

Amplitude analysis of $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$



The BESIII collaboration

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ABSTRACT: Using $(2712 \pm 14) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector, we perform the first amplitude analysis of the radiative decay $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$ within the mass region $M_{K_S^0 K_S^0} < 2.8 \text{ GeV}/c^2$. Employing a one-channel K-matrix approach for the description of the dynamics of the $K_S^0 K_S^0$ system, the data sample is well described with four poles for the f_0 -wave and three poles for the f_2 -wave. The determined pole positions are consistent with those of well-established resonance states. The observed f_0 and f_2 states are found to be in agreement with those produced in radiative J/ψ decays. The production behaviors of f_0 and f_2 poles in $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$ are qualified with their residues and the converted branching fractions. By comparing with $J/\psi \rightarrow \gamma K_S^0 K_S^0$ decay, the ratios $\frac{\mathcal{B}(\psi(3686) \rightarrow \gamma f_{0,2})}{\mathcal{B}(J/\psi \rightarrow \gamma f_{0,2})}$ are determined, which provides crucial experimental inputs on the internal structure of the $f_{0,2}$ states, especially their potential mixing with glueball components.

KEYWORDS: e^+e^- Experiments, Particle and Resonance Production, Quarkonium, Spectroscopy

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1 Introduction

Quantum chromodynamics (QCD) is now widely accepted as the theory for the strong interaction. In the framework of perturbative QCD, remarkable successes have been achieved in the prediction of hadronic phenomena in the high energy region such as heavy quarkonia [1]. In the non-perturbative region, several theoretical investigations have been conducted on glueball states, including bag models [2, 3], QCD-based potential models [4–6], QCD sum rules [7, 8], and Lattice QCD [9–14], with experimental confirmation still lacking as of now. Most studies suggest that the lightest glueball state has a scalar quantum number $J^{PC} = 0^{++}$ and a mass between (1.45, 1.75) GeV/ c^2 [10, 13, 15, 16]. With these properties, glueballs are likely to mix with other mesons with the same quantum number, such as the f_0 states. This property makes it rather challenging to identify them among several conventional $q\bar{q}$ states, necessitating a detailed study of the f_0 spectrum.

Experimentally, the radiative decays of the ψ states into two pseudo-scalar mesons via $\psi \rightarrow \gamma gg$, are particularly important for studying f_0 states and their potential mixing with the lightest scalar glueball. Conservation of parity and angular momentum restricts the quantum numbers to be $J^{PC} = \text{even}^{++}$ for systems consisting of two identical pseudo-scalars. With an unprecedentedly large J/ψ data sample, the BESIII collaboration has extensively studied the radiative decays of J/ψ into $\pi^0\pi^0$ [17], $K_S^0K_S^0$ [18], $\eta\eta$ [19], $\eta'\eta'$ [20], and $\eta\eta'$ [21, 22]. These studies have revealed abundant f_0 and f_2 structures, and precise measurements of

their properties have been performed. However, only few amplitude analyses of the radiative $\psi(3686)$ decays have been reported to date. For $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$, only a simple Breit-Wigner fit to the $M_{K_S^0 K_S^0}$ spectrum has been performed based on the limited CLEO-c data set [23]. Extensive studies of $\psi(3686)$ radiative decays are therefore crucial to extract the $f_{0,2}$ poles and compare the productions of $f_{0,2}$ states between J/ψ and $\psi(3686)$ radiative decays.

The BESIII experiment has collected $(2712 \pm 14) \times 10^6$ $\psi(3686)$ events [24], which provide an excellent opportunity to investigate f_0 and f_2 states with the radiative decay $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$. In this article, we present the first amplitude analysis of $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$ with a one-channel K-matrix approach.

2 Detector and data samples

The BESIII detector [25] records symmetric e^+e^- collisions provided by the BEPCII storage ring [26] in the center-of-mass energy (\sqrt{s}) 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 $\sqrt{s} = 3.773$ GeV. BESIII has collected large data samples in this energy region [27–29]. 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 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 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps [30–32], which benefits 83% of the data used in this analysis.

