

Observation of $\psi(3686) \rightarrow \gamma\eta(1405)$ via $\eta(1405) \rightarrow f_0(980)\pi^0$

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The decay $\psi(3686) \rightarrow \gamma\pi^+\pi^-\pi^0$ is studied using a sample of $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector. The decay $\eta(1405) \rightarrow \pi^+\pi^-\pi^0$ is observed for the first time in $\psi(3686)$ decays via the intermediate state $f_0(980)$ and the product branching fraction $\mathcal{B}(\psi(3686) \rightarrow \gamma\eta(1405)) \times \mathcal{B}(\eta(1405) \rightarrow f_0(980)\pi^0) \times \mathcal{B}(f_0(980) \rightarrow \pi^+\pi^-)$ is determined to be $(3.77 \pm 0.43 \pm 0.30) \times 10^{-7}$, where the first uncertainty is statistical and the second is systematic. The branching fraction of isospin-violating decay $\psi(3686) \rightarrow \gamma f_1(1285) \rightarrow \gamma f_0(980)\pi^0 \rightarrow \gamma\pi^+\pi^-\pi^0$ is determined to be $(7.36 \pm 2.25 \pm 2.36) \times 10^{-8}$ with statistical significance of 2.9σ . Since no η_c signal is evident in either the $\pi^+\pi^-\pi^0$ or $f_0(980)\pi^0$ mass spectrum, upper limits are set to be $\mathcal{B}(\psi(3686) \rightarrow \gamma\eta_c) \times \mathcal{B}(\eta_c \rightarrow \pi^+\pi^-\pi^0) < 3.09 \times 10^{-7}$ and $\mathcal{B}(\psi(3686) \rightarrow \gamma\eta_c) \times \mathcal{B}(\eta_c \rightarrow f_0(980)\pi^0) \times \mathcal{B}(f_0(980) \rightarrow \pi^+\pi^-) < 7.97 \times 10^{-8}$ at 90% confidence level, respectively.

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I. INTRODUCTION

A state near $1440 \text{ MeV}/c^2$, first discovered in $p\bar{p}$ annihilation at rest decaying to $\eta\pi^+\pi^-$ [1], was subsequently shown by experiments [2,3] to consist of two different pseudoscalar states; the $\eta(1405)$ and the $\eta(1475)$. The former couples strongly to $a_0(980)\pi$ and $K\bar{K}\pi$, while the latter mainly decays to $K^*\bar{K}$. Extensive theoretical and experimental efforts have been devoted to understanding the nature of the $\eta(1405)$ and $\eta(1475)$ [4–8].

The isospin violating process $\eta(1405) \rightarrow f_0(980)\pi^0$ was first observed in J/ψ radiative decays [9], with the ratio $\frac{\mathcal{B}(\eta(1405) \rightarrow f_0(980)\pi^0)}{\mathcal{B}(\eta(1405) \rightarrow a_0(980)\pi^0)} = (17.9 \pm 4.2)\%$, which is one order of magnitude larger than the most recent measurement of the $a_0(980) - f_0(980)$ mixing intensity (0.4%) [10]. To account for this unexpectedly large isospin violation and the anomalously narrow width of the $f_0(980)$, Wu *et al.* proposed that a triangle singularity mechanism could play a crucial role in this process [11]. Further theoretical and experimental studies are needed for a better understanding of the underlying dynamics.

The axial vector meson $f_1(1285)$ could be interpreted as a $K^*\bar{K}$ molecule [12] or a tetraquark state [13], however, its nature is still need to be understood. The isospin symmetry breaking decay $f_1(1285) \rightarrow 3\pi$ can proceed through

several different mechanisms, with the direct decay $f_1(1285) \rightarrow 3\pi$ expected to be small. One main mechanism is the $f_1(1285) - a_1(1260)$ mixing by assuming that the universality can be extended to the axial meson sector [14]. Another is the $f_1(1285) \rightarrow f_0(980)\pi$ decays through $f_1(1285) \rightarrow a_0(980)\pi$ via $a_0(980) - f_0(980)$ mixing. VES Collaboration [15] first observed the $f_1(1285) \rightarrow \pi^+\pi^-\pi^0$ and conclude that the decay caused presumably by the “ $a_0(980) - f_0(980)$ ” mixing, but extra decay mechanisms are necessary. In BESIII previous analysis of $J/\psi \rightarrow \phi\pi^0 f_0(980)$ with 1.3 billion J/ψ events [16], the evidence of $f_1(1285)$ is found in the $f_0(980)\pi^0$ mass spectrum.

A previous search for the decay $\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$ was performed by BESIII using a data sample of $(447.9 \pm 2.9) \times 10^6$ $\psi(3686)$ events and the upper limit (UL) at the 90% confidence level (CL) was set to be $\mathcal{B}^{\text{UL}}(\psi(3686) \rightarrow \gamma\eta(1405) \rightarrow \gamma f_0(980)\pi^0 \rightarrow \gamma\pi^+\pi^-\pi^0) = 5.0 \times 10^{-7}$ [17]. Currently, BESIII has accumulated $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events [18], which is approximately five times larger than the previous dataset, and allows further investigation of the decay $\eta(1405)/f_1(1285) \rightarrow f_0(980)\pi^0$.

