Search for $\eta$ and $\eta'$ → $\pi^+e^-\bar{\nu}_e + c.c.$ decays in $J/\psi - \phi \eta$ and $\phi \eta'$


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Using a sample of 225.3 million $J/\psi$ events collected with the BESIII detector at the BEPCII $e^+e^-$ collider in 2009, searches for the decays of $\eta$ and $\eta' \rightarrow \pi^+\pi^-\nu$ in $J/\psi \rightarrow \phi \eta$ and $\phi \eta'$ are performed. The $\phi$ signals, which are reconstructed in $K^+K^-$ final states, are used to tag $\eta$ and $\eta'$ semileptonic decays. No signals are observed for either $\eta$ or $\eta'$, and upper limits at the 90% confidence
level are determined to be $7.3 \times 10^{-4}$ and $5.0 \times 10^{-4}$ for the ratios \( \frac{B(\eta \to \pi^+ \pi^- \nu \bar{\nu})}{B(\eta \to \pi^+ \pi^- \pi^0 \pi^0)} \) and \( \frac{B(\eta' \to \pi^+ \pi^- \nu \bar{\nu})}{B(\eta' \to \pi^+ \pi^- \pi^0 \pi^0)} \), respectively. These are the first upper-limit values determined for \( \eta \) and \( \eta' \) semileptonic weak decays.

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I. INTRODUCTION

Weak decays of quarkonium states—such as \( \eta, \eta', J/\psi \), and \( Y \), etc.—offer a window into what may lie beyond the standard model (SM) [1–6]. The reason for the expected sensitivity is that the rates of the quarkonium weak decays are expected to be tiny in the framework of the SM [7]. As originally pointed out by Singer [8], the weak decays \( \eta \to \pi^+ \pi^- \bar{\nu} \) \((l = e, \mu, \) and charge-conjugate state implicitly included) are purely second-class with a vector-type coupling in the SM (see Ref. [9] for the definition of the second-class current), and hence vanish in the limit of exact isospin symmetry. They occur in the SM in first order in the weak interaction, but only due to \( G \)-parity breaking effects, i.e., due to electromagnetic corrections and the mass difference of the \( u \) and \( d \) quarks [10–17]. For \( \eta \) semileptonic weak decays, a one-loop calculation was performed in chiral perturbation theory within the SM, including a systematic treatment of the electromagnetic contributions to \( O(\alpha^2 p^2) \) \((e \text{ and } p \text{ are the electromagnetic coupling and typical momentum transfer in the decay, as defined in Ref. [12])}, and a rather accurate upper bound for the branching fraction of \( \eta \to \pi^+ \pi^- \bar{\nu} \) is predicted to be \( 2.6 \times 10^{-13} \). Therefore, any observation of \( \eta \to \pi l \nu \) violating this bound would be a clear indication for new physics beyond the SM.

The decays \( \eta \to \pi l \nu \) can be used to probe some types of possible new charged-current interactions [10,11]. A rather old suggestion would be the introduction of a new second-class vector current for the \( \eta \to \pi \) transition [15]. Scalar-type charged-current four-fermion interactions can arise in gauge theories, for example from the exchange of charged Higgs bosons in the two-Higgs-doublet model [18,19]. Also, light leptoquarks [20], occurring naturally in grand unified theories and composite models, may enhance the \( \eta \to \pi l \nu \) branching fraction considerably [21]. For example, by considering scalar- or vector-type interactions, the branching fraction of \( \eta \to \pi^+ \pi^- \bar{\nu} \) was estimated to be \( 10^{-8} \)–\( 10^{-9} \) [22,23], which is a few orders of magnitude higher than that in the SM. Therefore, searches for the \( \eta \to \pi^+ \pi^- \bar{\nu} \) and \( \eta' \to \pi^+ \pi^- \bar{\nu} \) at the branching-fraction level of \( 10^{-8} \)–\( 10^{-9} \) and below will provide information on the new physics beyond the SM. At present there is no experimental information on the decays \( \eta \to \pi l \nu \). In this paper, we present measurements of the branching fractions of \( \eta \) and \( \eta' \to \pi^+ \pi^- \bar{\nu} \) decays. This analysis is based on \((225.3 \pm 2.8) \times 10^6 J/\psi \) events [24], accumulated with the Beijing Spectrometer III (BESIII) detector [25], at the Beijing Electron Positron Collider II (BEP)
III. DATA ANALYSIS

