

Measurement of the branching fraction of $\eta \rightarrow \mu^+ \mu^-$ and search for $\eta \rightarrow e^+ e^-$

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We analyze the decay of $\eta \rightarrow \ell^+ \ell^-$ ($\ell = e, \mu$) via $J/\psi \rightarrow \gamma \eta'$ and $\eta' \rightarrow \pi^+ \pi^- \eta$, based on $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector at the BEPCII storage rings. The branching fraction of $\eta \rightarrow \mu^+ \mu^-$ is measured to be $(5.8 \pm 1.0_{\text{stat}} \pm 0.2_{\text{syst}}) \times 10^{-6}$, which is consistent with the previous measurements and theoretical expectations. In addition, no significant $\eta \rightarrow e^+ e^-$ signal is observed in the $e^+ e^-$ invariant mass spectrum, and an improved upper limit of $\mathcal{B}(\eta \rightarrow e^+ e^-) < 2.2 \times 10^{-7}$ is set at 90% confidence level.

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I. INTRODUCTION

Within the Standard Model (SM), the decay of η into lepton pairs ($\eta \rightarrow \ell^+ \ell^-$ with $\ell = e$ or μ) proceeds via a fourth-order electromagnetic transition. The process is dominated by a two-photon intermediate state, as depicted in Fig. 1, resulting in significant suppression of the decay. Especially for $\eta \rightarrow e^+ e^-$, the decay probability is expected to be very low, since the helicity factor is proportional to the square of the electron mass. Hence, a measurement of this decay probability higher than the SM model prediction could be indicative of hypothetical interactions arising from physics beyond the SM. This has stimulated considerable theoretical effort [1–14] devoted to calculating the decay rate of $\eta \rightarrow \ell^+ \ell^-$. The predicted branching fractions for $\eta \rightarrow \mu^+ \mu^-$ and $\eta \rightarrow e^+ e^-$, based on the Canterbury approximants method [15], are $(4.72^{+0.05}_{-0.21}) \times 10^{-6}$ and $(5.31^{+0.14}_{-0.04}) \times 10^{-9}$, respectively.

Experimentally, a stringent upper limit of $\mathcal{B}(\eta \rightarrow e^+ e^-) < 7 \times 10^{-7}$, at 90% confidence level (CL), was obtained from the inverse process $e^+ e^- \rightarrow \eta$ [16]. The world average of $\mathcal{B}(\eta \rightarrow \mu^+ \mu^-) = (5.7 \pm 0.8) \times 10^{-6}$ [17] is a combination of measurements performed by SATURNE II [18] and Lepton-G [19] more than thirty years ago. In recent years, taking advantage of the abundant production of η, η' mesons in J/ψ radiative decays and the high statistics J/ψ events, the BESIII experiment has made significant improvements in the study of their decays.

However, the investigation of $\eta \rightarrow \ell^+ \ell^-$ decays via the radiative decay $J/\psi \rightarrow \gamma \eta$ suffers from large backgrounds from $J/\psi \rightarrow \gamma \ell^+ \ell^-$ decays.

More recently, a novel approach [20] was proposed to investigate η decays, particularly for their rare or forbidden decays, with $\eta' \rightarrow \pi \pi \eta$ produced in J/ψ radiative decays. Therefore, using the sample of $(10087 \pm 44) \times 10^6$ [21] J/ψ events collected with the BESIII detector, we perform a study of $\eta \rightarrow \ell^+ \ell^-$ with $J/\psi \rightarrow \gamma \eta'$ and the subsequent decay of $\eta' \rightarrow \pi^+ \pi^- \eta$.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [22] is a magnetic spectrometer located at the Beijing Electron Positron Collider (BEPCII) [22]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and 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 magnetic field was 0.9 T in 2012, which affects 11% of the total J/ψ data. The solenoid is supported by an

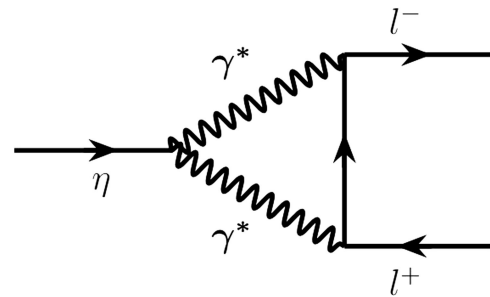


FIG. 1. The Feynman diagram for $\eta \rightarrow \ell^+ \ell^-$.

