

Improved measurement of $\eta' \rightarrow e^+ e^- \omega$ M. Ablikim *et al.*^{*}
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Using a sample of $(10087 \pm 44) \times 10^6 J/\psi$ events collected with the BESIII detector, an improved measurement of the decay $\eta' \rightarrow e^+ e^- \omega$, with $\omega \rightarrow \pi^+ \pi^- \pi^0$ and $\pi^0 \rightarrow \gamma\gamma$ is performed. The branching fraction is determined to be $\mathcal{B}(\eta' \rightarrow e^+ e^- \omega) = (1.79 \pm 0.09 \pm 0.12) \times 10^{-4}$, where the first uncertainty is statistical and the second is systematic. This result is consistent with the previous measurement and is obtained with significantly improved precision. Furthermore, the first measurement of the transition form factor cutoff parameter for this decay is reported, with $\Lambda^{-1} = (2.92 \pm 0.83 \pm 0.15) \text{ GeV}^{-1}$. These measurements provide valuable input for understanding the internal structure of the η' meson and testing theoretical models.

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I. INTRODUCTION

The pseudoscalar meson η' , discovered in 1964 [1,2], remains a subject of significant interest because its decay properties serve as a probe of meson internal structure and a testing ground for low-energy quantum chromodynamics (QCD). Its decay properties can be classified into two main categories. Hadronic decays, such as $\eta' \rightarrow \eta\pi\pi$, are dominant and governed by isospin conservation. Radiative decays into vector mesons, such as $\eta' \rightarrow \rho^0\gamma$ and $\eta' \rightarrow \omega\gamma$, serve as a testing ground for model-dependent approaches, including vector meson dominance (VMD) and chiral perturbation theory.

Decays of the form $\eta' \rightarrow V e^+ e^-$ (where V denotes a vector meson) are particularly insightful, as they proceed via a virtual photon $\eta' \rightarrow V \gamma^* \rightarrow V e^+ e^-$. The invariant mass spectrum of the $e^+ e^-$ pair provides direct access to the η' transition form factor (TFF). The TFF encapsulates the meson's internal structure and its dependence on the momentum transfer, q^2 , making it a valuable tool for phenomenological studies. A decay of similar nature, $\eta' \rightarrow \pi^+ \pi^- e^+ e^-$, has been previously measured [3] and agrees with the theoretical predictions [4].

The branching fraction (BF) for $\eta' \rightarrow e^+ e^- \omega$ was previously measured by BESIII to be $\mathcal{B}(\eta' \rightarrow e^+ e^- \omega) = (1.97 \pm 0.34(\text{stat}) \pm 0.17(\text{syst})) \times 10^{-4}$ using $(1310.6 \pm 7.2) \times 10^6 J/\psi$ events collected in 2009 and 2012 [5].

In this work, we present an improved analysis of the decay $\eta' \rightarrow e^+ e^- \omega$, with $\omega \rightarrow \pi^+ \pi^- \pi^0$ and $\pi^0 \rightarrow \gamma\gamma$, using the process $J/\psi \rightarrow \gamma\eta'$. The analysis utilizes a significantly larger data sample of $(10087 \pm 44) \times 10^6 J/\psi$ events collected in 2009, 2012 and 2017-2019 [6]. We report a more precise measurement of the BF and, for the first time, a measurement of the TFF parameter for this decay channel.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [7] records symmetric $e^+ e^-$ collisions provided by the BEPCII storage ring [8] in the center-of-mass energy range from 1.84 to 4.95 GeV, with a peak luminosity of $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ achieved at $\sqrt{s} = 3.773 \text{ GeV}$. The BESIII detector has accumulated the world's largest sample of J/ψ events in this energy region, which provides the foundation for this high-precision study [9]. 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 (TI) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid's magnetic field was 0.9 T during the data-taking period in 2012, which accounts for approximately 10% of the total J/ψ data sample. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for 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 in the TOF barrel region is 68 ps, while that in the end cap region was

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110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps [10], which benefits 87% of the data used in this analysis.

Simulated data samples produced with a GEANT4-based [11] Monte Carlo (MC) package, including the geometric description of the BESIII detector and the detector response, are used to determine detection efficiencies and to estimate backgrounds. The simulation models the beam energy spread and initial state radiation (ISR) in the e^+e^- annihilations with the generator KKMC [12,13]. All particle decays are modeled with EvtGen [14,15] using BFs either taken from the Particle Data Group (PDG) [16], when available, or

otherwise estimated with LUNDCHARM [17,18]. Final state radiation (FSR) from charged final state particles is incorporated using the PHOTOS package [19].

