Observation of two resonant structures in $e^+e^- \to \pi^+\pi^- h_c$

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Motivation

- We can know why charmonium-like states exist from the first paragraph . And we try to interpret one or some of them as hybrid states, tetraquark states, or molecular states.
- The process $e^+e^- \rightarrow \pi^+\pi^- h_c$ was first studied by CLEO at CM energies from 4.000 to 4.260 GeV. And a 10σ signal at 4.170 GeV and a hint of a rising cross section at 4.260 GeV were observed. Then BESIII also did it using data samples taken at 13 CM energies from 3.900 to 4.420 Gev. Due to the lack of experimental data in the high energy region, we can not get more information in the high energy region.
- In this letter, we just present a follow-up study of $e^+e^- \rightarrow \pi^+\pi^- h_c$ at CM energies from 3.896 to 4.600 GeV using data samples taken at 79 energies point.

Reconstruction

here, the h_c is reconstructed via its electric-dipole ($E1$) transition $h_c \to \gamma\eta_c$ with $\eta_c \to X_i$, where X_i signifies 16 exclusive hadronic final states: $p\bar{p}$, $2(\pi^+\pi^-)$, $2(K^+K^-)$, $K^+K^-\pi^+\pi^-$, $p\bar{p}\pi^+\pi^-$, $3(\pi^+\pi^-)$, $K^+K^-2(\pi^+\pi^-)$, $K_S^0K^\pm\pi^\mp$, $K_S^0K^\pm\pi^\mp\pi^\pm\pi^\mp$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $\pi^+\pi^-\eta$, $K^+K^-\eta$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-\pi^0\pi^0$, and $2(\pi^+\pi^-)\pi^0\pi^0$.

We select charged tracks, photons, and $K_S^0 \to \pi^+\pi^-$ candidates as described in Ref. [13]. A candidate π^0 (η) is reconstructed from pairs of photons with an invariant mass in the range $|M_{\gamma\gamma} - m_{\pi^0}| < 15\ \mathrm{MeV}/c^2$ ($|M_{\gamma\gamma} - m_\eta| < 15\ \mathrm{MeV}/c^2$), where m_{π^0} (m_η) is the nominal π^0 (η) mass [14].

In selecting $e^+e^- \to \pi^+\pi^-h_c$, $h_c \to \gamma\eta_c$ candidates, all charged tracks are assumed to be pions, and events with at least one combination satisfying $M^{\mathrm{recoil}}_{\pi^+\pi^-} \in [3.45, 3.65]\ \mathrm{GeV}/c^2$ and $M^{\mathrm{recoil}}_{\gamma\pi^+\pi^-} \in [2.8, 3.2]\ \mathrm{GeV}/c^2$ are kept for further analysis. Here $M^{\mathrm{recoil}}_{\pi^+\pi^-}$ ($M^{\mathrm{recoil}}_{\gamma\pi^+\pi^-}$) is the mass recoiling from the $\pi^+\pi^-$ ($\gamma\pi^+\pi^-$) pair, which should be in the mass range of the h_c (η_c).