In addition, according to perturbative quantum chromodynamics (QCD), the ratio of the branching fractions of $\psi(3686)$ and J/ψ decaying to the same hadronic final state is predicted to be

$$Q = \frac{\mathcal{B}_{\psi(3686) \rightarrow h}}{\mathcal{B}_{J/\psi \rightarrow h}} = \frac{\mathcal{B}_{\psi(3686) \rightarrow l^+l^-}}{\mathcal{B}_{J/\psi \rightarrow l^+l^-}} \approx (12.4 \pm 0.4)\%, \quad (1)$$

commonly referred to as the “12% rule” [19–21], which works reasonably well for many decay modes. However,

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significant violations of this rule have been observed by subsequent experiments [22,23], particularly in the $\rho\pi$ final state. Recent reviews [24–26] indicate that current theoretical explanations remain unsatisfactory. Whether or not the 12% rule also holds for radiative decays [17] is another motivation to study the decay $\psi(3686) \rightarrow \gamma\pi^+\pi^-\pi^0$.

The same data sample is also used to search for the isospin-violating process $\eta_c \rightarrow \pi^+\pi^-\pi^0$, which provides an important test of isospin symmetry. The η_c , the lowest-lying $c\bar{c}$ pseudoscalar state, has attracted considerable theoretical and experimental attention since its discovery [27]. It decays primarily via $c\bar{c}$ annihilation into two gluons and is expected to have numerous hadronic decay modes into two- or three-body hadronic final states, and many of them have been measured [28]. Using a subsample of $\psi(3686)$ events, BESIII previously set an UL of $\mathcal{B}(\eta_c \rightarrow \pi^+\pi^-\pi^0) < 4.0 \times 10^{-4}$ at the 90% CL [17], which can be improved significantly with the higher-statistics sample used in this analysis.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [29] records symmetric e^+e^- collisions provided by the BEPCII storage ring [30] 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 $\sqrt{s} = 3.773 \text{ GeV}$. BESIII has collected large data samples in this energy region [31–33]. 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 time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate chamber muon 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 plastic scintillator TOF barrel region is 68 ps, while that in the end cap region was 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps, which benefits about 83% of the data used in this analysis [34–36].

Monte Carlo (MC) simulated data samples produced with a GEANT4-based [37] software package, which includes 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 [38,39]. The inclusive MC sample includes the production

of the $\psi(3686)$ resonance, the ISR production of the J/ψ , and the continuum processes incorporated in KKMC [38,39].

All particle decays are modeled with EVTGEN [40,41] using branching fractions either taken from the Particle Data Group (PDG) [28], when available, or otherwise estimated with LUNDCHARM [42,43]. Final state radiation from charged final state particles is incorporated using the PHOTOS package [44].

Dedicated MC samples for the processes $\psi(3686) \rightarrow \gamma\eta(1405), \eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, $\psi(3686) \rightarrow \gamma\eta_c, \eta_c \rightarrow \pi^+\pi^-\pi^0$ and $\psi(3686) \rightarrow \gamma\eta_c, \eta_c \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$ are generated to optimize event selection criteria and to determine the detection efficiencies.

III. EVENT SELECTION AND DATA ANALYSIS

For the selection of the process $\psi(3686) \rightarrow \gamma\pi^+\pi^-\pi^0$ with $\pi^0 \rightarrow \gamma\gamma$, events with two oppositely charged pion tracks and at least three photons are required. Charged tracks detected in the MDC are required to be within $|\cos\theta| < 0.93$, where θ is the polar angle relative to the MDC's symmetry axis (z -axis). Each track must also originate within $|V_z| < 10 \text{ cm}$ and $|V_{xy}| < 1 \text{ cm}$ of the interaction point (IP).

Particle identification (PID) combines measurements of dE/dx and TOF information to form likelihoods $\mathcal{L}(h)$ for hypotheses $h = e, \pi$. $\mathcal{L}(\pi) > \mathcal{L}(e)$ is required to suppress the misidentification of electrons as pions.

Photon candidates are identified using isolated EMC showers with energy deposits exceeding 25 MeV (barrel, $|\cos\theta| < 0.80$) or 50 MeV (end cap, $0.86 < |\cos\theta| < 0.92$). To exclude track-induced backgrounds, showers must be separated from any charged track (measured from the IP) by at least 10 degrees. The EMC time must be within $[0, 700] \text{ ns}$ of the event start time to suppress electronic noise and showers unrelated to the event.

A four-constraint (4C) kinematic fit imposing energy-momentum conservation is applied to each $\pi^+\pi^-\gamma\gamma\gamma$ combination. If more than three photon candidates are present in an event, the combination with the smallest $\chi^2_{4C}(3\gamma)$ is retained, and the $\chi^2_{4C}(3\gamma)$ is required to be less than 20. In order to reduce backgrounds from processes with two or four photons, additional 4C kinematic fits with 2- and 4-photon hypotheses must yield χ^2 values greater than $\chi^2_{4C}(3\gamma)$.