A. Analyses for $\eta$ and $\eta' \rightarrow \pi^+ e^- \bar{\nu}_e$

In order to detect $\eta$ and $\eta' \rightarrow \pi^+ e^- \bar{\nu}_e$ decays, we use $J/\psi \rightarrow \phi \eta$ and $\phi \eta'$ decays. These two-body decays provide a very simple event topology, in which the $\phi$ signals can be reconstructed easily and cleanly decaying into $K^+ K^-$. The reconstructed $\phi$ particles can be used to tag $\eta$ and $\eta'$ in order to allow a search for their semileptonic decays. In addition, the $\eta$ and $\eta'$ decays are easy to define in the lab system due to the strong boost of the $\phi$ from $J/\psi$ decay.

Charged tracks in the BESIII detector are reconstructed using track-induced signals in the MDC. We select tracks within $\pm 10$ cm of the interaction point in the beam direction and within 1 cm in the plane perpendicular to the beam direction. The tracks must be within the MDC fiducial volume, $|\cos \theta| < 0.93$ ($\theta$ is the polar angle with respect to the $e^+$ beam direction). Candidate events require four charged tracks with a net charge of zero. The TOF and $dE/dx$ information are combined to form PID confidence levels for the $\pi$, $K$, and $e$ hypotheses; each track is assigned to the particle type that corresponds to the hypothesis with the highest confidence level. To suppress the background from $J/\psi \rightarrow \phi \eta (\eta')$, where $\eta (\eta')$ decays into nonleptonic modes, the electron candidate is further identified with the ratio of deposited energy in the EMC to $E_p$, which must be larger than 0.8.

We further require that $E_p$ be less than 0.8 for the pion candidate to suppress the background from $J/\psi \rightarrow \phi \eta (\eta \rightarrow \gamma e^+ e^-)$ decay.

Showers identified as photon candidates must satisfy fiducial and shower-quality requirements. The minimum energy is 25 MeV for EMC barrel showers ($|\cos \theta| < 0.8$) and 50 MeV for end-cap showers ($0.86 < |\cos \theta| < 0.92$). To eliminate showers produced by charged particles, a photon must be isolated from any charged track by more than 20° if not specified otherwise.

Since the mass of the neutrino is almost zero and it is invisible in the detectors, a one-constraint (1C) kinematic fit is performed to constrain the missing mass of the reconstructed tracks to be zero, and $\chi^2_{1C} < 200$ is required. The 1C fit improves the resolution of the recoil mass of the $K^+ K^-$ system by a factor of 2.5 for the $\eta$ case or a factor of 1.6 for the $\eta'$ case. After the 1C fit, the missing momentum $P_{miss} = |\vec{P}_{miss}|$ can be calculated; here, $\vec{P}_{miss} = - (\vec{P}_\phi + \vec{P}_{\pi^+} + \vec{P}_{e^-})$ in the rest frame of $J/\psi$, and we require that the missing momentum should be larger than 0.03 GeV/c to suppress backgrounds from final states with only four tracks, such as $J/\psi \rightarrow \phi \pi^+ \pi^- (\phi \rightarrow K^+ K^-)$. We count the number $N_{\text{shower}}$ of EMC showers that could originate from a $K_L$ or a photon, and require that $N_{\text{shower}}$ be zero in the region inside a cone of 0.3 (1.5) rad around the direction of the missing momentum for $J/\psi \rightarrow \phi \eta (\eta')$ [\(\eta(\eta') \rightarrow \pi^+ e^- \bar{\nu}_e\)]. These requirements reject most $\eta$ and $\eta'$ decays into nonleptonic final states. They also eliminate most backgrounds from multibody decays of $J/\psi \rightarrow \phi +$ anything. The different requirements on the cone angle for the $\eta$ and $\eta'$ cases are made for of the following two reasons: firstly, in the $J/\psi \rightarrow \phi \eta (\eta')$ decays, the booster for $\eta$ is stranger than that for $\eta'$ in the center-of-mass energy of $J/\psi$, which leads to a larger open angle for the $\eta'$ decay products than that for the $\eta$ decay products in the detector; secondly, the most dangerous backgrounds are from $\eta(\eta') \rightarrow \pi^+ \pi^- \gamma$ decay, in which one of the charged pions is misidentified as an electron. Meanwhile, the decay rate for $\eta' \rightarrow \pi^+ \pi^- \gamma$ is more than 6 times larger than the rate for $\eta \rightarrow \pi^+ \pi^- \gamma$ [29].