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octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel. The charged-particle momentum resolution at 1 GeV/ c is 0.5%, and the specific ionization energy loss dE/dx resolution is 6% for the electrons from Bhabha scattering. 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 in the end-cap part is 110 ps. The end-cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps [23–25], which benefits 87% of the data used in this paper.

Monte Carlo (MC) simulated data samples are produced with a Geant4-based [26] software package, which includes the geometric description of the BESIII detector and the detector response. These samples are used to determine detection efficiencies and estimate the backgrounds. To thoroughly investigate potential backgrounds, we utilize an inclusive MC sample comprising 10 billion J/ψ events. The inclusive MC sample includes both the production of the J/ψ resonance and the continuum processes incorporated in KKMC [27,28]. All particle decays are modeled with EVTGEN [29] using the branching fractions either taken from the Particle Data Group (PDG) [17], when available, or otherwise estimated with LUNDCHARM [30]. Final state radiation (FSR) from charged final state particles is incorporated using the PHOTOS package [31]. Specific generators using the appropriate theoretical amplitudes for $\eta' \rightarrow \pi^+\pi^-\ell^+\ell^-$ [32], $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-$ [33], and $\eta \rightarrow \gamma e^+e^-$ [34] decays were developed for this analysis.

III. EVENT SELECTION

The final state of interest is studied through the decay chain $J/\psi \rightarrow \gamma\eta'$, $\eta' \rightarrow \pi^+\pi^-\eta$, and $\eta \rightarrow \ell^+\ell^-$. Each event is required to contain at least one good photon candidate and four charged track candidates with a total charge of zero. Each charged track reconstructed from MDC hits is required to have a polar angle in the range $|\cos\theta| \leq 0.93$ and to pass the interaction point within ± 10 cm along the beam direction and within ± 1 cm in the plane perpendicular to the beam.

Photon candidates are reconstructed using isolated clusters of energy deposited in the EMC and must have a deposited energy larger than 25 MeV in the barrel region ($|\cos\theta| \leq 0.80$) and 50 MeV in the end-cap region ($0.86 < |\cos\theta| < 0.92$). The energy deposited in nearby TOF counters is included to improve the reconstruction efficiency and energy resolution. To eliminate clusters associated with charged tracks, the angle between the photon candidate and the extrapolation of any charged track to the EMC must be larger than 10 degrees. A requirement on the EMC cluster timing with respect to the event start time ($0 \leq T \leq 700$ ns) is used to suppress electronic noise and energy deposits unrelated to the event.

For each candidate, particle identification (PID) is performed using the TOF and dE/dx information, and four-constraint (4C) kinematic fits are performed imposing energy and momentum conservation under the hypotheses of $J/\psi \rightarrow \gamma\pi^+\pi^-\ell^+\ell^-$. For each event, the combination with the smallest $\chi^2_{\text{sum}}(\gamma\pi^+\pi^-\ell^+\ell^-)$ is kept for further analysis, where $\chi^2_{\text{sum}}(\gamma\pi^+\pi^-\ell^+\ell^-) = \chi^2_{4C} + \sum_{i=1}^4 \chi^2_{\text{PID}(i)}$ is the sum of the 4C kinematic fit χ^2 and PID χ^2 of the four charged tracks.

IV. ANALYSIS OF $\eta \rightarrow \mu^+\mu^-$

For the $\eta \rightarrow \mu^+\mu^-$ decay, the events with $\chi^2_{\text{sum}}(\gamma\pi^+\pi^-\mu^+\mu^-) < 40$ are retained. Here the requirement is optimized by the figure of merit [35] $S/\sqrt{S+B}$, where S is the number of signal events from MC simulation and B is the number of background events in the data. To reject possible background events from $J/\psi \rightarrow \gamma 2(\pi^+\pi^-)$, $\chi^2_{\text{sum}}(\gamma\pi^+\pi^-\pi^+\pi^-) > \chi^2_{\text{sum}}(\gamma\pi^+\pi^-\mu^+\mu^-)$ is required. The muon counter information is not further used due to the low momentum of the muons of interest.