Among the three selected photons, the $\gamma\gamma$ pair with the invariant mass closest to m_{π^0} and satisfying $|M(\gamma\gamma) - m_{\pi^0}| < 0.025 \text{ GeV}/c^2$ is taken as the π^0 candidate, where m_{π^0} is the nominal mass of the π^0 from the PDG [28]. The remaining photon is assigned to be the radiative one. To remove backgrounds stemming from $\eta \rightarrow \gamma\gamma$ decays, the invariant mass of any $\gamma\gamma$ pair is required to be outside the η region $(0.52, 0.57) \text{ GeV}/c^2$.

After applying the above mentioned selection criteria, there are still some residual background events from the processes $\psi(3686) \rightarrow \pi^0 J/\psi (J/\psi \rightarrow \pi^+ \pi^- \gamma)$, $\psi(3686) \rightarrow \gamma \chi_{cJ} (\chi_{cJ} \rightarrow \gamma J/\psi, J/\psi \rightarrow \pi^+ \pi^- \gamma)$ and $\psi(3686) \rightarrow \pi^+ \pi^- \omega (\gamma \pi^0)$, which are removed by requiring $|M(\pi^+ \pi^- \gamma) - m_{J/\psi}| > 0.05 \text{ GeV}/c^2$ and $|M(\pi^0 \gamma) - m_\omega| > 0.04 \text{ GeV}/c^2$, respectively. The nominal masses of the J/ψ and ω , $m_{J/\psi}$ and m_ω , are taken from the PDG [28]. In addition, an inclusive MC sample of 2.7 billion $\psi(3686)$ events is used to investigate other potential backgrounds, which will be discussed in detail later.

A. Analysis of $\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+ \pi^- \pi^0$

After requiring the invariant mass of the $\pi^+ \pi^- \pi^0$ system $[M(\pi^+ \pi^- \pi^0)]$ to be in the $\eta(1405)$ mass region $[(1.13, 1.93) \text{ GeV}/c^2]$, the $\pi^+ \pi^-$ invariant mass ($M(\pi^+ \pi^-)$) is shown in Fig. 1(a), where a clear $f_0(980)$ signal can be observed. An unbinned maximum likelihood fit is performed to the $M(\pi^+ \pi^-)$ distribution. In the fit, the $f_0(980)$ signal is modeled with a Breit-Wigner function, with the mass and width determined to be $M = 986.07 \pm 1.66 \text{ MeV}/c^2$ and $\Gamma = 21.23 \pm 5.68 \text{ MeV}/c^2$, respectively. Furthermore, the smooth backgrounds, mainly from $\psi(3686) \rightarrow \gamma \chi_{cJ} (J=0,1,2)$ with $\chi_{cJ} \rightarrow \pi^+ \pi^- \pi^0$ and $\psi(3686) \rightarrow \pi^+ \pi^- \pi^0 \pi^0$, are described using a third-order Chebychev polynomial. A further requirement of $0.96 \text{ GeV}/c^2 < M(\pi^+ \pi^-) < 1.02 \text{ GeV}/c^2$ is used to select $f_0(980)$ candidates.

After applying the above selection criteria, the $M(\pi^+ \pi^- \pi^0)$ distribution in the region of interest $(1.13, 1.93) \text{ GeV}/c^2$ is shown in Fig. 1(b), exhibiting a distinct $\eta(1405)$ signal. To determine the $\eta(1405)$ signal yield, an unbinned maximum likelihood fit is performed to the $M(\pi^+ \pi^- \pi^0)$ distribution. In the fit, the $\eta(1405)$ and $f_1(1285)$ signals are modeled using the MC-simulated shape convolved with a Gaussian function with floating parameters. The background is described by the $f_0(980)$ sidebands, $0.90 \text{ GeV}/c^2 < M(\pi^+ \pi^-) < 0.94 \text{ GeV}/c^2$ and $1.04 \text{ GeV}/c^2 < M(\pi^+ \pi^-) < 1.08 \text{ GeV}/c^2$, and the yield is fixed to the value estimated from the $M(\pi^+ \pi^-)$ fit result. Assuming no interference, the fit result is shown in Fig. 1(b), and the $\eta(1405)$ signal yield is determined to be $N_{\text{signal}} = 195.33 \pm 22.43$, with a statistical significance of 10.9σ , which is calculated from the likelihood difference ($\Delta \ln L = 64.77$) and the change in degrees of freedom ($\Delta \text{ndf} = 3$) between fits with and without the $\eta(1405)$ signal component. The branching fraction is calculated as

$$\mathcal{B}(\psi(3686) \rightarrow \gamma \eta(1405) \rightarrow \gamma f_0(980) \pi^0 \rightarrow \gamma \pi^+ \pi^- \pi^0) = \frac{N_{\text{signal}}}{N_{\psi(3686)} \cdot \mathcal{B}(\pi^0 \rightarrow \gamma \gamma) \cdot \epsilon} = (3.77 \pm 0.43) \times 10^{-7}, \quad (2)$$

where the uncertainty is only statistical. Here $N_{\psi(3686)} = (2712.4 \pm 14.3) \times 10^6$ is the total number of $\psi(3686)$