γ_3, γ_1 , and γ_2 correspond to the radiative photon and the two photons from the π^0 decay. The decay chain of the signal process $J/\psi \rightarrow \gamma_3 \eta', \eta' \rightarrow e^+e^-\omega, \omega \rightarrow \pi^+\pi^-\pi^0$, and $\pi^0 \rightarrow \gamma_1\gamma_2$ containing 5 million events is produced. In this analysis, the simulation of the $\eta' \rightarrow e^+e^-\omega$ process uses the parameters of the TFF, which is parametrized following the approach in Ref. [20]. Within the effective meson theory framework, the squared amplitude for the decay $\eta' \rightarrow e^+e^-\omega$ is given by

$$|\mathcal{A}_{\eta' \rightarrow e^+e^-\omega}|^2 = \frac{2^6 \pi^2 M_{\eta'}^3 \alpha \Gamma_{\eta' \rightarrow \gamma\omega}}{(M_{\eta'}^2 - M_\omega^2)^3} |F(q^2)|^2 \cdot \frac{(M_{\eta'}^2 - q^2 - M_\omega^2)^2 - 4M_\omega^2 q^2}{q^2} (2 - \beta^2 \sin^2 \theta), \quad (1)$$

where $\alpha = 1/137$, $q^2 = (q_{e^+} + q_{e^-})^2$, $q_{e^\pm}$ denotes the four-momentum of $e^\pm$; $\Gamma_{\eta' \rightarrow \gamma\omega}$ denotes the decay width of $\eta' \rightarrow \gamma\omega$ and is quoted from the PDG [16]; $M_{\eta'}$ and M_ω are the masses of the η' and ω , respectively, quoted from the PDG [16]; $\beta = \sqrt{1 - \frac{4M_{e^\pm}^2}{q^2}}$; and θ is the polar angle of $q_{e^\pm}$ in the e^+e^- rest frame with respect to the direction of the flight of the $q_{e^+}q_{e^-}$ in the pseudoscalar rest frame. In the VMD model, the interactions between a virtual photon and hadrons are assumed to be dominated by a superposition of neutral vector meson states. The TFF can be parametrized as [21]

$$F(q^2) = N \sum \frac{g_{\eta'\gamma\omega} m_\omega^2}{2g_{\omega\gamma} m_\omega^2 - q^2 - i\Gamma_\omega m_\omega}, \quad (2)$$

where N is a normalization constant ensuring $F(0) = 1$; m_ω and Γ_ω are the mass and width of ω , and $g_{\eta'\gamma\omega}$ and $g_{\omega\gamma}$ correspond to the respective coupling constants. When there is a single dominant vector meson, the single-pole approximation is often used

$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2}. \quad (3)$$

Here, the single parameter Λ can be experimentally determined from the slope of the TFF, defined as

$$\text{slope} \equiv \left. \frac{dF}{dq^2} \right|_{q^2=0} = \frac{1}{\Lambda^2}. \quad (4)$$

III. EVENT SELECTION AND BACKGROUND ANALYSIS

Charged tracks with a polar angle $|\cos \theta| \leq 0.93$ and passing the interaction point within ± 20 cm along the

beam direction and within ± 2 cm in the plane perpendicular to the beam are accepted. Photon candidates are required to have an energy deposition above 25 MeV in the barrel EMC ($|\cos \theta| < 0.8$) or 50 MeV in the end cap EMC ($0.86 < |\cos \theta| < 0.92$). To exclude showers from charged particles, the opening angle between the shower direction and the charged tracks extrapolated to the EMC must be greater than 10 degrees. A requirement on the EMC timing ($0 \leq t \leq 700$ ns) is used to suppress electronic noise and energy deposits unrelated to the event. The final state of interest is studied through the decay chain $J/\psi \rightarrow \gamma_3 \eta', \eta' \rightarrow e^+e^-\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma_1\gamma_2$, and candidate events are required to have four good charged tracks with a net charge of zero and at least three photons. In the two-body decay of $J/\psi \rightarrow \gamma\eta'$, the radiative photon carries a unique energy of 1.4 GeV. Hence, to suppress background events, the most energetic photon is required to have an energy greater than 1 GeV. The remaining two photons are used to form π^0 candidates. The ω candidates are reconstructed by combining two oppositely charged pion tracks with the π^0 , and η' candidates are formed by combining the pair of e^+e^- with the ω .

The combined information of the specific ionization energy loss (dE/dx) measurements in the MDC and the flight time measured in the TOF is used to form particle identification (PID) confidence levels for the e and π hypotheses. To help improve momentum resolution and suppress background events, the four-constraint (4C) kinematic fit assumes that the total four-momentum of the hypothesized final state $e^+e^-\pi^+\pi^-\gamma\gamma\gamma$ matches the initial four-momentum of the J/ψ . To select candidate events, the combination with the smallest χ_{4C+PID}^2 is retained [5]. Here, $\chi_{4C+PID}^2 = \chi_{4C}^2 + \sum_{i=1}^4 \chi_{PID}^2(i)$ is the sum of the chi-squares from the 4C kinematic fit and PID, where i denotes the index of the four charged tracks used to form an η'

candidate. The combination with $\chi^2_{4C+PID} < 70$ is kept as an $e^+e^-\pi^+\pi^-\gamma\gamma\gamma$ candidate. To reject possible backgrounds with misidentification between e and π , a 4C kinematic fit is performed under the hypotheses $J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\gamma\gamma\gamma$. The events with a χ^2_{4C} value for the signal hypothesis larger than that for the background hypothesis are discarded. The selected photon with maximum energy is taken as the radiative photon. The other two photons are further required to be consistent with a π^0 candidate, $|M(\gamma_1\gamma_2) - M(\pi^0)| < 0.015 \text{ GeV}/c^2$, where $M(\pi^0)$ is the π^0 nominal mass [16].