Figures 1(a) and 1(b) show the invariant mass distribution of $K^+ K^-$ candidates, $m_{K^+ K^-}$, after the above selections. Clear $\phi$ signals are seen. The invariant mass of $\pi^+ e^- \bar{\nu}_e$ can be obtained as $m_{\pi^+ e^- \bar{\nu}_e} = \sqrt{(E_{\pi^+} + E_{e^-} + E_{\bar{\nu}_e})^2 - (\vec{P}_{\pi^+} + \vec{P}_{e^-} + \vec{P}_{\bar{\nu}_e})^2}$, where $E_{\bar{\nu}_e} = E_{miss} = |\vec{P}_{miss}|$ and $\vec{P}_{miss} = \vec{P}_{\bar{\nu}_e}$. Figures 2(a) and 2(b) show the $m_{\pi^+ e^- \bar{\nu}_e}$ distributions for events with $1.01 < m_{K^+ K^-} < 1.03$ GeV/c$^2$ for the decays $J/\psi \rightarrow \phi \eta (\eta \rightarrow \pi^+ e^- \bar{\nu}_e)$ and $J/\psi \rightarrow \phi \eta' (\eta' \rightarrow \pi^+ e^- \bar{\nu}_e)$, respectively. No events are observed in the $\eta$ and $\eta'$ signal regions. The signal regions for $\eta$ and $\eta'$ are defined in the ranges $[0.51, 0.58]$ and $[0.92, 0.99]$ GeV/c$^2$, respectively, on the mass of $\pi^+ e^- \bar{\nu}_e$.

![FIG. 1 (color online). The $m_{K^+ K^-}$ distributions of candidate events for (a) $J/\psi \rightarrow \phi \eta$ and (b) $J/\psi \rightarrow \phi \eta'$. The arrows on the plots indicate the signal region of $\phi$ candidates.](image-url)
We use MC-simulated events to determine selection efficiencies for the signal channels and study possible backgrounds. With phase-space MC simulations, we obtain efficiencies of 17.9% and 17.4% for \(\eta\) and \(\eta'\) semileptonic decays, respectively. According to the study of the \(J/\psi\)-inclusive MC sample, more than 20 exclusive decay modes are identified as potential background modes, and are studied with full MC simulations in order to understand the backgrounds. The sources of backgrounds are divided into two classes. In Class I, the background is from \(J/\psi \to \phi \eta(\eta')\), \(\phi \to K^+ K^-\), and \(\eta(\eta')\) decays into modes other than the signal final states. We find that the expected number of background events from this class is 0.18 ± 0.05 (0.58 ± 0.09) in the signal region for \(\eta(\eta')\). In Class II, the background is mainly from \(J/\psi\) decays to the final states without \(\eta\) or \(\eta'\), such as \(\phi \pi^+ \pi^-\), \(\phi f_0(980)\) \(f_0(980) \to \pi^+ \pi^-\), and \(K^0\bar K^{*0}\) \(K^{*0} \to K^+ \pi^-\). The expected number of background events from Class II is 0.05 ± 0.04 (0.45 ± 0.13) in the signal region for \(\eta(\eta')\). The total number of background events is 0.23 ± 0.06 (1.03 ± 0.16) in the signal region for \(\eta(\eta')\).

After all selection criteria are applied, no event survives in the \(\eta\) and \(\eta'\) signal regions. The signal components and the expected background shapes are projected and compared to data for both the \(\eta\) and \(\eta'\) cases, as shown in Figs. 2(a) and 2(b). We set an upper limit at the 90% confidence level (C.L.) to be \(N^\eta_{UL} = 2.36\) \(N^\eta_{UL} = 1.59\) for \(\eta(\eta')\), using the POLEB++ program [32] with the Feldman-Cousins frequentist approach [33]. The information used to obtain the upper limit includes the number of observed events in the signal region, and the expected number of background events and their uncertainty.