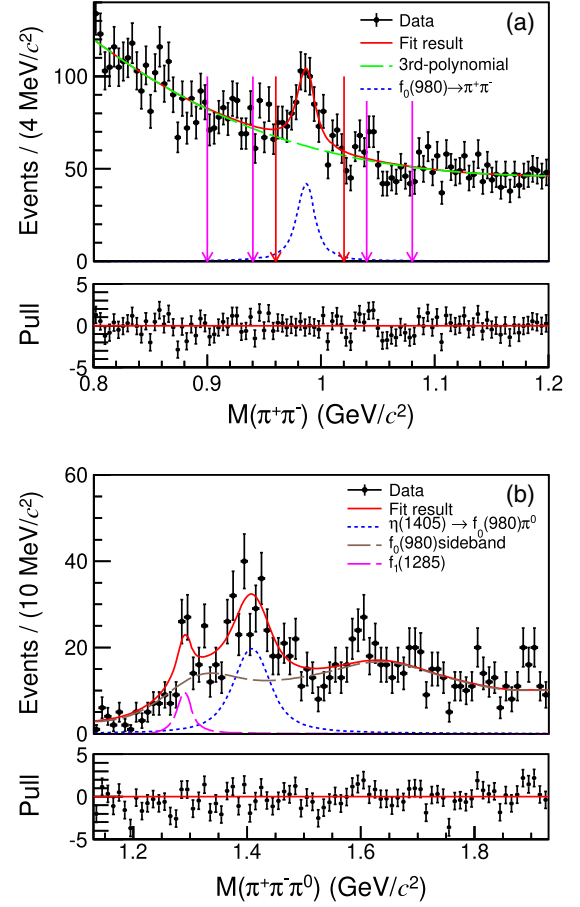


FIG. 1. (a) The $M(\pi^+ \pi^-)$ distribution. The red arrows and pink arrows show the $f_0(980)$ signal region and the sideband regions, respectively. (b) The $M(\pi^+ \pi^- \pi^0)$ distributions after selecting events in the $f_0(980)$ mass window. The black dots with error bars are data, the red solid line is the total fit result, the blue dashed line is the $\eta(1405)$ signal, the brown long-dashed line is the $f_0(980)$ sideband, and the pink long-dashed line is the $f_1(1285)$ peak.

events [18], $\mathcal{B}(\pi^0 \rightarrow \gamma \gamma) = (98.823 \pm 0.034)\%$ is the branching fraction of $\pi^0 \rightarrow \gamma \gamma$ from the PDG [28], and $\epsilon = 19.33\%$ is the detection efficiency estimated from dedicated MC simulation. The yield of $f_1(1285)$ is 37.7 ± 11.5 and the selection efficiency is 19.11% estimated with a phase space distributed MC simulation. The branching fraction is measured to be $\mathcal{B}(\psi(3686) \rightarrow \gamma f_1(1285) \rightarrow \gamma f_0(980) \pi^0 \rightarrow \gamma \pi^+ \pi^- \pi^0) = (7.36 \pm 2.25) \times 10^{-8}$, with statistical uncertainties only. The statistical significance is only 2.9σ .

B. Search for $\psi(3686) \rightarrow \gamma \eta_c, \eta_c \rightarrow \pi^+ \pi^- \pi^0$

To suppress additional background from $\psi(3686) \rightarrow \omega \pi^0$ with $\omega \rightarrow \pi^+ \pi^- \pi^0$ in the η_c mass region, a requirement of $0.7 \text{ GeV}/c^2 < M(\pi^+ \pi^- \gamma) < 0.8 \text{ GeV}/c^2$ is applied. The $M(\pi^+ \pi^- \pi^0)$ distribution in the mass region $(2.8, 3.18) \text{ GeV}/c^2$ is shown in Fig. 2(a). There is no η_c