The primary peaking background comes from $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma$ events, where a photon converts to an e^+e^- pair at the beam pipe or the inner wall of the MDC. Converted photons can be reconstructed from the e^+e^- pairs using the photon conversion finder (PCF) package [22]. $\cos\theta_{eg}$ is defined as the cosine of the angle between the momentum of the e^+e^- pair and the direction from the interaction point to the conversion point of the virtual photon $\gamma^* \rightarrow e^+e^-$. The electron and positron tracks project to two circles in the x - y plane, and Δ_{xy} is the distance between the intersections of these two circles along the line connecting their centers. R_{xy} is the distance from the reconstructed vertex of the e^+e^- pair to the interaction point in the x - y plane. For such conversion backgrounds, the invariant mass of the e^+e^- pair, $M(e^+e^-)$, is expected to be close to zero. However, since the default BESIII tracking algorithm assumes the interaction point as the common origin of all tracks, the directions of tracks originating elsewhere are misreconstructed. As a result, the conversion pair acquires an artificial opening angle, leading to a reconstructed invariant mass larger than the true value. Therefore, the conversion background appears as a pronounced peak at about $0.015 \text{ GeV}/c^2$ in the $M(e^+e^-)$ distribution, as shown in Fig. 1(a). The distribution of the distance from the reconstructed vertex of an e^+e^- pair to the z axis, R_{xy} [22], is shown in Fig. 1(b). The peaks around $R_{xy} = 3.5 \text{ cm}$ and $R_{xy} = 6.5 \text{ cm}$ correspond to the position of the beam pipe and the inner wall of the MDC, respectively. These structures are characteristic of photon conversion backgrounds. Events with $R_{xy} < 2 \text{ cm}$ are retained. For events with $R_{xy} \geq 2 \text{ cm}$, those satisfying both $\cos\theta_{eg} > 0$ and $-1.0 < \Delta_{xy} < 0.8 \text{ cm}$ are excluded as shown in Fig. 2(a), while the others are retained to improve statistics.

To suppress potential background events from the $\pi^0 \rightarrow \gamma e^+e^-$ decay, we require events to satisfy $|M(\gamma_1\gamma_2) - M(\pi^0)| < |M(\gamma_1 e^+e^-) - M(\pi^0)|$, $|M(\gamma_1\gamma_2) - M(\pi^0)| < |M(\gamma_2 e^+e^-) - M(\pi^0)|$. Additionally, events with $0.52 < M(\gamma_3 e^+e^-) < 0.58 \text{ GeV}/c^2$ are vetoed to suppress the background from the $\eta \rightarrow \gamma e^+e^-$ process. The distributions of the invariant masses of $\gamma_1 e^+e^-$, $\gamma_2 e^+e^-$ and $\gamma_3 e^+e^-$ are shown in Fig. 3. To further suppress the potential background from $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \pi^+\pi^-\eta, \eta \rightarrow \gamma e^+e^-$, events

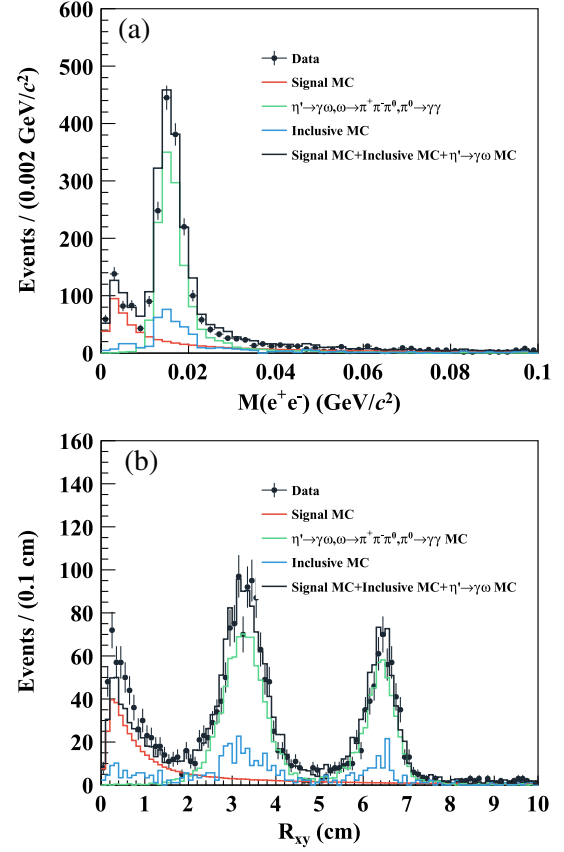


FIG. 1. The distributions of (a) $M(e^+e^-)$ and (b) the transverse distance R_{xy} of the e^+e^- vertex from the interaction point. The dots with error bars represent the data, the red line is the simulated signal MC shape, the green line is the $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma$ MC shape, the blue line denotes the background from the inclusive MC sample, and the black line is the sum of all components.

with $M(\gamma_1 e^+e^-) > 0.5 \text{ GeV}/c^2$ are rejected, as shown in Fig. 3(a).