**B. Analyses for \(\eta(\eta') \to \pi^+ \pi^- \pi^0(\pi^0)\)**

The \(\eta \to \pi^+ \pi^- \pi^0\) and \(\eta' \to \pi^+ \pi^- \eta\) decays are also studied in \(J/\psi \to \phi \eta\) and \(\phi \eta'\) processes, in order to obtain the ratio of \(\mathcal{B}(\eta(\eta') \to \pi^+ \pi^- \nu_e + \text{c.c.})\) to \(\mathcal{B}(\eta \to \pi^+ \pi^- \pi^0)\) \(\mathcal{B}(\eta \to \pi^+ \pi^- \eta)\). The advantage of measuring the ratios of semileptonic weak decays over hadronic decays, \(\frac{\mathcal{B}(\eta(\eta') \to \pi^+ \pi^- \nu_e + \text{c.c.})}{\mathcal{B}(\eta \to \pi^+ \pi^- \pi^0)}\) and \(\frac{\mathcal{B}(\eta(\eta') \to \pi^+ \pi^- \nu_e + \text{c.c.})}{\mathcal{B}(\eta \to \pi^+ \pi^- \eta)}\), is that the uncertainties due to the total number of \(J/\psi\) events, the tracking efficiency, the PID for a kaon and one pion, the number of the charged tracks, and the residual noise in the EMC cancel.

The selection criteria for the charged tracks are the same as those for the \(J/\psi \to \phi \eta(\eta')\), \(\eta(\eta') \to \pi^+ \pi^- \nu_e\) decays except for the electron identification requirement. The candidate events are required to have two charged kaons and two charged pions with opposite charge. In addition, two photon candidates are required to reconstruct \(\pi^0 \to \gamma\gamma\) and \(\eta \to \gamma\gamma\) in the \(\eta \to \pi^+ \pi^- \pi^0\) and \(\eta' \to \pi^+ \pi^- \eta\) decays, respectively. The photon candidates are required to be isolated from all charged tracks by more than 10° which is different from the selection criteria for the \(J/\psi \to \phi \eta(\eta')\), \(\eta(\eta') \to \pi^+ \pi^- \nu_e\) decays in order to improve the efficiency of the \(\pi^0(\eta)\) reconstruction. A four-constraint (4C) energy-momentum conservation kinematic fit is performed on the \(J/\psi \to K^+ K^- \pi^+ \pi^- \gamma\gamma\) hypothesis, and only events with \(\chi^2_{4C} < 200\) are accepted. For events with more than two photon candidates, the combination with the minimum \(\chi^2_{4C}\) is selected. After the 4C fits, the \(\pi^0\) and \(\eta\) signal windows on the \(\gamma\gamma\) invariant mass distributions are defined in the ranges \(0.115 < m_{\gamma\gamma} < 0.150\) GeV/c^2 and \(0.518 < m_{\gamma\gamma} < 0.578\) GeV/c^2, respectively.

The number of \(J/\psi \to \phi \eta(\eta'), \eta(\eta') \to \pi^+ \pi^- \pi^0(\eta)\) events are obtained from an unbinned extended maximum likelihood (ML) fit to the \(K^+ K^- \) versus \(\pi^+ \pi^- \pi^0(\eta)\) invariant mass distributions. The projection of the fit on the \(m_{KK} \) \(m_{\pi^+ \pi^- \eta}\) axis is shown in Figs. 3(a) and 4(a) [Figs. 3(b) and 4(b)] for the \(\eta\) and \(\eta'\) cases, respectively. In the ML fits, we require that \(0.99\) GeV/c^2 < \(m_{KK} < 1.09\) GeV/c^2 and \(0.50\) GeV/c^2 < \(m_{\pi^+ \pi^- \eta} < 0.60\) GeV/c^2 \(0.87\) GeV/c^2 < \(m_{\pi^+ \pi^- \eta} < 1.07\) GeV/c^2, for the \(\eta(\eta')\) case. The signal shape for \(\phi\) is modeled with a relativistic Breit-Wigner (RBW) function [34] convoluted with a Gaussian function that represents the detector resolution. In the fit, the width of \(\phi\) is fixed at the PDG value, its central mass value is floated, and the width of the Gaussian is fixed; the signal shape for \(\eta(\eta')\) is described by a Crystal Ball (CB) function [35], and its
parameters are floated. The backgrounds are divided into three categories: a non-$\phi \eta$-$\eta'$-peaking background (i.e., $J/\psi \rightarrow \pi^+ \pi^- \pi^0 K^+ K^-$), a non-$\phi$-peaking background [i.e., $J/\psi \rightarrow K^+ K^- \eta(\eta')$], and a non-$\eta$-$\eta'$-peaking background (i.e., $J/\psi \rightarrow \phi \pi^+ \pi^- \pi^0$). The probability density functions (PDF) for the non-$\phi$-peaking background in the $m_{KK}$ distribution are parametrized by \[36\]

