e^- \to \phi\chi_{c2}$,	$\phi \to \pi^+\pi^-\pi^0$ (15.24%),	$\chi_{c2} \to \gamma J/\psi$ (19.0%)
$e^+e^- \to \gamma\gamma\psi(2S)$,	$\psi(2S) \to \pi^+\pi^-J/\psi$ (34.68%)	

Table 1. The background processes (all J/ψ mesons decay into $\ell^+\ell^-$).

3692.5 MeV/c^2 (as indicated by red dashed boxes or the ranges between two arrows in figure 1). Significant clusters can be seen in the mass windows of the η and $\psi(2S)$.

4 Background analysis

To study background processes, we generated a series of MC samples for final states that include a $\pi^+\pi^-$ pair, two leptons with high momenta, and at least two photons in the final state using the KKMC generator at each energy point. These background processes are listed in table 1. The dominant background contribution is $e^+e^- \to \gamma\gamma\psi(2S)$, and it is measured directly in this analysis. The yields for each of the other background processes in the 2D signal region ($N_{\mathrm{bkg},i}$) are calculated using external input by:

$$N_{\mathrm{bkg},i} = \mathcal{L}_{\mathrm{int}}(1+\delta)_i|1-\Pi|^{-2}\epsilon_i\mathcal{B}_i\sigma^{\mathrm{B}}_{\mathrm{bkg},i}, \tag{4.1}$$

where i represents each background channel; $\mathcal{L}_{\mathrm{int}}$ is the integrated luminosity; $|1-\Pi|^{-2}$ is the vacuum polarization factor [44]; ϵ_i and $\mathcal{B}_i$ are the selection efficiency and the product branching fraction of the intermediate states taken from the PDG [16] for the ith background mode, respectively; and $\sigma^{\mathrm{B}}_{\mathrm{bkg},i}$ is the measured Born cross section of the ith background mode. The production cross sections for these background processes are taken from refs. [21, 45–50]. Assuming an input lineshape from refs. [21, 45–50], ISR correction factor $(1+\delta)_i$ is obtained from a quantum electrodynamics calculation [41, 42, 51] using the KKMC generator.

The irreducible background process $e^+e^- \to \gamma\gamma\psi(2S)$, $\psi(2S) \to \pi^+\pi^-J/\psi$, $J/\psi \to \ell^+\ell^-$ with the two photons not from resonance decay has the same final state particles as the signal channel; thus we measure its yield with the data directly. After applying all