The distribution of $M(\pi^+\pi^-\pi^0 e^+e^-)$ versus $M(\pi^+\pi^-\pi^0)$ is shown in Fig. 4(a), where a significant background contribution is observed, the dominant contribution comes from the decay processes $\eta' \rightarrow \eta\pi^+\pi^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$, as indicated in Fig. 4(b). To suppress this background, the invariant mass $M(\pi^+\pi^-\pi^0 e^+e^-)$ is required to be between $0.90 \text{ GeV}/c^2$ and $1.02 \text{ GeV}/c^2$.

Possible backgrounds are studied with a MC sample containing inclusive J/ψ decays. In this analysis, the main backgrounds are the inclusive MC sample, the peaking background from $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma$, and the background from $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma e^+e^-$ that is not included in the inclusive MC sample.

The same selection criteria are applied to the inclusive MC sample of 10 billion J/ψ events. No significant peaking background is observed in the distribution of $M(\pi^+\pi^-\pi^0 e^+e^-) - M(\pi^+\pi^-\pi^0)$.

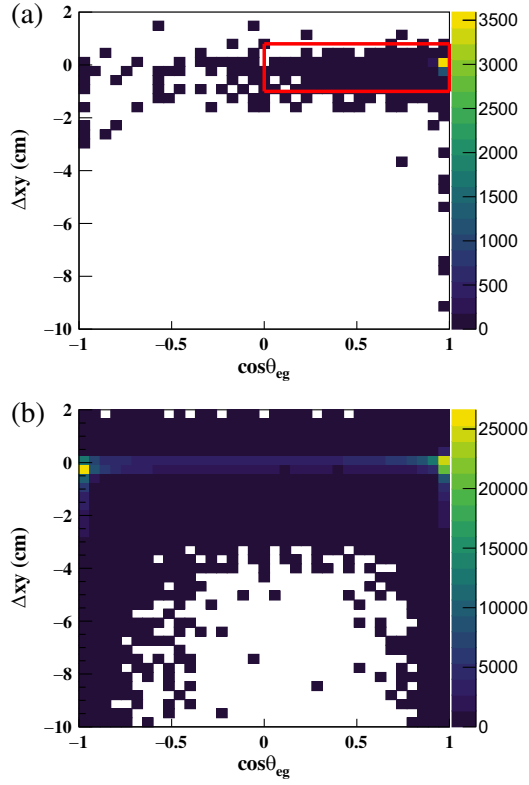


FIG. 2. The distributions of Δ_{xy} versus $\cos\theta_{eg}$ for the MC events of (a) the background $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma$ and (b) the signal process, where $R_{xy} > 0$. Events located in the red rectangle are rejected.

An off-resonance data sample of 167.06 pb^{-1} taken at $\sqrt{s} = 3.08 \text{ GeV}$ is employed to estimate the possible background contribution from the continuum process. After applying the same selection criteria, no event survives. Therefore, the continuum background is neglected.

IV. BRANCHING FRACTION MEASUREMENT

To further exclude the impact of peaking backgrounds on the signal extraction, the number of signal events is determined by fitting the distribution of $M(\pi^+\pi^-\pi^0 e^+e^-) - M(\pi^+\pi^-\pi^0)$, which effectively suppress η' or ω peaking backgrounds by rendering them smoother. To extract the signal yield of $\eta' \rightarrow e^+e^-\omega$, an unbinned maximum-likelihood fit is performed to the distribution of $M(\pi^+\pi^-\pi^0 e^+e^-) - M(\pi^+\pi^-\pi^0)$. The signal probability density function is modeled using the shape obtained from the signal MC simulation. Since the decay $\eta' \rightarrow \gamma\omega$ is not included in the inclusive MC sample, exclusive MC samples are generated for $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma e^+e^-$. Accordingly, the nonpeaking background is described by the combined shape from the inclusive MC sample and the exclusive MC sample of $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma e^+e^-$. The peaking background from photon