The resulting $\pi^+\pi^-\mu^+\mu^-$ invariant mass distribution ($M_{\pi^+\pi^-\mu^+\mu^-}$) is shown in Fig. 2. A clear η' peak is observed, while the small peak around 0.93 GeV/ c^2 comes from the background $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-$ decay. The distribution of $M_{\pi^+\pi^-\mu^+\mu^-}$ versus the $\mu^+\mu^-$ invariant mass ($M_{\mu^+\mu^-}$) is displayed in Fig. 3. The cluster within the marked region corresponds to the $\eta' \rightarrow \pi^+\pi^-\eta$ decay. Requiring $M_{\pi^+\pi^-\mu^+\mu^-} \in (0.945, 0.970)$ GeV/ c^2 , an evident η peak is seen in the $M_{\mu^+\mu^-}$ distribution, as shown in Fig. 4. Although the η' peak in Fig. 2 is dominated by background events from $\eta' \rightarrow \pi^+\pi^-\mu^+\mu^-$, these events are primarily concentrated in

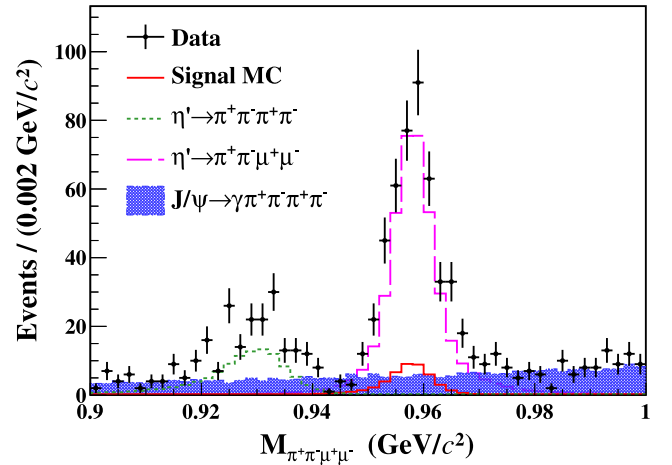


FIG. 2. The distribution of $M_{\pi^+\pi^-\mu^+\mu^-}$. The dots with error bars represent the data, and the red histogram is the signal MC sample. The dashed green line, dashed pink line, and shaded blue histogram represent the backgrounds from $\eta \rightarrow \pi^+\pi^-\pi^+\pi^-$, $\eta' \rightarrow \pi^+\pi^-\mu^+\mu^-$ and $J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$, respectively.

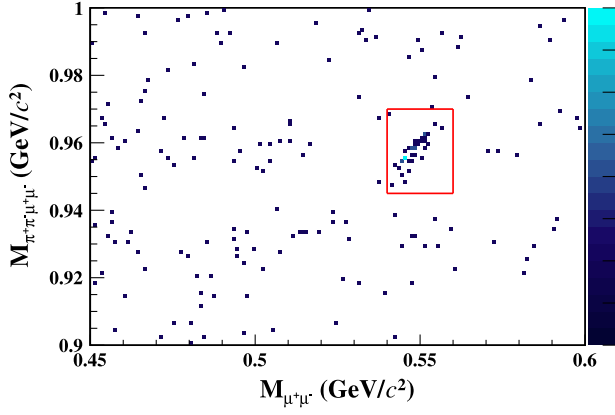


FIG. 3. The distribution of $M_{\pi^+\pi^-\mu^+\mu^-}$ versus $M_{\mu^+\mu^-}$ for data.

the low-energy region of $M_{\mu^+\mu^-}$ and contribute very little in the mass range of interest, as shown in Fig. 4.

To investigate background events in the $M_{\mu^+\mu^-}$ distribution, an inclusive MC sample of 10 billion J/ψ events is analyzed with the same procedure. The background events are mainly from the decays $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \pi^+\pi^-\pi^+\pi^-$, $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \pi^+\pi^-\mu^+\mu^-$ and $J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$. Dedicated MC samples for these background channels are generated to estimate their contributions. We find that none of these possible background channels contributes to the η peak, as seen in Fig. 4.