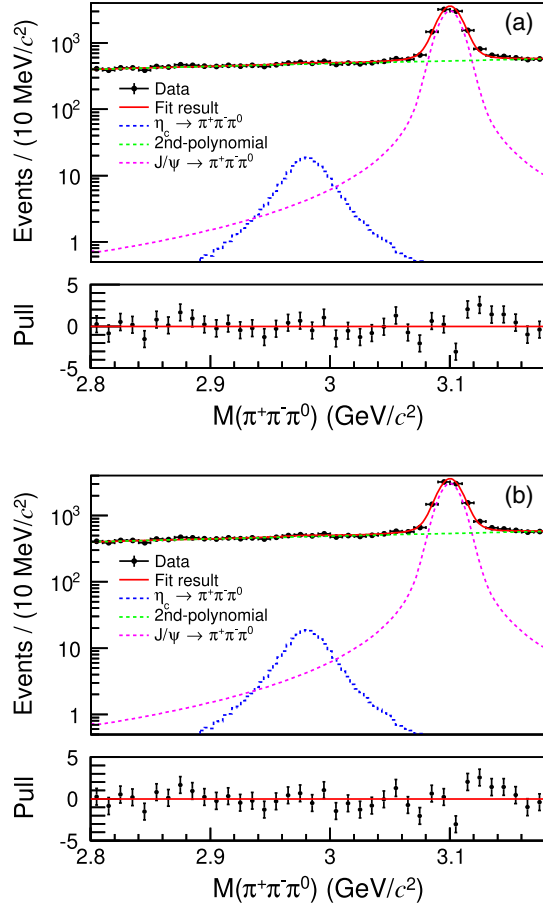


FIG. 2. Fits to the $M(\pi^+\pi^-\pi^0)$ distributions in the η_c mass region (a) without and (b) with the requirement that $M(\pi^+\pi^-)$ is within the $f_0(980)$ mass window. The black dots with error bars are data, the red solid line is the total fits result, the blue dashed line is the η_c signal shape, the pink dashed line is the J/ψ background, and the green dashed line is the combinatorial background.

signal but a clear J/ψ peak is observed. According to a topology analysis of the inclusive MC sample, these J/ψ backgrounds come from $\psi(3686) \rightarrow \pi^0 J/\psi$, $\gamma\chi_{cJ}(J=0,1,2)$ with $\chi_{cJ} \rightarrow \gamma J/\psi$ and the QED process $e^+e^- \rightarrow \gamma_{\text{ISR}} J/\psi$. The other combinatorial background events mainly come from $\psi(3686) \rightarrow \gamma\chi_{cJ}(\chi_{cJ} \rightarrow \pi^+\pi^-\pi^0)$ and $\psi(3686) \rightarrow \pi^+\pi^-\pi^0\pi^0$. None of the backgrounds create a peak in the η_c mass region.

The result of an unbinned maximum likelihood fit to the $M(\pi^+\pi^-\pi^0)$ distribution is shown in Fig. 2(a). In the fit, the potential η_c signal is modeled using the MC-simulated shape, while the J/ψ peak is described by a Breit-Wigner function convolved with a Gaussian resolution function and the combinatorial background is described by a second-order polynomial. The signal yield from this fit is 95 ± 87 with a statistical significance of 1.3σ .

Using the Bayesian method [45], the UL on the η_c signal yield at the 90% CL, defined as N^{UL} , is determined. A scan

of unbinned maximum likelihood fits are performed to the $M(\pi^+\pi^-\pi^0)$ distributions, testing the η_c signal yield hypotheses from 0 to 200 in steps of 1. The probability density function (PDF) is obtained according to the normalized likelihood values of the fits, defined as $\mathcal{L}(N) = \exp(-[\mathcal{S}(N) - \mathcal{S}_{\text{min}}])$, where $\mathcal{S}_{\text{min}}$ is the minimum negative log-likelihood value obtained from the fits. The 90% CL upper limit on the signal yield, denoted as N^{UL} , is determined by integrating the PDF up to the value that contains 90% of the total probability,

$$\frac{\int_0^{N^{\text{UL}}} \mathcal{L}(N) dN}{\int_0^\infty \mathcal{L}(N) dN} = 0.9, \quad (3)$$

where N is the expected number of signal events. To account for the additive systematic uncertainties, alternative fits are performed by enlarging, reducing, and shifting the fit range. In these fits, second- or third-order polynomials are tested in describing the background. The η_c signal shape is modeled using the MC-simulated shape convolved with a Gaussian function. In addition, individual MC samples are produced with different η_c widths to describe the signal shape in alternative fits. The maximum UL on the signal yield at the 90% CL, $N^{\text{UL}} = 221.7$, is taken as the nominal value.

We also determine the UL of the signal yield of the subprocess via the $f_0(980)$ resonance. To select the $f_0(980)$ signal region, an additional requirement of $0.96 \text{ GeV}/c^2 < M(\pi^+\pi^-) < 1.02 \text{ GeV}/c^2$ is applied. An unbinned maximum likelihood fit to the $M(\pi^+\pi^-\pi^0)$ distribution is performed, as presented in Fig. 2(b), where no significant η_c signal is observed. The statistical significance of the η_c signal is estimated to be 1.5σ . Similarly, the η_c signal is modeled using the MC-simulated shape, the J/ψ background is described by a Breit-Wigner function convolved with a Gaussian resolution function, and the combinatorial background is described by a third-order polynomial. To obtain a conservative UL on the signal yield, alternative fits are performed by varying the η_c width, signal shape, fit range and background shape. The maximum UL of the signal yield at the 90% CL is found to be $N^{\text{UL}} = 59$.

IV. SYSTEMATIC UNCERTAINTY

Systematic uncertainties arising from various sources are investigated and summarized below. Assuming all the sources are independent, the total systematic uncertainty of each decay mode is calculated by adding the individual contributions in quadrature. Table I summarizes the systematic uncertainty results.