\[
B(m_{KK}) = (m_{KK} - 2m_{K})^2 \cdot e^{-b_{m_{KK}} - c m_{KK}^2},
\]

where $a$, $b$, and $c$ are free parameters, and $m_{K}$ is the nominal mass value of the charged kaon from the PDG [29]. The shape for the non-$\eta$-$\eta'$-peaking background in the $m_{\pi^+ \pi^- \pi^0(\eta)}$ distribution is modeled by a first-order Chebychev polynomial function $[B(m_{\pi^+ \pi^- \eta(\eta')})]$. All parameters related to the background shape are floated in the fit to data. In total, 14 parameters including signal and background yields are floated in the fit. The PDFs for signal and backgrounds are combined in the likelihood function $L$, defined as a function of the free parameters $N^\eta$, $N_{bkg}^{non-\phi \eta}$, $N_{bkg}^{non-\phi}$, and $N_{bkg}^{non-\eta}$:

\[
L = \frac{e^{-N + N_{bkg}^{non-\phi \eta} + N_{bkg}^{non-\phi} + N_{bkg}^{non-\eta}}}{N!} \times \prod_{i=1}^{N} \left[ N^\eta \text{RBW}(m_{KK}^i) \times \text{CB}(m_{\pi^+ \pi^- \eta(\eta')}^i) + N_{bkg}^{non-\phi \eta} \text{RBW}(m_{KK}^i) \times B(m_{\pi^+ \pi^- \eta(\eta')}^i) + N_{bkg}^{non-\phi} \text{RBW}(m_{KK}^i) \times CB(m_{\pi^+ \pi^- \eta(\eta')}^i) + N_{bkg}^{non-\eta} \text{RBW}(m_{KK}^i) \times B(m_{\pi^+ \pi^- \eta(\eta')}^i) \right],
\]

where $N^\eta$ is the number of $J/\psi \rightarrow \phi \eta$, $\phi \rightarrow K^+ K^-$, $\eta \rightarrow \pi^+ \pi^- \pi^0$ events, and $N_{bkg}^{non-\phi \eta}$, $N_{bkg}^{non-\phi}$, and $N_{bkg}^{non-\eta}$ are the numbers of the corresponding three kinds of backgrounds. The fixed parameter $N$ is the total number of selected
TABLE I. The fitted signal and background yields for $J/\psi \rightarrow \phi \eta(\eta')$, $\eta(\eta') \rightarrow \pi^{+} \pi^{-} \pi^{0}(\eta)$, and $e^{+}(e^{-})$ is its selection efficiency.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
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<tr>
<td>$N^{\eta}(\eta')$</td>
<td>$3850 \pm 73$ $1623 \pm 44$</td>
</tr>
<tr>
<td>$N_{bkg}^{\eta}(N_{bkg}^{\eta'})$</td>
<td>$24 \pm 8$ $49 \pm 10$</td>
</tr>
<tr>
<td>$N_{bkg}^{\eta\eta}(N_{bkg}^{\eta\eta'})$</td>
<td>$367 \pm 43$ $22 \pm 17$</td>
</tr>
<tr>
<td>$N_{bkg}^{\eta\eta\eta}(N_{bkg}^{\eta\eta\eta'})$</td>
<td>$88 \pm 14$ $61 \pm 12$</td>
</tr>
<tr>
<td>$\epsilon^{\eta}(\epsilon^{\eta'})$</td>
<td>$20.37%$ $20.89%$</td>
</tr>
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</table>