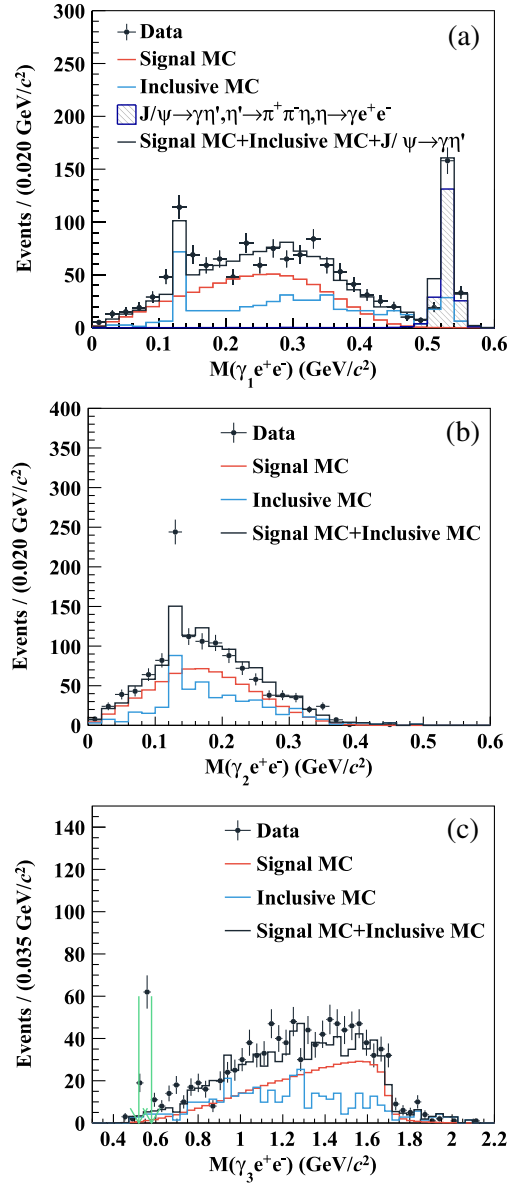


FIG. 3. The distributions of (a) $M(\gamma_1 e^+ e^-)$, (b) $M(\gamma_2 e^+ e^-)$ and (c) $M(\gamma_3 e^+ e^-)$. The dots with error bars represent data, the red line represents the signal MC sample, the blue line represents the inclusive MC sample, and the gray histogram represents the background from $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \pi^+\pi^-\eta, \eta \rightarrow \gamma e^+ e^-$, and the black line is the sum of all components. The background region for $\eta \rightarrow \gamma e^+ e^-$ is indicated by the green arrows in panel (c).

conversion events in $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma$ process is modeled using the corresponding MC shape. The fit yields $N_{\text{sig}} = 609.1 \pm 27.7$ signal events, as shown in Fig. 5. The BF of $\eta' \rightarrow e^+e^-\omega$ is determined as

$$\mathcal{B}(\eta' \rightarrow e^+e^-\omega) = \frac{N_{\text{sig}}}{N_{J/\psi} \cdot \mathcal{B}_{\text{sub}} \cdot \epsilon}, \quad (5)$$

where $N_{J/\psi}$ is the total number of J/ψ events in data, $\epsilon = 7.30\%$ is the detection efficiency, and $\mathcal{B}_{\text{sub}}$ denotes the

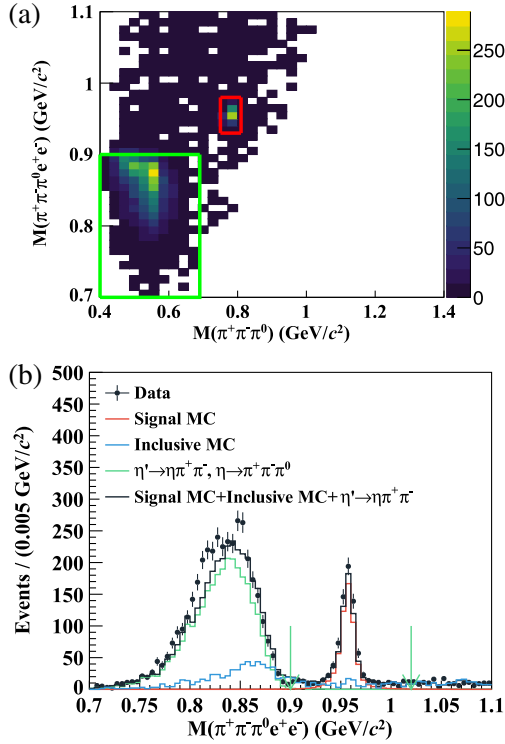


FIG. 4. (a) The distribution of $M(\pi^+\pi^-\pi^0e^+e^-)$ versus $M(\pi^+\pi^-\pi^0)$ for data. The region for the background from $\eta' \rightarrow \eta\pi^+\pi^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$ is indicated by the green square and the signal region is indicated by the red square. (b) The distribution of $M(\pi^+\pi^-\pi^0e^+e^-)$. The dots with error bars represent data, the red line represents the signal MC sample, the blue line represents the inclusive MC sample, and the green line represents the background from $\eta' \rightarrow \eta\pi^+\pi^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$, and the black line is the sum of all components. The η' signal region is shown in the green arrows.