For the process $e^+e^- \to \pi^+\pi^-h_c$

In Ref[17] Phys. Rev. Lett. 111,242001

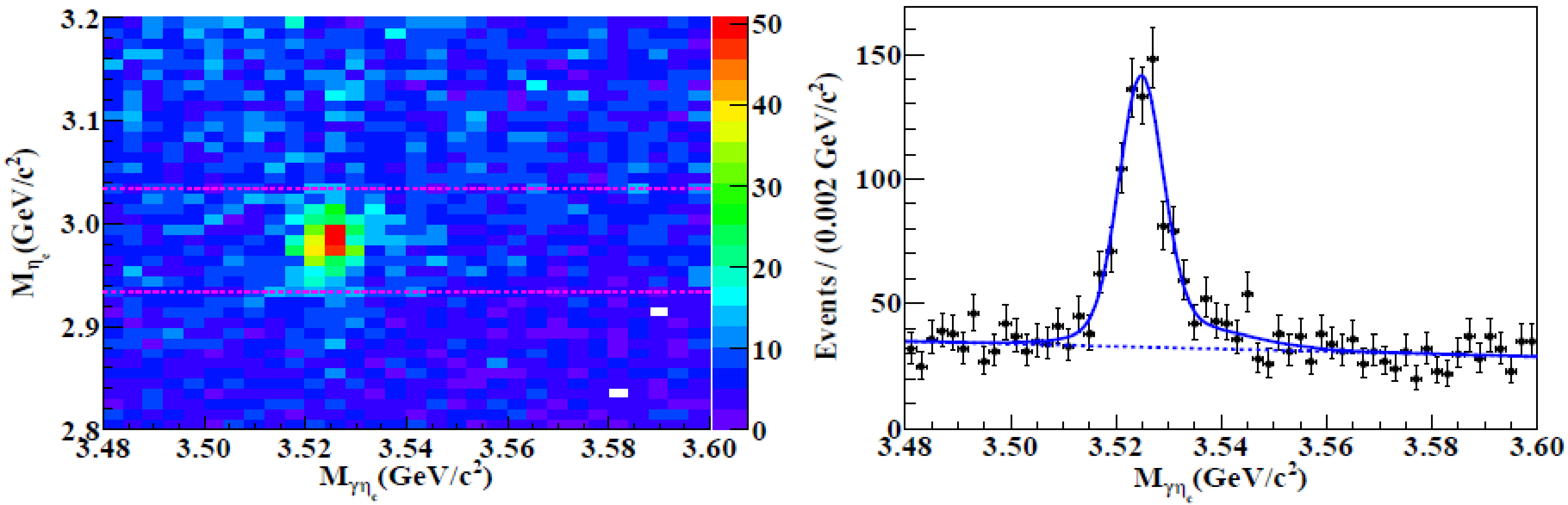


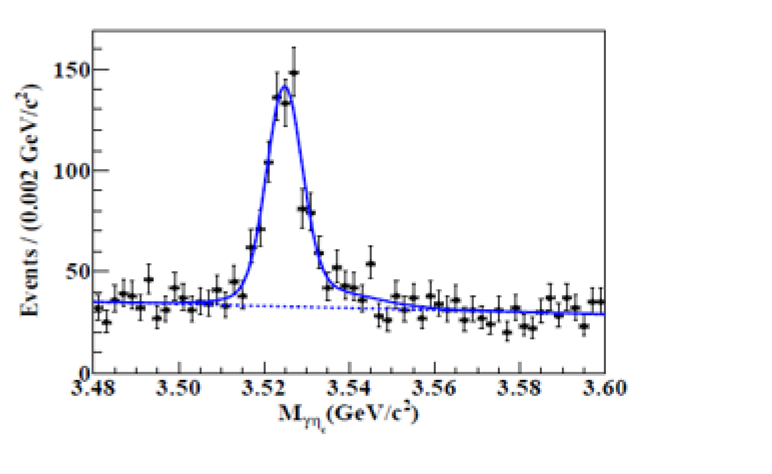
FIG. 1. (*left panel*) Scatter plot of the mass of the η_c candidate M_{η_c} versus the mass of the h_c candidate $M_{\gamma\eta_c}$. (*right panel*) Distribution of $M_{\gamma\eta_c}$ for events in the η_c signal region. Points with error bars show the data at $\sqrt{s} = 4.416$ GeV and the curves are the best fit described in the text.

gion. A clear $h_c \to \gamma\eta_c$ signal is observed. The η_c signal region is defined by a mass window around the nominal η_c mass [3], which is ± 50 MeV/c^2 with efficiency about 84% (± 45 MeV/c^2 with efficiency about 80%) from MC simulation for final states with only charged or K_S^0 particles (for those including π^0 or η).

Observed signal events

- we determine the number of $e^+e^- \to \pi^+\pi^- h_c$ signal events from the $\gamma\eta_c$ invariant mass distribution.

number of signal events is calculated by counting the entries in the h_c signal region [3.515, 3.535] GeV/c^2 ($n^{\rm sig}$) and the entries in the h_c sideband regions [3.475, 3.495] GeV/c^2 and [3.555, 3.575] GeV/c^2 ($n^{\rm side}$) using the formula $n^{\rm obs}_{h_c} = n^{\rm sig} - f \cdot n^{\rm side}$. Here, the scale factor $f = 0.5$ is the ratio of the size of the signal region and the background region, and the background is assumed to be distributed linearly in the region of interest.