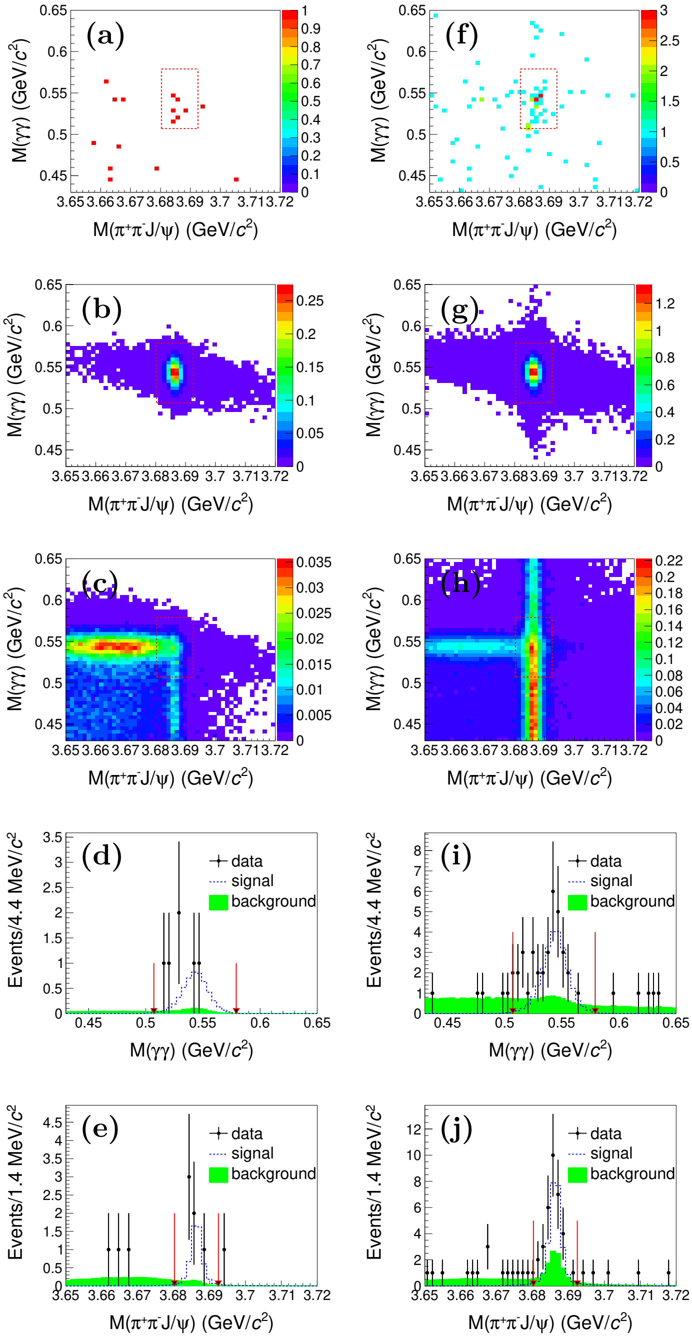

Figure 1. Two-dimensional distributions of $M(\gamma\gamma)$ versus $\mathrm{M}(\pi^+\pi^- J/\psi)$ for (a) data, (b) signal MC simulation, and (c) background MC contributions with the red dashed boxes for the defined η and $\psi(2S)$ signal regions, and the corresponding projections of (d) $M(\gamma\gamma)$ distribution in the $\psi(2S)$ mass window and (e) $M(\pi^+\pi^- J/\psi)$ distribution in the η mass window with red arrows for the defined signal regions at $\sqrt{s} = 4.258\,\mathrm{GeV}$, where the dots with error bars, the dashed blue lines, and the green histograms represent data, signal MC, and background MC simulations, respectively. The same distributions for the sum of the 14 data samples and MC samples are shown in (f), (g), (h), (i), and (j) correspondingly.

$\sqrt{s}$ (GeV)	$N^0_{\gamma\gamma\psi(2S)}$	F
4.236	$5.94^{+3.12}_{-2.40}$	0.11
4.242	$1.79^{+1.80}_{-1.16}$	0.13
4.244	$5.99^{+2.80}_{-2.12}$	0.13
4.258	$1.35^{+2.49}_{-1.35}$	0.18
4.267	$1.81^{+2.13}_{-1.40}$	0.21
4.278	$2.48^{+2.53}_{-1.81}$	0.24
4.308	$0.00^{+1.29}_{-0.00}$	0.26
4.358	$5.04^{+3.12}_{-2.44}$	0.25
4.387	$0.00^{+1.29}_{-0.00}$	0.24
4.416	$11.28^{+4.49}_{-3.79}$	0.23
4.467	$2.25^{+2.12}_{-1.34}$	0.20
4.527	$0.00^{+1.29}_{-0.00}$	0.18
4.575	$1.00^{+1.36}_{-0.70}$	0.16
4.600	$4.02^{+2.97}_{-2.34}$	0.15

Table 2. The number of $e^+e^- \to \gamma\gamma\psi(2S)$ events outside the η signal region $[N^0_{\gamma\gamma\psi(2S)}]$ and the F factor at each c.m. energy.

the selection criteria as for signal but the η mass window, we veto processes from $e^+e^- \to \gamma_{\rm ISR}\psi(2S)$, $e^+e^- \to \pi^0\psi(2S)$, and $e^+e^- \to \eta\psi(2S)$ by requiring the mass range of $\gamma\gamma$ larger than $300\,{\rm MeV}/c^2$ and not in $[507.1, 579.1]\,{\rm MeV}/c^2$. We fit $M(\pi^+\pi^-J/\psi)$ distribution of data using the line shape of MC simulated $e^+e^- \to \gamma\gamma\psi(2S)$ events to obtain the number of $e^+e^- \to \gamma\gamma\psi(2S)$ events $[N^0_{\gamma\gamma\psi(2S)}]$ at each c.m. energy. The number of $e^+e^- \to \gamma\gamma\psi(2S)$ events in the η and $\psi(2S)$ signal regions $[N^1_{\gamma\gamma\psi(2S)}]$ is obtained from the $N^0_{\gamma\gamma\psi(2S)}$ as follows:

$$N^1_{\gamma\gamma\psi(2S)} = F \cdot N^0_{\gamma\gamma\psi(2S)}, \tag{4.2}$$

$$F = \frac{\epsilon^1_e \mathcal{B}_e + \epsilon^1_\mu \mathcal{B}_\mu}{\epsilon^0_e \mathcal{B}_e + \epsilon^0_\mu \mathcal{B}_\mu}, \tag{4.3}$$

where F is a factor constructed from branching fractions and selection efficiencies; ϵ^1_e and ϵ^1_μ are the detection efficiencies for $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ decay channels in the η and $\psi(2S)$ signal regions, respectively; ϵ^0_e and ϵ^0_μ are the detection efficiencies for $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ decay channels, respectively, in the $\psi(2S)$ signal region but outside the η signal region; $\mathcal{B}_e$ and $\mathcal{B}_\mu$ are the branching fractions of decays $J/\psi \to e^+e^-$, and $J/\psi \to \mu^+\mu^-$, respectively [16]. The number of $e^+e^- \to \gamma\gamma\psi(2S)$ events in the $\psi(2S)$ signal region but outside the η signal region $[N^0_{\gamma\gamma\psi(2S)}]$ and the F factor at each c.m. energy are listed in table 2.

The total number of background events ($n^{\rm b}$) in the 2D signal region is obtained with

$$n^{\rm b} = \sum_i N_{{\rm bkg},i} + N^1_{\gamma\gamma\psi(2S)}. \tag{4.4}$$

Finally, the total numbers of background events in the signal region at different energy points, together with the numbers of background events from different final states are listed in table 3. The uncertainty on F is neglected, since it is too little to affect the number of $e^+e^- \to \gamma\gamma\psi(2S)$ events in the signal region. Therefore, the uncertainties on numbers of $e^+e^- \to \gamma\gamma\psi(2S)$ events are statistical only, and the uncertainties on numbers of other background events in table 3 are statistical and systematic.

5 Cross section measurement

It is assumed that the number of observed events (n^{obs}) with the numbers of expected background (n^{b}) and signal (μ) events in the signal region, follows a Poisson distribution,

$$P(n^{\text{obs}};\mu,n^{\text{b}}) = \frac{(\mu+n^{\text{b}})^{n^{\text{obs}}}}{n^{\text{obs}}!}e^{-(\mu+n^{\text{b}})}. \tag{5.1}$$

There are some energy points where the number of observed events is zero, but the number of background events is non-zero, such as $\sqrt{s} = 4.244\,\text{GeV}$ in table 4. Using the same method as in ref. [52], the value of μ with the maximum $P(n^{\text{obs}};\mu,n^{\text{b}})$ is taken as the non-negative number of signal events (n^{sig}). Thus, $n^{\text{sig}} = \max(0,\, n^{\text{obs}} - n^{\text{b}})$ is the best estimation of the number of signal events in the physically-allowed region.

The statistical uncertainty of the number of signal events at a 68.27% C.L. is estimated with the Feldman-Cousins (FC) method [52]. Since no significant $\eta\psi(2S)$ signal events are observed at some energy pints, the confidence intervals with the lower and upper limits at a 90% C.L. for the number of signal events are obtained with the Poissonian limit estimator (POLE) computer program [53].

The Born cross section of $e^+e^- \to \eta\psi(2S)$ is calculated with

$$\sigma^{\text{B}} = \frac{n^{\text{sig}}}{\mathcal{L}_{\text{int}}(1+\delta)|1-\Pi|^{-2}\mathcal{B}_1\mathcal{B}_2(\epsilon_e\mathcal{B}_e+\epsilon_\mu\mathcal{B}_\mu)}, \tag{5.2}$$

where $\mathcal{B}_1$ and $\mathcal{B}_2$ are the branching fractions of $\psi(2S) \to \pi^+\pi^- J/\psi$ and $\eta \to \gamma\gamma$ [16], respectively; $(1+\delta)$ is the radiative correction factor obtained from the quantum electrodynamics calculation [41, 42, 51] using the KKMC generator, assuming an input lineshape of the $Y(4260)$ cross section [16]. The Born cross sections (and the confidence intervals with the lower and upper limits at the 90% C.L.), and the numbers used in the calculation are listed in table 4. Figure 2 shows the measured Born cross sections for $e^+e^- \to \eta\psi(2S)$ as a function of the collision energy. The statistical uncertainties of the cross sections at some energy points are different due to different accumulated luminosities.