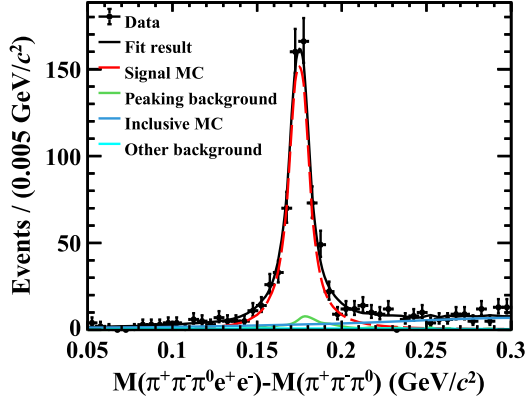


FIG. 5. The fit to the distribution of $M(\pi^+\pi^-\pi^0e^+e^-) - M(\pi^+\pi^-\pi^0)$. The dots with error bars represent the data, the black line represents the total fit result and the red line represents the signal MC sample, the green line represents the peaking background from $J/\psi \rightarrow \gamma\eta'$, $\eta' \rightarrow \gamma\omega$, $\omega \rightarrow \pi^+\pi^-\pi^0$, $\pi^0 \rightarrow \gamma\gamma$, the blue line represents the background from the inclusive MC sample and the cyan line represents the background from $J/\psi \rightarrow \gamma\eta'$, $\eta' \rightarrow \gamma\omega$, $\omega \rightarrow \pi^+\pi^-\pi^0$, $\pi^0 \rightarrow \gamma e^+e^-$.

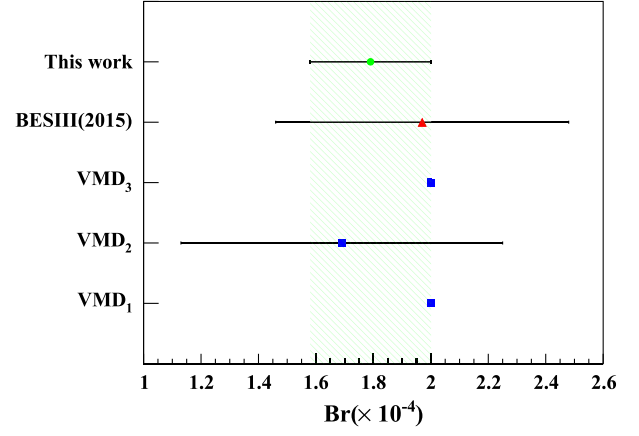


FIG. 6. The BF's of the $\eta' \rightarrow e^+e^-\omega$ from different theoretical predictions [4,23,24] (blue squares), the previous experiments [5] (red triangle), and the results of this work (green squares and green dot).

product BF's $\mathcal{B}(J/\psi \rightarrow \gamma\eta') \cdot \mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0) \cdot \mathcal{B}(\pi^0 \rightarrow \gamma\gamma)$, with BF's quoted from the PDG [16]. The BF of $\eta' \rightarrow e^+e^-\omega$ is calculated to be $(1.79 \pm 0.09) \times 10^{-4}$, where the uncertainty is statistical only. This result is consistent with the previous measurement and theoretical predictions, as shown in Fig. 6. Furthermore, this study enhances the experimental precision by a factor of 2.7 relative to the PDG estimate.

V. TRANSITION FORM FACTOR MEASUREMENT

To extract the TFF, a cleaner data sample is required. The signal region is further refined as $M(\pi^+\pi^-\pi^0e^+e^-) \in [0.94, 0.98] \text{ GeV}/c^2$ and $M(\pi^+\pi^-\pi^0e^+e^-) - M(\pi^+\pi^-\pi^0) \in [0.14, 0.20] \text{ GeV}/c^2$, which enhances the signal purity. With all the selection criteria applied, 586 events are retained for the TFF analysis. The distribution of $M(\pi^+\pi^-\pi^0e^+e^-)$ versus $M(\pi^+\pi^-\pi^0e^+e^-) - M(\pi^+\pi^-\pi^0)$ is shown in Fig. 7. Background contributions are estimated using the inclusive and exclusive MC samples.

The TFF of the η' is extracted by performing an unbinned maximum-likelihood fit on the e^+e^- invariant mass spectrum of the selected $\eta' \rightarrow \omega e^+e^-$ candidates. The likelihood function is defined as

$$\mathcal{L} = \prod_{i=1}^N P(\xi_i), \quad (6)$$

where N is the number of observed events, and ξ_i represents the set of four-momenta of the final-state particle for the i th event. The probability $[P(\xi_i)]$ for observing the i th event is given by

$$P(\xi_i) = \frac{\sigma(\xi_i)\epsilon(\xi_i)}{\int d\xi \sigma(\xi)\epsilon(\xi)}, \quad (7)$$