To obtain the signal yield of $\eta \rightarrow \mu^+\mu^-$, an extended unbinned maximum likelihood fit is performed to the $M_{\mu^+\mu^-}$ distribution. In the fit, the total probability density function consists of a signal component and various background contributions. The signal component is modeled with the simulated shape. The background components considered are subdivided into two classes. For the

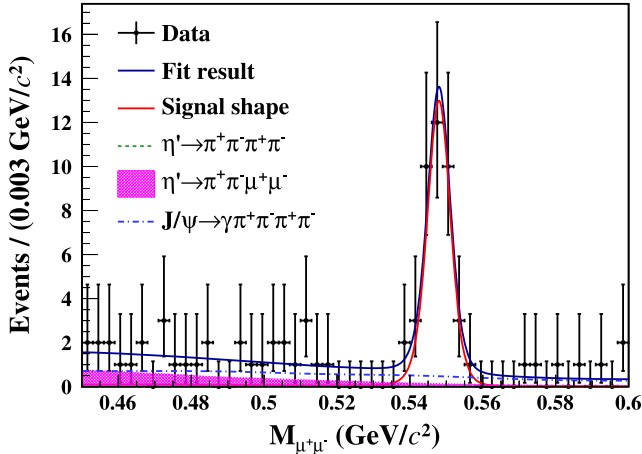


FIG. 4. The fit to the $M_{\mu^+\mu^-}$ distribution. The dots with error bars represent the data. The blue line represents the total fit result, and the red line represents the signal component. The dashed green line, shaded pink shape, and dot-dash blue line are the contributions from the decays $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-$, $\eta' \rightarrow \pi^+\pi^-\mu^+\mu^-$ and $J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$, respectively.

first, the shapes of the background events from η' decays $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \pi^+\pi^-\mu^+\mu^-$ and $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \pi^+\pi^-\pi^+\pi^-$ are taken from dedicated MC simulations. The magnitudes of these backgrounds are fixed at 15.0 ± 3.0 and 0.8 ± 0.1 , respectively, normalized using the branching fractions of $J/\psi \rightarrow \gamma\eta'$ and their subsequent decays. The second class is the $J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$ component, also described with the MC-simulated shape, with a magnitude left as a free parameter in the fit.

The fit, shown in Fig. 4, gives $37.9 \pm 6.7 \eta \rightarrow \mu^+\mu^-$ events with a statistical significance of 9.8σ . This significance is calculated from the change in the negative log likelihood function $-\ln \mathcal{L}$ with and without the signal component, accounting for the change in degrees of freedom between the two fit configurations. Taking into account the detection efficiency of $(29.19 \pm 0.07)\%$ obtained from the MC simulation, the branching fraction of $\eta \rightarrow \mu^+\mu^-$ is measured to be

$$\begin{aligned} \mathcal{B}(\eta \rightarrow \mu^+\mu^-) &= \frac{N_{\text{obs}}}{N_{J/\psi} \cdot \mathcal{B}_{\text{int}} \cdot \epsilon_{\eta \rightarrow \mu^+\mu^-}} \\ &= (5.8 \pm 1.0) \times 10^{-6}, \end{aligned} \quad (1)$$

where N_{obs} is the signal yield, $N_{J/\psi}$ is the total number of J/ψ events, $\mathcal{B}_{\text{int}} \equiv \mathcal{B}(J/\psi \rightarrow \gamma\eta')\mathcal{B}(\eta' \rightarrow \pi^+\pi^-\eta)$ is taken from the PDG [17], $\epsilon_{\eta \rightarrow \mu^+\mu^-}$ is the detection efficiency, and the uncertainty is statistical only.

V. ANALYSIS OF $\eta \rightarrow e^+e^-$

To select $\eta \rightarrow e^+e^-$ events, the $\chi^2_{\text{sum}}(\gamma\pi^+\pi^-e^+e^-)$ is required to be less than 40. The $\pi^+\pi^-e^+e^-$ invariant mass ($M_{\pi^+\pi^-e^+e^-}$) is shown in Fig. 5(a). No evident η' signal is observed. We then select the η' mass window to be within $(0.945, 0.97)$ GeV/c^2 . Figure 5(b) shows the e^+e^- invariant mass ($M_{e^+e^-}$) distribution for candidates passing all selection criteria. No events are observed in the η mass region.