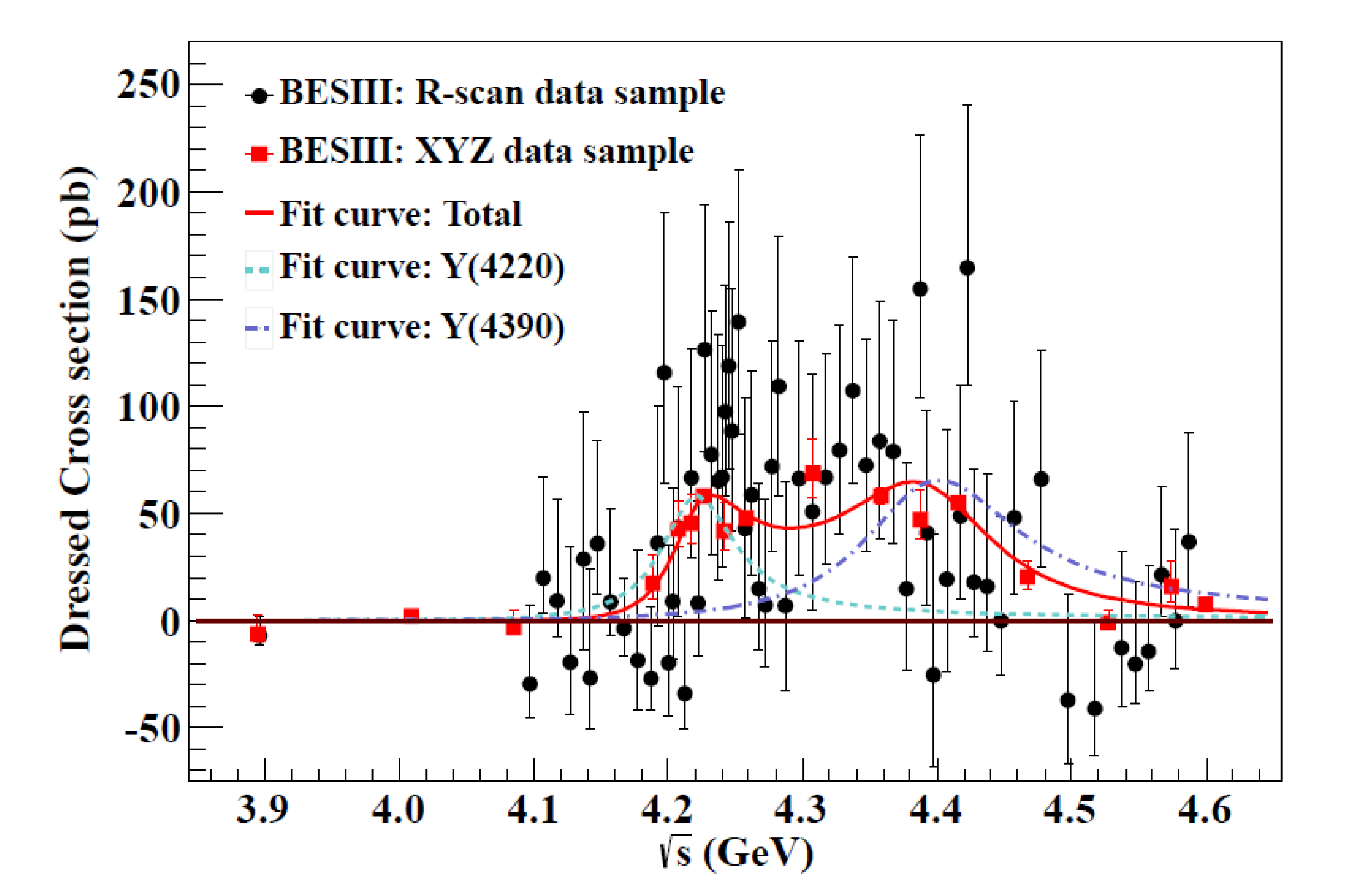


Born cross section

The Born cross section is calculated from

$$\sigma^{\mathrm{B}} = \frac{n_{h_c}^{\mathrm{obs}}}{\mathcal{L}(1+\delta)|1+\Pi|^2 \sum_{i=1}^{16} \epsilon_i \mathcal{B}(\eta_c \to X_i)\mathcal{B}(h_c \to \gamma\eta_c)},$$

where $n_{h_c}^{\mathrm{obs}}$ is the number of observed signal events, $\mathcal{L}$ is the integrated luminosity, $(1+\delta)$ is the ISR correction factor obtained using the QED calculation as described in Ref. [28] and taking the formula used to fit the cross section measured in this analysis after two iterations as input, $|1+\Pi|^2$ is the correction factor for vacuum polarization [29], ϵ_i and $\mathcal{B}(\eta_c \to X_i)$ are the detection efficiency and branching fraction for the i-th η_c decay mode [27], $\mathcal{B}(h_c \to \gamma\eta_c)$ is the branching fraction of $h_c \to \gamma\eta_c$ [3]. The Born cross sections are shown in Fig. 2 with dots and squares for R-scan and XYZ data sample, respectively, and the results are summarised in the supplemental material [19] together with all numbers used in the calculation of the Born cross sections.