events in the fit region, and $m_{KK}^{i}$ ($m_{\pi^{+} \pi^{-} \pi^{0}}^{i}$) is the value of $m_{KK}$ ($m_{\pi^{+} \pi^{-} \pi^{0}}$) for the $i$th event. We use the product of the PDFs, since we have verified that $m_{KK}$ and $m_{\pi^{+} \pi^{-} \pi^{0}}$ are uncorrelated for each component. The negative log-likelihood ($-\ln L$) is then minimized with respect to the extracted yields. The resulting fitted signal and background yields are summarized in Table I. We also obtain the results for the $\eta'$ case by replacing $\eta$ and $\pi^{0}$ with $\eta'$ and $\eta$ in Eq. (2). The fitted results for $\eta(\eta') \rightarrow \pi^{+} \pi^{-} \pi^{0}(\eta)$ are shown in Fig. 3 (Fig. 4). The detection efficiencies are determined with MC simulations to be $20.37\%$ and $20.89\%$ for $\eta$ and $\eta'$, respectively.

IV. SYSTEMATIC UNCERTAINTIES

Contributions to the systematic error on the ratios are summarized in Table II. The uncertainty, due to the requirement of no neutral showers in the EMC inside a cone spanning 0.3 (1.5) rad around the direction of the missing momentum for $\eta(\eta')$ decay, is obtained using the control sample of $J/\psi \rightarrow \phi \eta(\eta')$, $\phi \rightarrow K^{+}K^{-}$, $\eta(\eta') \rightarrow \gamma \pi^{+} \pi^{-}$ decays. We calculated the missing momentum of the $K^{+}K^{-} \pi^{+} \pi^{-}$ system, and define the same cones around the direction of the missing momentum as in the $\eta(\eta')$'s semileptonic analysis. The ratios of events with the requirement on the number of extra photons to events without the requirement are obtained for both data and MC simulations. The difference of 0.1% (1.1%) is considered as a systematic error for the $\eta(\eta')$ case.

We also use the control sample of $J/\psi \rightarrow \phi \eta'$, $\phi \rightarrow K^{+}K^{-}$, $\eta(\eta') \rightarrow \gamma \pi^{+} \pi^{-}$ to obtain the uncertainty due to the requirement on the missing momentum $P_{\text{miss}} > 0.03$ GeV/$c$ for both the $\eta$ and $\eta'$ cases. Thus we calculate the missing momentum of the $K^{+}K^{-} \pi^{+} \pi^{-}$ system. The ratios of events with the requirement on the missing momentum $P_{\text{miss}} > 0.03$ GeV/$c$ to events without the requirement are obtained for both data and MC simulations. The difference of 2.5% is considered as a systematic error for both the $\eta$ and $\eta'$ cases.

The phase-space MC is used to generate $\eta(\eta') \rightarrow \pi^{+} \pi^{-} \pi^{0} \nu_{\nu}$ decays. In Ref. [12], the transition form factors $F_{\eta\pi}$ are calculated at the one-loop level in the chiral perturbation theory. We use the model predictions to generate signal MC events, and find that the uncertainty on the detection efficiency is changed by 1.0% (5.0%) for the $\eta(\eta')$ case.

Since the uncertainties on the PID of the electron and one of the pions do not cancel in the ratio, the efficiencies for pion and electron PID are obtained with the control samples of $J/\psi \rightarrow \pi^{+} \pi^{-} \pi^{0}$ and radiative Bhabha scattering $e^{+}e^{-} \rightarrow \gamma e^{+}e^{-}$ (including $J/\psi \rightarrow \gamma e^{+}e^{-}$), respectively. Samples with backgrounds less than 1.0% are obtained [37]. The differences between data and MC for the efficiencies of pion and electron PID are about 1.0% and 1.2%, respectively, which are taken as systematic errors. Using the same control samples, we estimate the uncertainty due to the requirement of $E/p$ for the electron selection to be 3.5% (3.4%) for the $\eta(\eta')$ case, and the uncertainty due to the requirement of $E/p$ for the pion selection in the $\eta$ semileptonic decay is estimated to be 0.8%. The systematic uncertainty due to the requirements of the $\phi$ and $\eta(\eta')$ mass windows are estimated to be 1.4% and 0.04% (0.2%) by using the control sample of $J/\psi \rightarrow \phi \eta(\eta')$, $\eta(\eta') \rightarrow \pi^{+} \pi^{-} \pi^{0}(\eta)$.