The P-value is obtained by calculating the probability of the expected number of background events to fluctuate to the number of observed events or more in the signal region assuming a Poisson distribution. The total number of observed events is 34 in the sum of the 14 data samples at different c.m. energies. The total number of the background events in this analysis is 10.77 ± 1.85, where the uncertainty combines statistical and systematic ones. Considering the statistical and systematic uncertainties of background events, the P-value and the corresponding statistical significance of $e^+e^- \to \eta\psi(2S)$ signals from the

$\sqrt{s}$ (GeV)	4.236	4.242	4.244	4.258	4.267	4.278	4.308
$\pi^+\pi^-\psi(2S), \psi(2S) \to J/\psi\eta$	<0.005	<0.005	0.01	0.49±0.05	0.87	0.39	0.03±0.01
$\pi^+\pi^-\psi(2S), \psi(2S) \to \gamma\chi_{c0}$	<0.005	<0.005	<0.005	0.01	0.02	0.01	<0.005
$\pi^+\pi^-\psi(2S), \psi(2S) \to \gamma\chi_{c1}$	<0.005	<0.005	<0.005	0.08±0.01	0.13	0.05	0.01
$\pi^+\pi^-\psi(2S), \psi(2S) \to \gamma\chi_{c2}$	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
$\pi^0\pi^0\psi(2S)$	<0.005	<0.005	0.00±0.02	0.04±0.01	0.02	0.01	0.00±0.01
$\omega\chi_{c0}$	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
$\omega\chi_{c1}$	—	—	—	—	—	—	0.00±0.01
$\omega\chi_{c2}$	—	—	—	—	—	—	—
$\gamma X(3872)$	—	—	—	—	—	—	—
$\phi\chi_{c1}$	—	—	—	—	—	—	—
$\phi\chi_{c2}$	—	—	—	—	—	—	—
$\gamma\gamma\psi(2S)$	$0.63^{+0.33}_{-0.25}$	$0.22^{+0.23}_{-0.15}$	$0.78^{+0.36}_{-0.27}$	$0.25^{+0.46}_{-0.25}$	$0.38^{+0.45}_{-0.29}$	$0.59^{+0.60}_{-0.43}$	$0.00^{+0.34}_{-0.00}$
n^{b}	0.63±0.33	0.22±0.23	0.79±0.36	0.88±0.46	1.41±0.45	1.06±0.60	0.04±0.34
$\sqrt{s}$ (GeV)	4.358	4.387	4.416	4.467	4.527	4.575	4.600
$\pi^+\pi^-\psi(2S), \psi(2S) \to J/\psi\eta$	<0.005	<0.005	<0.005	—	—	—	—
$\pi^+\pi^-\psi(2S), \psi(2S) \to \gamma\chi_{c0}$	<0.005	<0.005	<0.005	—	—	—	—
$\pi^+\pi^-\psi(2S), \psi(2S) \to \gamma\chi_{c1}$	<0.005	<0.005	<0.005	—	—	—	—
$\pi^+\pi^-\psi(2S), \psi(2S) \to \gamma\chi_{c2}$	<0.005	<0.005	<0.005	—	—	—	—
$\pi^0\pi^0\psi(2S)$	0.20±0.03	0.00±0.03	0.29±0.04	0.00±0.02	0.00±0.02	0.00±0.01	0.02±0.01
$\omega\chi_{c0}$	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
$\omega\chi_{c1}$	0.00±0.01	0.00±0.01	0.00±0.04	0.00±0.01	<0.005	—	—
$\omega\chi_{c2}$	0.00±0.05	0.00±0.02	0.16±0.03	0.00±0.02	<0.005	<0.005	0.00±0.01
$\gamma X(3872)$	<0.005	—	<0.005	—	—	—	<0.005
$\phi\chi_{c1}$	—	—	—	—	—	—	<0.005
$\phi\chi_{c2}$	—	—	—	—	—	—	<0.005
$\gamma\gamma\psi(2S)$	$1.28^{+0.79}_{-0.62}$	$0.00^{+0.31}_{-0.00}$	$2.57^{+1.02}_{-0.86}$	$0.44^{+0.42}_{-0.26}$	$0.00^{+0.23}_{-0.00}$	$0.16^{+0.22}_{-0.11}$	$0.59^{+0.44}_{-0.34}$
n^{b}	1.49±0.80	0.00±0.31	3.03±1.02	0.44±0.42	0.00±0.23	0.16±0.22	0.62±0.44