The uncertainties of the MDC tracking for each charged pion and the photon selection are investigated using a control sample of $J/\psi \rightarrow \rho\pi$ [46,47]. The difference between data and MC simulation is 1.0% per charged pion and also 1.0% per photon. The uncertainty related to the

TABLE I. Systematic uncertainties (in %) on the measurements of the branching fraction and ULs (multiplicative ones). Assuming the uncertainties are uncorrelated, the total uncertainty is the quadratic sum of the individual values.

Source	$\eta(1405)$	$f_1(1285)$	η_c	$\eta_c \rightarrow f_0(980)\pi^0$
Tracking	2.0	2.0	2.0	2.0
Photon detection	3.0	3.0	3.0	3.0
PID	2.0	2.0	2.0	2.0
Kinematic fit	1.0	2.3	1.3	1.2
π^0 mass window	0.8	0.8	0.8	0.8
Width of $f_0(980)$	4.0	23.2	...	8.2
Signal shape	2.9	4.2	...	...
Fitting range	0.5	2.7	...	...
Background estimation	3.0	21.1	...	...
Width of $\eta(1405)$	3.2	...	...	...
$\mathcal{B}(\pi^0 \rightarrow \gamma\gamma)$	0.03	0.03	0.03	0.03
Number of $\psi(3686)$ events	0.5	0.5	0.5	0.5
Total	7.9	32.1	4.4	9.3

pion PID is studied with the same sample [48], and a 1.0% difference per charged pion is assigned. Therefore, charged pions tracking, PID and photon selection contribute 2.0%, 2.0%, and 3.0% uncertainties, respectively.

The uncertainties associated with the kinematic fits come from the inconsistency of the track helix parameters between data and MC simulation. Corrections are applied to improve agreement, especially in χ^2_{4C} distributions. Following the method described in Ref. [49], the differences in the selection efficiencies with and without the correction are taken as the systematic uncertainties, estimated to be 1.0% for $\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, 2.3% for $f_1(1285) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, 1.3% for $\eta_c \rightarrow \pi^+\pi^-\pi^0$, and 1.2% for $\eta_c \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, respectively. A 0.8% uncertainty is assigned due to the π^0 mass window requirement, based on the study in Ref. [17].

In the fits to the $M(\pi^+\pi^-\pi^0)$ distributions for the $\eta(1405) \rightarrow f_0(980)\pi^0$ channel, the signal shape is represented by the MC-simulated shape convolved with a Gaussian function. To estimate the associated uncertainty, the fit is repeated using a Breit-Wigner function convolved with a Gaussian resolution function. The difference in the branching fractions between these two approaches, 2.9% and 4.2%, are taken as the associated uncertainties for the $\eta(1405) \rightarrow f_0(980)\pi^0$ channel and the $f_1(1285) \rightarrow f_0(980)\pi^0$ channel, respectively.

The $f_0(980)$ width exhibits significant variation across decay channels. To estimate the related uncertainties, the values of the width in MC simulation are varied by one standard deviation, extracted from a fit to the $M(\pi^+\pi^-)$ distribution in $\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$ decay. The resulting shifts in the branching fraction, 4.0% for $\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, 23.2% for $f_1(1285) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, and 8.2% for the UL of

$\eta_c \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, are taken as the systematic uncertainties.

The uncertainty of the background estimation comes from the choice of sideband ranges and the kernel bandwidth factor in the fit. Different $f_0(980)$ sideband ranges are used in the fit and the maximum differences in branching fraction, 2.7% and 18.9%, are taken as the systematic uncertainties for the $\eta(1405) \rightarrow f_0(980)\pi^0$ channel and the $f_1(1285) \rightarrow f_0(980)\pi^0$ channel, respectively. The kernel bandwidth factors are expanded or reduced by 20% in the fit and the maximum differences, 1.2% and 9.3%, are taken as the systematic uncertainties, for the $\eta(1405) \rightarrow f_0(980)\pi^0$ channel and the $f_1(1285) \rightarrow f_0(980)\pi^0$ channel, respectively.

For $\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, the uncertainty associated with the fit range is checked by using different fit ranges. The maximum differences in the measured branching fraction, 0.5% and 2.7%, are taken as the systematic uncertainties for the $\eta(1405) \rightarrow f_0(980)\pi^0$ channel and the $f_1(1285) \rightarrow f_0(980)\pi^0$ channel, respectively. The uncertainty associated with the signal shape mainly comes from the width of the $\eta(1405)$, which is estimated by varying the width by one standard deviation in the MC simulation according to the PDG value [28]. The maximum difference in the branching fraction of $\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, 3.2%, is taken as the systematic uncertainty. For the ULs of $\eta_c \rightarrow \pi^+\pi^-\pi^0$ and $\eta_c \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, the additive uncertainties associated with the fit range, background shape, and signal shape are considered in the nominal ULs.