The uncertainty in the determination of the numbers of observed events for $J/\psi \rightarrow \phi \eta$ [$\eta \rightarrow \pi^{+} \pi^{-} \pi^{0} \times (\pi^{0} \rightarrow \gamma \gamma)$] and $J/\psi \rightarrow \phi \eta'$ [$\eta' \rightarrow \pi^{+} \pi^{-} \pi^{0} \eta(\eta \rightarrow \gamma \gamma)$] decays are estimated on the basis of earlier published results. The photon detection efficiency and its uncertainty are studied by three different methods in Ref. [37]. The systematic error of photon detection is estimated to be 1.0% per photon. In the fit to the $\phi$ mass distribution, the
mass resolution is fixed to the MC simulation; the level of possible discrepancy is determined with a smearing Gaussian, for which a nonzero $\sigma$ would represent an MC-data difference in the mass resolution. The uncertainty associated with the difference determined in this way is 0.03% (0.06%) for the $\eta(\eta')$ case. The systematic uncertainty due to the choice of parametrization for the shape of the non-$\phi\eta(\eta')$-peaking background is estimated by varying the order of the polynomial in the fit; we find that the relative changes on the $\eta(\eta')$ signal yield are 1.3% (0.8%), which is taken as the uncertainty due to the background shapes. The systematic errors from $\pi^0(\eta)$ reconstruction from $\gamma\gamma$ decays is determined to be 1.0% per $\pi^0(\eta)$ by using a high-purity control sample of $J/\psi \rightarrow \pi^0p\bar{p}$ ($J/\psi \rightarrow \eta p\bar{p}$) decay [38]. The branching fractions for the $\pi^0$ and $\eta \rightarrow \gamma\gamma$ decays are taken from the PDG [29]. The uncertainties on the branching fractions are taken as a systematic uncertainty in our measurements. The total systematic error $\sigma^{sys}(\sigma^{stat})$ on the ratio is 5.6% (7.4%) for $\eta(\eta')$, as summarized in Table II.

V. RESULTS

The upper limit on the ratio of branching fractions of the semileptonic decay $B(\eta \rightarrow \pi^+ e^- \nu_e +\text{c.c.})$ over the hadronic decay $B(\eta \rightarrow \pi^+ \pi^- \pi^0)$ is calculated with

$$\frac{B(\eta \rightarrow \pi^+ e^- \nu_e +\text{c.c.})}{B(\eta \rightarrow \pi^+ \pi^- \pi^0)} < \frac{N^{UL}_{\eta}/e^{SL}_{\eta}}{N^{UL}/e^{UL}_{\eta}} \frac{B(\pi^0 \rightarrow \gamma\gamma)}{(1-\sigma_{\eta})}, \quad (3)$$

where $N^{UL}_{\eta}$ is the 90% upper limit of the observed number of events for $J/\psi \rightarrow \phi \eta$, $\phi \rightarrow K^+ K^-$, $\eta \rightarrow \pi^+ e^- \nu_e$ decay, $e^{SL}_{\eta}$ is the MC-determined efficiency for the signal channel, $N^{UL}$ is the number of events for the $J/\psi \rightarrow \phi \eta$, $\phi \rightarrow K^+ K^-$, $\eta \rightarrow \pi^+ \pi^- \pi^0$ decay, $e^{UL}_{\eta}$ is the MC-determined efficiency for the decay mode, and $\sigma_{\eta} = \sqrt{(\sigma^{sys}_{\eta})^2 + (\sigma^{stat}_{\eta})^2} = 5.9\%$, where $\sigma^{sys}_{\eta}$ and $\sigma^{stat}_{\eta}$ are the total relative systematic error for the $\eta$ case from Table II and the relative statistical error of $N^{UL}_{\eta}$, respectively. For $\eta'$, $\sigma_{\eta'} = \sqrt{(\sigma^{sys}_{\eta'})^2 + (\sigma^{stat}_{\eta'})^2} = 7.9\%$. The relative statistical error of $N^{UL}(N^{UL}_{\eta'})$ is 1.9% (2.7%). We also obtain the upper limit on the ratio of $B(\eta' \rightarrow \pi^+ e^- \nu_e +\text{c.c.})$ to $B(\eta' \rightarrow \pi^+ \pi^- \eta)$ by replacing $\eta$ and $B(\pi^0 \rightarrow \gamma\gamma)$ with $\eta'$ and $B(\eta' \rightarrow \gamma\gamma)$, respectively, in Eq. (3). Since only the statistical error is considered when we obtain the 90% upper limit of the number of events, to be conservative, $N^{UL}_{\eta}$ and $N^{UL}_{\eta'}$ are shifted up by one sigma of the additional uncertainties ($\sigma_{\eta}$ or $\sigma_{\eta'}$).