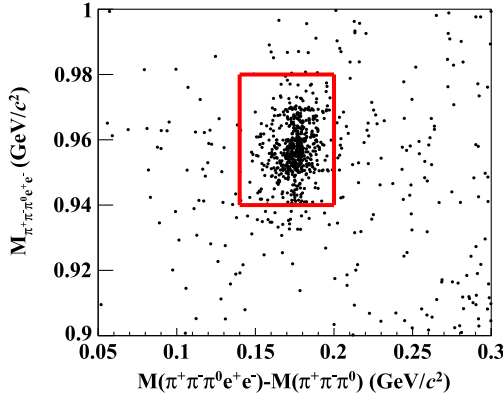


FIG. 7. The distribution of $M(\pi^+\pi^-\pi^0e^+e^-)$ versus $M(\pi^+\pi^-\pi^0e^+e^-) - M(\pi^+\pi^-\pi^0)$. The signal region for the TFF measurement is shown in the red square.

where $\sigma(\xi_i) \equiv (d\sigma/d\phi)_i$ represents the differential cross section, $\epsilon(\xi_i)$ the detection efficiency, and $\int d\xi \sigma(\xi)\epsilon(\xi)$ represents the measured total cross section.

In this analysis, the squared amplitude for the decay $\eta' \rightarrow e^+e^-\omega$ is given by Eq. (1).

In the log-likelihood calculation, background events are assigned negative weights, i.e.

$$-\ln \mathcal{L} = W[-(\ln \mathcal{L}_{\text{data}} - W_j \cdot \ln \mathcal{L}_{\text{bkg}})], \quad (8)$$

where i runs over all accepted data events, and j runs over the considered background events. The estimated number of background events, listed in Table I, are fixed according to their normalization to the data luminosity. To obtain an unbiased uncertainty, a normalization factor derived from Ref. [25] is defined as

$$W = \frac{N_{\text{data}} - \sum_j N_{\text{bkg}}^j W_j}{N_{\text{data}} + \sum_j N_{\text{bkg}}^j W_j^2}, \quad (9)$$

where N_{data} and N_{bkg}^j are the numbers of data events and the j -th background component, respectively, and W_j is the corresponding background weight.

The fit yields $\Lambda^{-1} = (2.92 \pm 0.83) \text{ GeV}^{-1}$, where the uncertainty is statistical only. A comparison between the fit results and the e^+e^- invariant mass distribution of the data is presented in Fig. 8.

TABLE I. The estimated numbers of background events N_{bkg} for different background components.

Component	N_{bkg}
$\eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma$	32.8
$\eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma e^+e^-$	8.4
Inclusive MC	18.0
Total	59.2

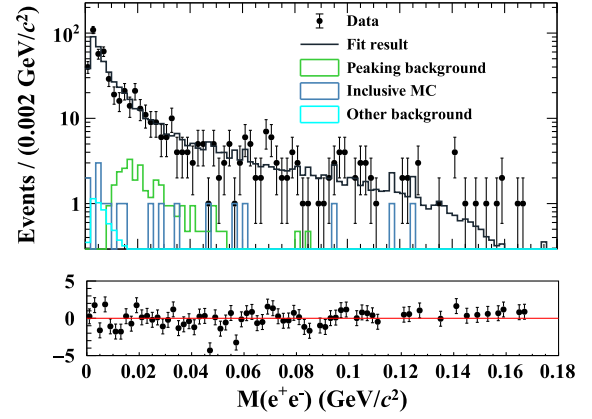


FIG. 8. The e^+e^- invariant mass distribution and the fit result of the TFF. The dots with error bars represent the data, the black line represents the total fit result, the green histogram represents the peaking background from $J/\psi \rightarrow \gamma\eta'$, $\eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma$, the blue histogram represents the background from the inclusive MC sample and the cyan histogram represents the background from $J/\psi \rightarrow \gamma\eta', \eta' \rightarrow \gamma\omega, \omega \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma e^+e^-$.

VI. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties of the TFF measurement originate mainly from the MDC tracking and PID of charged particles, the photon detection, the kinematic fit, the background suppression criteria, and the estimation of background contamination. The BF measurement shares these uncertainties and suffers from additional effects from the mass fit range, the total number of J/ψ events, and the external BFs from the PDG [16]. All systematic uncertainties are assumed to be independent and added in quadrature. The individual contributions are summarized in Table II and are described in detail below.

TABLE II. Summary of the systematic uncertainties for BF and TFF measurements (in percent).

Source	BF	TFF
MDC tracking	5.7	0.7
PID	1.1	0.3
Photon detection	1.2	0.3
Kinematic fit	0.6	1.0
Photon conversion veto	0.6	1.4
π^0 mass window	0.6	3.1
η' mass window	1.1	3.1
$M(\gamma_1 e^+e^-)$ range	0.1	0.3
$M(\gamma_3 e^+e^-)$ range	0.6	0.7
Peaking background	1.1	1.0
Nonpeaking background	0.6	0.7
Fit range	2.2	...
Number of J/ψ events	0.4	...
Intermediate decays	1.4	...
Total	6.8	5.0