Table 3. The total numbers of background events in the signal region (n^{b}) at different energy points, together with the numbers of background events from different final states. Ellipses mean that the results are not applicable. The numbers of background events which are less than 0.005, are represented with < 0.005. The asymmetric uncertainty for the number of $e^+e^- \to \gamma\gamma\psi(2S)$ events $[N^1_{\gamma\gamma\psi(2S)}]$ is obtained with the eq. (4.2), which is associated with the asymmetric uncertainty of $N^0_{\gamma\gamma\psi(2S)}$ and F. The symmetric uncertainties for the numbers of other individual background sources are calculated with eq. (4.1), and are dominated by the uncertainties of the input cross sections [21, 45–50]. For the numbers of background events with uncertainties less than 0.005, only the mean values are quoted in the table. The ratio of the uncertainty in the number of background events to the number of signal events is taken as the systematic uncertainty on the background estimation.

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$n^{\rm obs}$	$n^{\rm b}$	$n^{\rm sig}$	$n^{\rm sig}_{\rm POLE}$	$\Sigma(10^{-2})$	$(1+\delta)$	$\lvert 1-\Pi\rvert^{-2}$	σ^{B} (pb)	$\sigma^{\rm B}_{\rm POLE}$ (pb)
4.236	530.3	2	0.63 ± 0.33	$1.4^{+2.2}_{-1.0}$	$(0.0, 5.9)$	0.430	0.76	1.056	$0.8^{+1.2}_{-0.5}$	(0.0, 3.2)
4.242	55.9	0	0.22 ± 0.23	$0.0^{+1.1}_{-0.0}$	$(0.0, 2.5)$	0.430	0.76	1.055	$0.0^{+5.7}_{-0.0}$	(0.0, 12.9)
4.244	538.1	0	0.79 ± 0.36	$0.0^{+0.7}_{-0.0}$	$(0.0, 2.5)$	0.422	0.77	1.056	$0.0^{+0.4}_{-0.0}$	(0.0, 1.4)
4.258	828.4	6	0.88 ± 0.46	$5.1^{+3.3}_{-2.1}$	$(1.6, 10.9)$	0.412	0.78	1.054	$1.8^{+1.2}_{-0.8}$	(0.6, 3.9)
4.267	531.1	7	1.41 ± 0.45	$5.6^{+3.3}_{-2.8}$	$(2.1, 11.8)$	0.399	0.79	1.053	$3.2^{+1.9}_{-1.6}$	(1.2, 6.7)
4.278	175.7	2	1.06 ± 0.60	$0.9^{+2.3}_{-0.8}$	$(0.0, 8.0)$	0.384	0.82	1.053	$1.5^{+3.9}_{-1.4}$	(0.0, 13.7)
4.308	45.1	0	0.04 ± 0.34	$0.0^{+1.3}_{-0.0}$	$(0.0, 2.4)$	0.351	0.94	1.052	$0.0^{+8.3}_{-0.0}$	(0.0, 15.3)
4.358	543.9	3	1.49 ± 0.80	$1.5^{+2.3}_{-1.2}$	$(0.0, 9.2)$	0.281	1.18	1.051	$0.8^{+1.2}_{-0.6}$	(0.0, 4.9)
4.387	55.6	0	0.00 ± 0.31	$0.0^{+1.3}_{-0.0}$	$(0.0, 2.5)$	0.252	1.32	1.051	$0.0^{+6.7}_{-0.0}$	(0.0, 12.9)
4.416	1043.9	8	3.03 ± 1.02	$5.0^{+3.3}_{-2.7}$	$(1.4, 12.4)$	0.223	1.46	1.052	$1.4^{+0.9}_{-0.8}$	(0.4, 3.5)
4.467	111.1	4	0.44 ± 0.42	$3.6^{+2.7}_{-1.7}$	$(1.2, 8.4)$	0.194	1.72	1.055	$9.2^{+6.9}_{-4.4}$	(3.1, 21.5)
4.527	112.1	0	0.00 ± 0.23	$0.0^{+1.3}_{-0.0}$	$(0.0, 2.4)$	0.166	2.02	1.054	$0.0^{+3.3}_{-0.0}$	(0.0, 6.1)
4.575	48.9	0	0.16 ± 0.22	$0.0^{+1.1}_{-0.0}$	$(0.0, 2.4)$	0.151	2.25	1.054	$0.0^{+6.2}_{-0.0}$	(0.0, 13.6)
4.600	586.9	2	0.62 ± 0.44	$1.4^{+2.2}_{-1.0}$	$(0.0, 6.2)$	0.143	2.38	1.055	$0.7^{+1.0}_{-0.5}$	(0.0, 2.9)
Sum		34	10.77 ± 1.85		P-value	4.6×10^{-7}		Statistical significance		4.9σ