Fit analysis

A maximum likelihood method is used to fit the dressed cross sections (with vacuum polarization effects) to determine the parameters of the resonant structures. The likelihood is constructed taking the fluctuations of the number of signal and background events into account (the definition is described in the supplemental material [19]). Assuming that the $\pi^+\pi^- h_c$ signal comes from two resonances, the cross section is parameterized as the coherent sum of two constant width relativistic Breit-Wigner functions, *i.e.*,

$$\sigma(m) = |\mathrm{B}_1(m) \cdot \sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi}\mathrm{B}_2(m) \cdot \sqrt{\frac{P(m)}{P(M_2)}}|^2,$$

where $\mathrm{B}_j(m) = \frac{\sqrt{12\pi\Gamma_j^{el}\Gamma_j}}{m^2 - M_j^2 + iM_j\Gamma_j}$ with $j = 1$ or 2 is the Breit-Wigner function, and $P(m)$ is the 3-body phase space factor. The masses M_j, the total widths Γ_j, the products of the electronic partial width and the branching fraction to $\pi^+\pi^- h_c$ $\Gamma_j^{el} = (\Gamma_{e^+e^-}\mathcal{B}(\pi^+\pi^- h_c))_j$, and the relative phase ϕ between the two Breit-Wigner functions are free parameters in the fit. Only the statistical uncertainty is considered

The free parameter ϕ indicates there could be interference between two Breit-Wigner function

Fitting the dressed cross section with only one resonance yields a worse result, the change of the likelihood value from two resonances to one resonance is [$\Delta(-2\ln L) = 113.5$]. Taking the change in the number of degrees of freedom (4) into account, the significance for the assumption of two resonant structures over the assumption of one resonant structure is 10σ. We also fit the cross section with the coherent sum of three Breit-Wigner functions, or the coherent sum of two Breit-Wigner functions and a phase space term. Both assumptions improve the fit quality, but the significances of the third resonance and the phase space term are only 2.6σ and 2.9σ, respectively.

The reason why we use two resonances to fit dressed cross section

Systematic uncertainties of cross section

Assuming all of the sources are independent, the total systematic uncertainty in the $\pi^+\pi^- h_c$ cross section measurement is determined to be 9.4%–13.6% depending on the CM energy. The uncertainty in $\mathcal{B}(h_c \to \gamma\eta_c)$ is 11.8% [3], common to all energy points, and quoted separately in the cross section measurement. Altogether, about 95% of the total systematic errors are common to all the energy points.

I can not know clearly about specific details

Systematic uncertainties of resonance parameters

TABLE I. The systematic uncertainty in the measurement of the resonance parameters, where $\Gamma^{el} = \Gamma_{e^+e^-}\mathcal{B}(\pi^+\pi^- h_c)$ is the product of the electronic partial width and the branching fraction to $\pi^+\pi^- h_c$. CM energy^1 represents the uncertainty from the systematic uncertainty of CM energy measurement and CM energy^2 is the uncertainty from assumption made in the measurement of CM energy for R-scan data sample. Cross section$^{1(2)}$ represents the uncertainty from the systematic uncertainties of the cross section measurement which are un-correlated (common) in each energy point.

Sources	$Y(4220)$			$Y(4390)$			ϕ (rad)
	M (MeV/c^2)	Γ (MeV)	Γ^{el} (eV)	M (MeV/c^2)	Γ (MeV)	Γ^{el} (eV)	
CM energy$^{1(2)}$	0.8(0.1)	−(0.1)	−(0.2)	0.8(0.1)	−(0.2)	−(0.3)	−(0.1)
CM energy spread	0.1	0.3	0.3	0.1	0.1	0.7	0.1
Cross section$^{1(2)}$	0.1(−)	−(−)	0.2(0.7)	0.6(−)	0.5(−)	0.4(1.7)	0.1(−)
Total	0.9	0.4	0.8	1.0	0.6	1.9	0.2