Using the numbers in Table III, the upper limits on the ratios $\frac{B(\eta \rightarrow \pi^+ e^- \nu_e +\text{c.c.})}{B(\eta \rightarrow \pi^+ \pi^- \pi^0)}$ and $\frac{B(\eta' \rightarrow \pi^+ e^- \nu_e +\text{c.c.})}{B(\eta' \rightarrow \pi^+ \pi^- \eta)}$ are obtained at the 90% C.L. of $7.3 \times 10^{-4}$ and $5.0 \times 10^{-4}$, respectively.

### Table III

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
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<tbody>
<tr>
<td>$N^{UL}<em>{\eta}$ ($N^{UL}</em>{\eta'}$)</td>
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</tr>
<tr>
<td>$e^{SL}<em>{\eta}$ ($e^{SL}</em>{\eta'}$)</td>
<td>17.9%</td>
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<tr>
<td>$e^{UL}<em>{\eta}$ ($e^{UL}</em>{\eta'}$)</td>
<td>17.4%</td>
</tr>
<tr>
<td>$N^{UL}$ ($N^{UL}_{\eta'}$)</td>
<td>1623 ± 44</td>
</tr>
<tr>
<td>$e^{UL}<em>{\eta}$ ($e^{UL}</em>{\eta'}$)</td>
<td>20.89%</td>
</tr>
<tr>
<td>$\sigma^{stat}<em>{\eta}$ ($\sigma^{stat}</em>{\eta'}$)</td>
<td>2.7%</td>
</tr>
<tr>
<td>$\sigma_{\eta}$ ($\sigma_{\eta'}$)</td>
<td>7.9%</td>
</tr>
</tbody>
</table>

VI. SUMMARY

A search for the semileptonic weak decay modes $\eta(\eta') \rightarrow \pi^+ e^- \nu_e$ has been performed for the first time in the process of $J/\psi \rightarrow \phi \eta(\eta')$ using the $(225.3 \pm 2.8) \times 10^6 J/\psi$ events measured at BESIII. We find no signal yields for the semileptonic weak decays of $\eta$ and $\eta'$. The upper limits at the 90% C.L. are $7.3 \times 10^{-4}$ and $5.0 \times 10^{-4}$ for the ratios of semileptonic over hadronic decay modes, $\frac{B(\eta \rightarrow \pi^+ e^- \nu_e +\text{c.c.})}{B(\eta \rightarrow \pi^+ \pi^- \eta)}$ and $\frac{B(\eta' \rightarrow \pi^+ e^- \nu_e +\text{c.c.})}{B(\eta' \rightarrow \pi^+ \pi^- \eta)}$, respectively. The advantage of measuring the ratios instead of the branching fractions of the semileptonic weak decays is that many uncertainties cancel. Using the hadronic branching fraction values of $\eta \rightarrow \pi^+ \pi^- \eta$ and $\eta' \rightarrow \pi^+ \pi^- \eta$ as listed by PDG [29], we determine the semileptonic decay rates to be $B(\eta \rightarrow \pi^+ e^- \nu_e +\text{c.c.}) < 1.7 \times 10^{-4}$ and $B(\eta' \rightarrow \pi^+ e^- \nu_e +\text{c.c.}) < 2.2 \times 10^{-4}$ at the 90% C.L.

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