Table 4. The cross sections $\sigma^{\rm B}$ and the confidence intervals with the lower and upper limits on $\sigma^{\rm B}$ with the POLE ($\sigma^{\rm B}_{\rm POLE}$) method for $e^+e^- \to \eta\psi(2S)$ at different energy points, together with integrated luminosities $\mathcal{L}_{\rm int}$, numbers of observed events $n^{\rm obs}$, background events $n^{\rm b}$, and signal events $n^{\rm sig}$, the confidence intervals with the lower and upper limits for the numbers of signal events $n^{\rm sig}_{\rm POLE}$, products of detection efficiencies and branching fractions $\Sigma = \mathcal{B}_1\mathcal{B}_2(\epsilon_e\mathcal{B}_e + \epsilon_\mu\mathcal{B}_\mu)$, ISR correction factors $(1+\delta)$, vacuum polarization factors $\lvert 1-\Pi\rvert^{-2}$, the P-value, and the statistical significance. The uncertainties of $n^{\rm sig}$ and $\sigma^{\rm B}$ are statistical only. All limits are given at 90% confidence level.

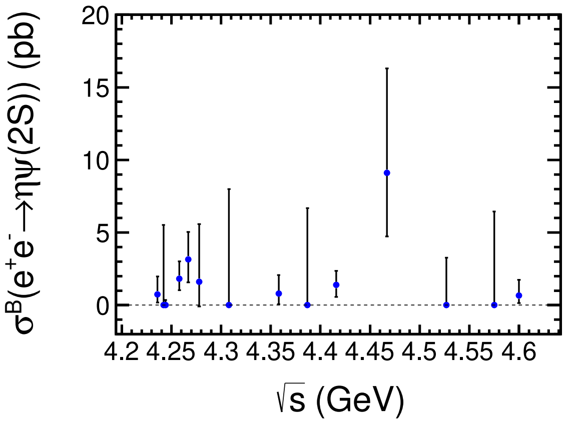

Figure 2. The measured Born cross section as a function of the collision energy. The uncertainties are statistical only.

5.25 fb^{-1} BESIII data are 4.6×10^{-7} and 4.9 standard deviations (σ), respectively, which are listed in table 4.

6 Systematic uncertainties

The systematic uncertainties in the cross-section measurement mainly come from the luminosity, tracking efficiency, photon detection efficiency, the branching fractions of intermediate particle decays, ISR correction factor, kinematic fit, background estimation, and mass windows of J/ψ, η, and $\psi(2S)$ mesons. The uncertainty from the vacuum polarization is negligible. Different systematic uncertainties at the same energy are assumed to be uncorrelated, and that systematic uncertainties between different energies are assumed to be fully correlated.

- *Luminosity.* The integrated luminosity was measured using Bhabha scattering events with an uncertainty of 1.0% [34, 35], which is taken as the systematic uncertainty.

- *Tracking efficiency.* The uncertainty of the tracking efficiency is 1.0% per track, which is taken from ref. [29].

- *Photon detection efficiency.* The uncertainty from photon reconstruction is 1.0% per photon, which is determined from the study of the process $J/\psi \to \rho^0\pi^0$, $\rho^0 \to \pi^+\pi^-$, $\pi^0 \to \gamma\gamma$ [54].

- *Branching fraction.* The uncertainties on the branching fractions of the intermediate states are taken from the PDG [16].

- *ISR correction factor.* Due to insufficient information from previous experiments, we obtain the ISR correction factor according to the decay of the $Y(4260)$ resonant structure in this work. Changing the Breit-Wigner (BW) function for the $Y(4260)$

to that for the $\psi(4415)$, the difference between these two assumptions is taken as the systematic uncertainty.