A background study based on the inclusive MC sample indicates that the dominant background originates from $J/\psi \rightarrow \gamma\eta'$ with the subsequent decays $\eta' \rightarrow \pi^+\pi^-\eta$, $\eta \rightarrow \gamma e^+e^-$ and $\eta' \rightarrow \pi^+\pi^-e^+e^-$. Dedicated MC samples are generated to evaluate contributions from these channels. The background yields are 0.5 ± 0.3 and 1.0 ± 0.2 events, respectively.

The signal region is defined as the interval within 3.5 standard deviations. The standard deviation represents the mass resolution obtained from signal MC events, corresponding to a mass interval of $(0.534, 0.560)$ GeV/c^2 . No events are observed in this interval, $N_{\text{sig}} = 0$. The background contribution, N_{bkg} , in the signal region is estimated using events in sideband regions. Symmetric sideband regions, each with the same width as the signal region, are defined as $(0.508, 0.534)$ GeV/c^2 and $(0.560, 0.586)$ GeV/c^2 , giving $N_{\text{bkg}} = 1.5$. With the

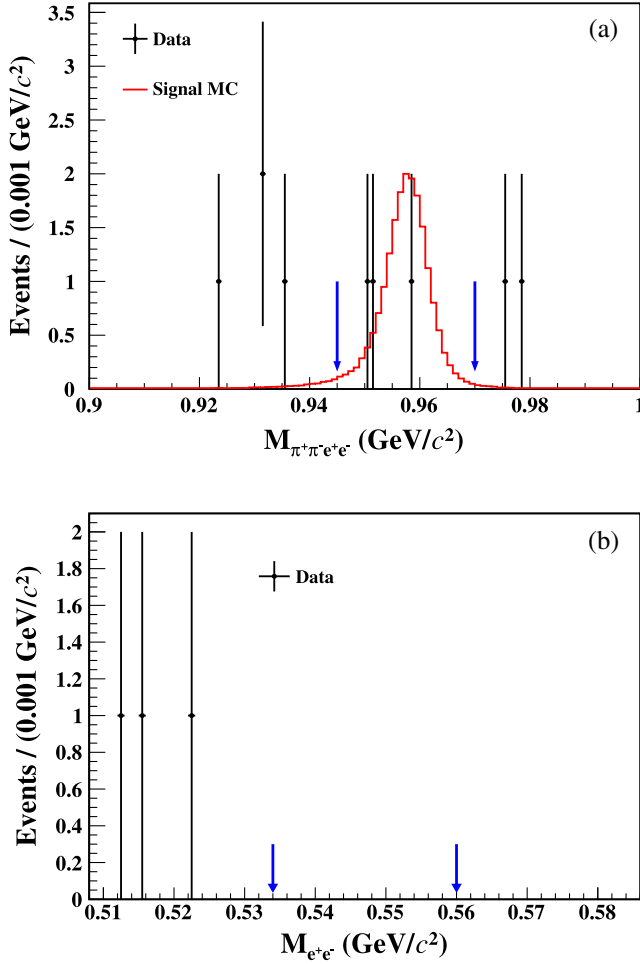


FIG. 5. The distributions of (a) $M_{\pi^+\pi^-e^+e^-}$ and (b) $M_{e^+e^-}$. Dots with error bars represent the data, the red histogram is the signal MC shape. Two blue arrows represent the signal region.

dedicated MC sample, the detection efficiency is determined to be $(27.48 \pm 0.04)\%$, where the uncertainty is statistical only.

The upper limit on the signal yield, N_{UL} , is estimated at a CL of 90% using the method from Ref. [36], which is suitable for small signals in the presence of background. Given N_{sig} and N_{bkg} , N_{UL} of $\eta \rightarrow e^+e^-$ is estimated to be 1.3. Accounting for efficiency and systematic uncertainty δ_{sys} (see Sec. VI below for details), the upper limit on the branching fraction of $\eta \rightarrow e^+e^-$ is determined as

$$\begin{aligned} \mathcal{B}(\eta \rightarrow e^+e^-) &< \frac{N_{UL}}{N_{J/\psi} \cdot \mathcal{B}_{int} \cdot \epsilon_{\eta \rightarrow e^+e^-} \cdot (1 - \delta_{sys})} \\ &= 2.2 \times 10^{-7}. \end{aligned} \quad (2)$$

VI. SYSTEMATIC UNCERTAINTIES

The sources of systematic uncertainties include the efficiency differences between the data and MC simulation for the MDC tracking, the PID, the photon

detection, and the kinematic fit, as well as the fitting procedure and the total number of J/ψ events. Their effects on the branching fractions are discussed below:

- (i) Total number of J/ψ events: The total number of J/ψ events, $(10087 \pm 44) \times 10^6$ [21], is determined from an analysis of inclusive J/ψ hadronic events, and the uncertainty, 0.4%, is taken as the systematic uncertainty;
- (ii) Uncertainties of $\mathcal{B}(J/\psi \rightarrow \gamma\eta')$ and $\mathcal{B}(\eta' \rightarrow \pi^+\pi^-\eta)$: The branching fractions of $J/\psi \rightarrow \gamma\eta'$ and $\eta' \rightarrow \pi^+\pi^-\eta$ are taken from the PDG [17]. Their uncertainties are 1.3% and 1.2%, respectively;
- (iii) MDC tracking: The single charged pion track efficiency has been studied with respect to the transverse momentum and polar angle θ in the MDC by means of a high-purity sample of $J/\psi \rightarrow \pi^+\pi^-\pi^0$ [37] obtained by using one pion to tag the presence of the other. Two-dimensional tracking efficiencies as a function of the transverse momentum and $\cos\theta$ are evaluated for both the data and MC simulation. To correct the MC efficiencies to those of the data, the corresponding two-dimensional correction factors and their uncertainties are derived. To estimate its impact on the systematic uncertainty, the MC simulation events are then weighted to determine the detection efficiency. Since the mass and the behavior of low-momentum muons are similar to those of pions, we weight the muon tracks by assuming them to be pions. In the case of electrons, the clean samples of $e^+e^- \rightarrow e^+e^-\gamma$ at the J/ψ meson mass and $J/\psi \rightarrow e^+e^-\gamma_{FSR}$ are used to evaluate the MC-data tracking difference as a function of momentum and polar angle, which are then used to weight the MC simulated events. The changes in the detection efficiencies with and without correction, 0.8% for $\eta \rightarrow \mu^+\mu^-$ and 2.1% for $\eta \rightarrow e^+e^-$, are considered as the systematic uncertainties;
- (iv) PID and 4C kinematic fit: In case of $\eta \rightarrow \mu^+\mu^-$, the uncertainties from PID and the kinematic fit are evaluated separately. To estimate the pion PID efficiency uncertainty, we have studied the pion PID efficiency using the control samples of $J/\psi \rightarrow \pi^+\pi^-\pi^0$. The results show that the pion PID efficiency for data agrees well with that of the MC simulation. The minor MC-data discrepancy as a function of the momentum and the polar angle is used to estimate the systematic uncertainty with the same approach as for the tracking efficiency. Due to a lack of a specific control sample for low-momentum muons, the PID efficiency correction is performed with the correction factor obtained from pions. The uncertainty associated with the 4C kinematic fit is studied by correcting the track helix parameters [38] to reduce the difference between

TABLE I. Relative systematic uncertainties (in %) in the branching fraction measurements.

Source	$\eta \rightarrow \mu^+\mu^-$	$\eta \rightarrow e^+e^-$
Number of J/ψ events	0.4	0.4
$\mathcal{B}(J/\psi \rightarrow \gamma\eta')$	1.3	1.3
$\mathcal{B}(\eta' \rightarrow \pi^+\pi^-\eta)$	1.2	1.2
MDC tracking	0.8	2.1
PID and kinematic fit	2.7	4.6
Photon detection	0.5	0.5
Signal shape	0.1	...
Background shape	0.2	...
Total	3.4	5.6

data and MC simulation. The differences between the efficiencies with and without corrections, summarized in Table I, are taken as the systematic uncertainties from PID and 4C kinematic fit. For $\eta \rightarrow e^+e^-$, we use a clean control sample of $J/\psi \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma e^+e^-$ to study the uncertainty. This control sample has the same topology as the decay of interest. Using the same charged tracks and photon selection criteria, we first select the candidate events with a very loose requirement on χ^2_{sum} . Then, we further tighten the selection by requiring $\chi^2_{\text{sum}} < 40$. The efficiency difference between data and MC simulation, 4.6%, is taken as the systematic uncertainty. Although the systematic uncertainty from PID and the 4C kinematic fit is larger than other individual contributions, its combination with the tracking efficiency correction yields a small net effect on the detection efficiency. We therefore use the result without the tracking efficiency correction as the nominal value and take the difference between the results with and without the correction as the systematic uncertainty;