The uncertainty on the branching fraction $\pi^0 \rightarrow \gamma\gamma(98.823 \pm 0.034)\%$ from the PDG [28] is 0.03%. The total number of $\psi(3686)$ events is determined to be $(2712.4 \pm 14.3) \times 10^6$ in Ref. [18], which contributes an uncertainty of 0.5%.

V. RESULT

Considering the systematic uncertainty, the branching fraction of the decay $\psi(3686) \rightarrow \gamma\eta(1405) \rightarrow \gamma f_0(980)\pi^0 \rightarrow \gamma\pi^+\pi^-\pi^0$ is determined using Eq. (2) to be

$$\mathcal{B}(\psi(3686) \rightarrow \gamma\eta(1405) \rightarrow \gamma f_0(980)\pi^0 \rightarrow \gamma\pi^+\pi^-\pi^0) = (3.77 \pm 0.43 \pm 0.30) \times 10^{-7}. \quad (4)$$

The branching fraction of the decay $\psi(3686) \rightarrow \gamma f_1(1285) \rightarrow \gamma f_0(980)\pi^0 \rightarrow \gamma\pi^+\pi^-\pi^0$ is determined to be

$$\mathcal{B}(\psi(3686) \rightarrow \gamma f_1(1285) \rightarrow \gamma f_0(980)\pi^0 \rightarrow \gamma\pi^+\pi^-\pi^0) = (7.36 \pm 2.25 \pm 2.36) \times 10^{-8}. \quad (5)$$

The $\eta(1405) \rightarrow f_0(980)\pi^0$ signal could arise from $\eta(1405) \rightarrow a_0(980)\pi^0$ via $a_0(980) - f_0(980)$ mixing. The $a_0(980) - f_0(980)$ mixing intensity has been measured by BESIII to be $(0.40 \pm 0.07 \pm 0.14) \times 10^{-2}$ via $\chi_{c1} \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$ and $\chi_{c1} \rightarrow a_0(980)\pi^0 \rightarrow \eta\pi^0\pi^0$ [10]. In combination with the ratio $\Gamma(\eta(1405) \rightarrow a_0(980)\pi)/\Gamma(\eta(1405) \rightarrow \eta\pi\pi) = 0.56 \pm 0.04 \pm 0.03$ and the branching fraction $\mathcal{B}(\psi(3686) \rightarrow \gamma\eta(1405) \rightarrow \gamma\pi^+\pi^-\pi^0) = (0.36 \pm 0.25 \pm 0.05) \times 10^{-4}$ taken from the PDG [28], the expected branching fraction $\mathcal{B}(\psi(3686) \rightarrow \gamma\eta(1405) \rightarrow \gamma a_0(980)\pi^0 \rightarrow \gamma\pi^0\eta\pi^0)$ is calculated to be $(1.01 \pm 0.71) \times 10^{-5}$. Therefore, the branching fraction of $\psi(3686) \rightarrow \gamma\eta(1405) \rightarrow \gamma a_0(980)\pi^0 \rightarrow \gamma f_0(980)\pi^0 \rightarrow \gamma\pi^+\pi^-\pi^0$ via $a_0(980) - f_0(980)$ mixing is expected to be $(4.04 \pm 3.24) \times 10^{-8}$, which is significantly smaller than the result measured by this analysis. This indicates that $a_0(980) - f_0(980)$ mixing is insufficient to explain the branching fraction of $\eta(1405) \rightarrow f_0(980)\pi^0$.

For the $\eta_c \rightarrow \pi^+\pi^-\pi^0$ and $\eta_c \rightarrow f_0(980)\pi^0$, the UL on the branching fraction is conservatively estimated by incorporating multiplicative systematic uncertainties into the PDF using a convolution method [50]:

$$L'(N) = \int_0^1 L\left(\frac{\mathcal{S}}{\hat{\mathcal{S}}}N\right) \exp\left[-\frac{(\mathcal{S} - \hat{\mathcal{S}})^2}{2\sigma_{\mathcal{S}}^2}\right] d\mathcal{S}, \quad (6)$$

where $\mathcal{S}$ and $\hat{\mathcal{S}}$ are the detection efficiency and the nominal efficiency, respectively; L represents the likelihood distribution without taking into account the systematic uncertainty and $\sigma_{\mathcal{S}}$ denotes the multiplicative systematic uncertainty. Figure 3 illustrates the normalized likelihood distributions before and after accounting for the multiplicative systematic uncertainty.