- *Kinematic fit.* The systematic uncertainty from the kinematic fit is estimated by correcting the helix parameters of charged tracks according to the method described in ref. [55]. The MC sample with the track helix parameter correction applied is taken as the nominal one. The difference between detection efficiencies obtained from MC samples with and without correction is taken as the uncertainty.

- *Background estimation.* From eq. (4.1), the number of background events is estimated using the measured cross sections. The ratio of the uncertainty in the number of background events to the number of signal events is taken as the uncertainty of the background estimation.

- *Mass window.* The mass resolution discrepancy between MC simulation and the data will lead to a bias in the efficiency determination when a mass window requirement is applied to the invariant mass distribution. The process $e^+e^- \to \pi^+\pi^-\psi(2S)$ with $\psi(2S) \to \eta J/\psi$ at $\sqrt{s} = 4.416\,\mathrm{GeV}$ is taken as the control sample to estimate the uncertainty due to the J/ψ and η mass windows. The discrepancies in efficiency between data and MC samples for J/ψ and η mass windows are $(0.80 \pm 0.12)\%$ and $(-0.35 \pm 2.27)\%$, respectively. The uncertainties of J/ψ and η mass windows are quoted as 0.92% and 2.62%, respectively. The uncertainty of the $\psi(2S)$ mass window is determined to be 2.3%, using a large data sample observed in $e^+e^- \to \pi^+\pi^-\psi(2S)$ [45]. Finally, the total systematic uncertainty on mass windows is 3.6% by adding these numbers in quadrature.

Table 5 summarizes the systematic uncertainties from all the sources. The total systematic uncertainty is obtained by summing the individual uncertainties in quadrature, assuming that all sources are independent.

7 Summary

In summary, using 5.25 fb^{-1} data collected at c.m. energies from 4.236 to 4.600 GeV, the process $e^+e^- \to \eta\psi(2S)$ is observed for the first time with a 4.9σ statistical significance. The energy-dependent cross section has been measured and the results are listed in table 4. Because of the limited statistics, the signals at some energy points are not significant, thus it is impossible to extract the couplings of the Y states to $\eta\psi(2S)$ from a fit to the cross sections of $e^+e^- \to \eta\psi(2S)$. Further experimental studies with higher statistics are needed to draw a clear conclusion on the structure in the $e^+e^- \to \eta\psi(2S)$ process. BESIII plans to collect additional data samples over a variety of c.m. energies in the future [56]. Furthermore, a partial event reconstruction technique with a missing track may improve the detection efficiency of this process. This will allow us to study the structure of the $\eta\psi(2S)$ and explore the nature of the vector charmonium-like states.

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$\sqrt{s}$ (GeV)	Luminosity	Tracking	Photon	BR	ISR	Kinematic fit	Background	Mass window	Sum
4.236	1.0	4.0	2.0	1.2	10.4	2.6	23.6	3.6	26.6
4.242	1.0	4.0	2.0	1.2	10.9	2.6	—	3.6	12.7
4.244	1.0	4.0	2.0	1.2	10.5	2.8	—	3.6	12.4
4.258	1.0	4.0	2.0	1.2	7.4	2.7	9.0	3.6	13.4
4.267	1.0	4.0	2.0	1.2	5.3	3.1	8.0	3.6	11.7
4.278	1.0	4.0	2.0	1.2	2.4	3.1	66.7	3.6	67.0
4.308	1.0	4.0	2.0	1.2	5.1	3.2	—	3.6	8.5
4.358	1.0	4.0	2.0	1.2	10.6	3.5	53.3	3.6	54.8
4.387	1.0	4.0	2.0	1.2	12.4	3.5	—	3.6	14.2
4.416	1.0	4.0	2.0	1.2	11.4	3.1	20.4	3.6	24.3
4.467	1.0	4.0	2.0	1.2	2.0	3.3	11.7	3.6	13.6
4.527	1.0	4.0	2.0	1.2	1.2	3.1	—	3.6	6.8
4.575	1.0	4.0	2.0	1.2	4.4	2.8	—	3.6	7.9
4.600	1.0	4.0	2.0	1.2	5.0	2.9	31.4	3.6	32.5

Table 5. The relative systematic uncertainties from luminosity, tracking efficiency, photon detection efficiency, branching fraction (BR), ISR correction factor, kinematic fit, background estimation, and mass windows (in units of %). Ellipses mean that the results are not applicable.

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