- (v) Photon detection efficiency: The systematic uncertainty from the reconstruction of photons has been extensively studied in the processes $e^+e^- \rightarrow \gamma\mu^+\mu^-$. The relative difference in efficiency between data and MC simulation, up to 0.5%, is assigned as the systematic uncertainty;
- (vi) Signal shape: The uncertainties due to the signal MC shape is estimated by performing an alternative fit in which the signal is modeled by the MC shape convolved with a single Gaussian function. It is found that the difference of the determined number of signal events, 0.1%, which is taken as the systematic uncertainty;
- (vii) Background shape: In the fit to $M_{\mu^+\mu^-}$, the numbers of background events from $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-$ and $\eta' \rightarrow \pi^+\pi^-\mu^+\mu^-$ are fixed at the normalized values according to the branching fractions from the PDG [17]. To estimate the effect of the uncertainty of the used branching fractions, the numbers of events for

these two backgrounds are varied randomly within the uncertainties of the branching fractions. Using these randomly scaled parameters, we perform a series of fits to the $M_{\mu^+\mu^-}$ distribution. The difference of the determined number of signal events, 0.2%, is taken as the systematic uncertainty;

- (viii) Fit range: The systematic uncertainty due to the η fit range is evaluated by varying the nominal range by ± 0.01 or ± 0.02 GeV/ c^2 in six variations. For each variation, the deviation between the alternative and nominal one is defined as $\zeta = \frac{|\mathcal{B}_{\text{nominal}} - \mathcal{B}_{\text{test}}|}{\sqrt{|\sigma_{\mathcal{B}_{\text{nominal}}}^2 - \sigma_{\mathcal{B}_{\text{test}}}^2|}}$,

where $\mathcal{B}$ denotes the branching fraction of $\eta \rightarrow \mu^+\mu^-$ and σ denotes the statistical uncertainty. According to the method discussed in Ref. [39], this uncertainty source is negligible because all ζ values are below 1σ .

Table I summarizes all contributions to the systematic uncertainties on the branching fraction measurements. In each case, the total systematic uncertainty is obtained by adding the individual contributions in quadrature.

VII. SUMMARY

With a sample of $(10087 \pm 44) \times 10^6$ [21] J/ψ events collected with the BESIII detector, we perform a study of $\eta \rightarrow \ell^+\ell^-$ tagging with $\eta' \rightarrow \pi^+\pi^-\eta$ in J/ψ radiative decays. The decay $\eta \rightarrow \mu^+\mu^-$ is observed with a significance of 9.8σ , and its branching fraction is measured to be $(5.8 \pm 1.0_{\text{stat}} \pm 0.2_{\text{syst}}) \times 10^{-6}$. This is consistent with theoretical predictions [14] and the $(5.8 \pm 0.8) \times 10^{-6}$ PDG value [17]. No signal is observed for $\eta \rightarrow e^+e^-$, and the upper limit on its branching fraction at 90% CL is set to 2.2×10^{-7} . This represents an improvement over the previous upper limit of 7×10^{-7} (CL = 90%) from the SND experiment [16], providing a stricter experimental constraint on new physics. Recently, theoretical predictions based on a dispersive representation for the η transition form factors give $\mathcal{B}(\eta \rightarrow \mu^+\mu^-) = (4.54 \pm 0.04 \pm 0.02) \times 10^{-6}$ and $\mathcal{B}(\eta \rightarrow e^+e^-) = (5.37 \pm 0.04 \pm 0.02) \times 10^{-9}$ [40]. Our measured branching fraction for $\eta \rightarrow \mu^+\mu^-$ is in good agreement with this prediction, with the difference being well within 1.2σ .

In the future, new experimental facilities, such as the super τ -charm facility (STCF) [41], the JLab Eta Factory (JEF) [42], REDTOP [43], and the η factory of HIAF [44] experiments, will provide larger η samples, enabling improved measurements of $\eta \rightarrow \ell^+\ell^-$ decays, deeper exploration of the internal structure of the η meson, and searches for new physics beyond the SM.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they are owned by a third party and the terms of use prevent public distribution. The data are available from the authors upon reasonable request.

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