With the convolved PDF, the UL on the signal yield at 90% CL are $N^{\text{UL}} = 222.2$ for $\eta_c \rightarrow \pi^+\pi^-\pi^0$ and $N^{\text{UL}} = 59.7$ for $\eta_c \rightarrow f_0(980)\pi^0$, respectively. The corresponding ULs on the branching fraction of $\psi(3686) \rightarrow \gamma\eta_c, \eta_c \rightarrow \pi^+\pi^-\pi^0$ and $\psi(3686) \rightarrow \gamma\eta_c, \eta_c \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$ are calculated to be

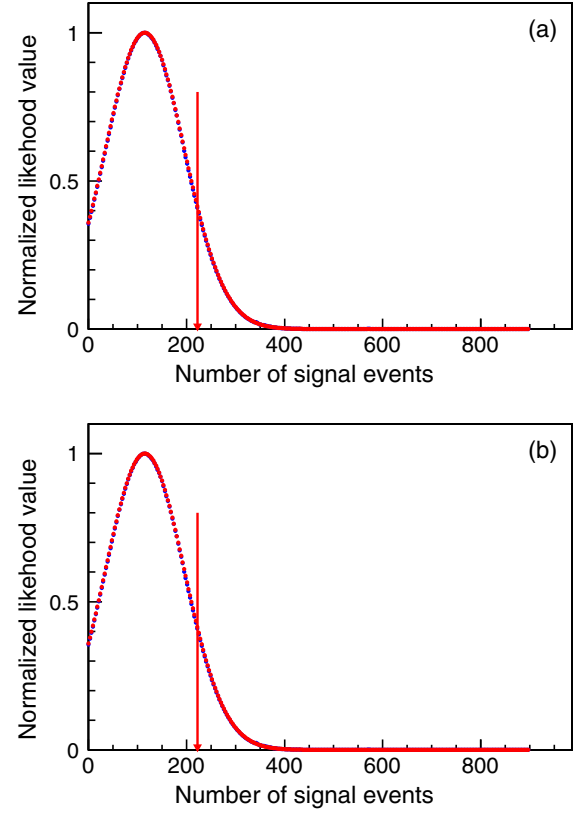


FIG. 3. Normalized likelihood distribution before (blue dots) and after (red dots) considering the multiplication uncertainties for (a) $\eta_c \rightarrow \pi^+\pi^-\pi^0$ and (b) $\eta_c \rightarrow f_0(980)\pi^0$.

$$\mathcal{B}^{\text{UL}}(\psi(3686) \rightarrow \gamma\eta_c, \eta_c \rightarrow \pi^+\pi^-\pi^0) = 3.09 \times 10^{-7}, \quad (7)$$

$$\mathcal{B}^{\text{UL}}(\psi(3686) \rightarrow \gamma\eta_c, \eta_c \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0) = 7.97 \times 10^{-8}. \quad (8)$$

VI. SUMMARY

Using a sample of $(2712.4 \pm 14.3) \times 10^6 \psi(3686)$ events collected with the BESIII detector, the decay $\psi(3686) \rightarrow \gamma\eta(1405) \rightarrow \gamma f_0(980)\pi^0 \rightarrow \gamma\pi^+\pi^-\pi^0$ is observed for the first time. The branching fraction is measured to be $(3.77 \pm 0.43 \pm 0.30) \times 10^{-7}$, where the first uncertainty is statistical and the second is systematic. The branching fraction cannot be explained solely by $f_0(980) - a_0(980)$ mixing. Additional contributions, such as those from the triangle singularity mechanism, are necessary. By combining the branching fraction of $J/\psi \rightarrow \gamma\eta(1405) \rightarrow \gamma f_0(980)\pi^0 \rightarrow \gamma\pi^+\pi^-\pi^0$, $(1.5 \pm 0.11 \pm 0.11) \times 10^{-5}$ [28], we determine the ratio $\frac{\mathcal{B}(\psi(3686) \rightarrow \gamma\eta(1405))}{\mathcal{B}(J/\psi \rightarrow \gamma\eta(1405))} = (2.51 \pm 0.44)\%$, which indicates that this process violates the “12% rule”.

Although the uncertainty is somewhat large, evidence for the process $f_1(1285) \rightarrow f_0(980)\pi^0$ in $\psi(3686)$ radiative

decays is reported for the first time. By combining the branching fraction of $J/\psi \rightarrow \gamma f_1(1285) \rightarrow \gamma f_0(980)\pi^0 \rightarrow \gamma\pi^+\pi^-\pi^0$, $(9.99 \pm 3.00 \pm 1.03) \times 10^{-7}$ [28], we determine the ratio $\frac{B(\psi(3686) \rightarrow \gamma f_1(1285))}{B(J/\psi \rightarrow \gamma f_1(1285))} = (13.57 \pm 7.41)\%$, which indicates that this process satisfies the “12% rule”.

In addition, we search for the decay $\psi(3686) \rightarrow \gamma\eta_c \rightarrow \gamma\pi^+\pi^-\pi^0(f_0(980) \rightarrow \pi^+\pi^-)$, but no clear η_c signal is observed in either the $\pi^+\pi^-\pi^0$ or $f_0(980)\pi^0$ mass spectra. The ULs on the branching fractions at the 90% CL are calculated to be 3.09×10^{-7} for $\psi(3686) \rightarrow \gamma\eta_c, \eta_c \rightarrow \pi^+\pi^-\pi^0$ and 7.97×10^{-8} for $\psi(3686) \rightarrow \gamma\eta_c, \eta_c \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$, respectively. Compared with previous results in the PDG [28], the obtained ULs are improved by a factor of 5.2.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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