- (i) MDC tracking and PID: The efficiency differences of data and MC simulation for pion MDC tracking and PID are studied using the control sample of $J/\psi \rightarrow \pi^+\pi^-\pi^0$ [26]. The tracking efficiencies for electrons are obtained with the control sample of radiative Bhabha scattering $e^+e^- \rightarrow e^+e^-\Gamma_{\text{ISR}}$ [27] (including $J/\psi \rightarrow e^+e^-\gamma_{\text{FSR}}$) at $\sqrt{s} = 3.097$ GeV. The differences between data and MC simulation are parametrized as the momentum- and polar-angle-dependent correction factors, which are applied according to the event weights in the signal MC sample. The weighted uncertainties are taken as the systematic uncertainties.
- (ii) Photon detection: The systematic uncertainty associated with photon reconstruction is obtained with the control sample of $e^+e^- \rightarrow \mu^+\mu^-\gamma_{\text{ISR}}$. The photon detection efficiencies are determined as two-dimensional functions of the photon energy and polar angle. The uncertainty associated with the energy scale calibration is neglected. For the TFF measurement, the efficiency of signal MC simulation is corrected by the ratio $\epsilon_{\text{data}}/\epsilon_{\text{MC}}$, where ϵ_{data} and ϵ_{MC} are the 2D efficiency obtained from the control sample, respectively. The resulting variation in the extracted TFF is assigned as the associated systematic uncertainty. For the BF measurement, the systematic uncertainties are weighted according to the photon energy and angular distributions in data and MC simulation, and are taken as the corresponding uncertainties.
- (iii) Kinematic fit: To investigate the systematic uncertainty associated with the kinematic fit, the track helix parameter correction method [28] is used. The difference in detection efficiencies between samples with and without the helix parameter correction is taken as the systematic uncertainty.
- (iv) Photon conversion veto: The systematic uncertainty due to the photon conversion veto is estimated by varying the nominal criterion to $R_{xy} > 1.9$ cm or $R_{xy} > 2.1$ cm. The resulting change in the final results is assigned as the associated uncertainty.
- (v) π^0 or η' mass window: The systematic uncertainty arising from the π^0 or η' mass window is determined by varying the corresponding mass window by one standard deviation. The resulting differences of the BF and the TFF are taken as the uncertainty.
- (vi) $M(\gamma_{1/3}e^+e^-)$ range: The uncertainty arising from the $M(\gamma_{1/3}e^+e^-)$ range is determined by changing the $M(\gamma_{1/3}e^+e^-)$ range by $0.02 \text{ GeV}/c^2$ and $0.008 \text{ GeV}/c^2$, respectively. The corresponding changes in the BF and the TFF are taken as the systematic uncertainties.
- (vii) Peaking background: The peaking background contribution is estimated using the BFs of $J/\psi \rightarrow \gamma\eta'$, $\eta' \rightarrow \gamma\omega$, $\omega \rightarrow \pi^+\pi^-\pi^0$, $\pi^0 \rightarrow \gamma\gamma$ quoted from the PDG [16]. By varying the BFs within their $\pm 1\sigma$ of uncertainties, the change in the final result is taken as the corresponding uncertainty.
- (viii) Nonpeaking background: The nonpeaking background contribution is estimated using the BFs of $J/\psi \rightarrow \gamma\eta'$, $\eta' \rightarrow \gamma\omega$, $\omega \rightarrow \pi^+\pi^-\pi^0$, $\pi^0 \rightarrow \gamma e^+e^-$ quoted from the PDG [16]. The number of background events is varied by $\pm 1\sigma$, and the resulting change in the final results is taken as the systematic uncertainty.
- (ix) Fit range: The uncertainty arising from the fit range in the BF is determined to be 2.2% by changing the fit range by $\pm 0.02 \text{ GeV}/c^2$.
- (x) Number of J/ψ events: The number of J/ψ events is determined to be $(10087 \pm 44) \times 10^6$ from the inclusive hadron events, corresponding to a relative uncertainty of 0.4% [6].
- (xi) Intermediate decay: The uncertainties of the quoted BFs for the intermediate decays $J/\psi \rightarrow \gamma\eta'$, $\omega\pi^+\pi^-\pi^0$, and $\pi^0 \rightarrow \gamma\gamma$ are taken from the PDG [16].

VII. SUMMARY

The decay $\eta' \rightarrow e^+e^-\omega$ is studied based on a sample of $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector. The BF is determined to be $\mathcal{B}(\eta' \rightarrow e^+e^-\omega) = (1.79 \pm 0.09(\text{stat}) \pm 0.12(\text{syst})) \times 10^{-4}$. This result is consistent with the previous measurement and theoretical predictions, and improves the experimental precision by a factor of 2.7.

The transition form factor parameter Λ^{-1} of $\eta' \rightarrow e^+e^-\omega$ is measured for the first time to be $(2.92 \pm 0.83(\text{stat}) \pm 0.15(\text{syst})) \text{ GeV}^{-1}$. This parameter provides important input for phenomenological studies of η' electromagnetic transitions. Since the present measurement is limited by statistics, a larger η' data sample is needed to further improve the precision in the future.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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