Simulated data samples produced with a GEANT4-based [33] Monte Carlo (MC) 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 [34]. 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 [34]. All particle decays are modeled with EVTGEN [35, 36] using branching fractions either taken from the particle data group (PDG) [37], when available, or otherwise estimated with LUNDCHARM [38, 39]. Final state radiation (FSR) from charged final state particles is incorporated using the PHOTOS package [40].

3 Event selection and background study

Candidates for $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$ are reconstructed via the decay $K_S^0 \rightarrow \pi^+ \pi^-$. Charged tracks are required to originate from the region $|d_z| < 20$ cm and $|\cos \theta| < 0.93$, where $|d_z|$ is the distance of closest approach to the interaction point (IP) along the z -axis, and θ is

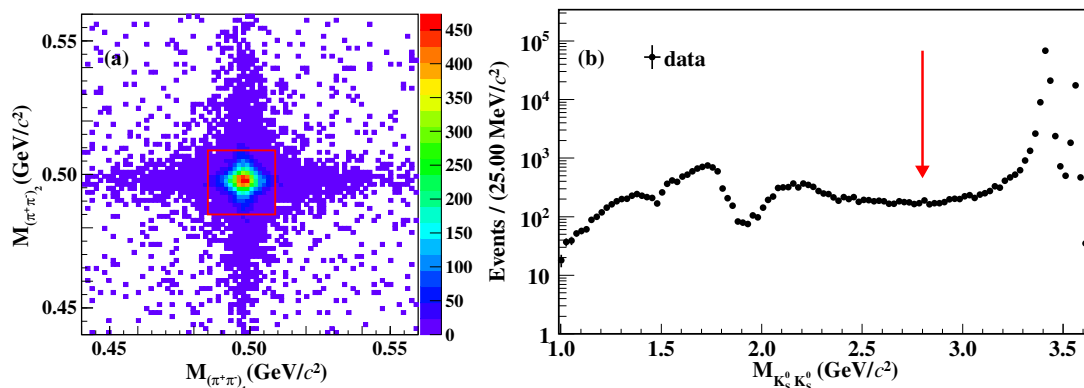


Figure 1. (a) The distribution of $M_{(\pi^+\pi^-)_1}$ versus $M_{(\pi^+\pi^-)_2}$ from the data sample. The red box delineates the K_S^0 signal zone $|M_{\pi^+\pi^-} - M_{K_S^0}| < 12 \text{ MeV}/c^2$. (b) The invariant mass of the $K_S^0 K_S^0$ system of the data sample in log-scale. The red arrow indicates the requirement $M_{K_S^0 K_S^0} < 2.8 \text{ GeV}/c^2$.

the polar angle relative to the z -axis, which is defined as the symmetry axis of the MDC. Only four charged tracks with zero net charge are allowed.

To reconstruct K_S^0 candidates, all possible pairs of oppositely charged tracks satisfying the above requirement are assigned as $\pi^+\pi^-$ without particle identification. The $\pi^+\pi^-$ trajectories are constrained to originate from a common vertex by applying a vertex fit. The decay length of each K_S^0 candidate, namely the distance between the IP and the decay vertex of K_S^0 , is required to be greater than twice its resolution. The invariant mass of $\pi^+\pi^-$ is required to satisfy $|M_{\pi^+\pi^-} - M_{K_S^0}| < 12 \text{ MeV}/c^2$ corresponding to 2.5 times the resolution, where $M_{K_S^0}$ is the known K_S^0 mass as quoted from PDG [37] and $M_{\pi^+\pi^-}$ is calculated at the IP for simplicity. The number of surviving K_S^0 candidates is required to be exactly two. Figure 1(a) shows the distribution of invariant masses of two K_S^0 candidates, where a significant signal contribution is observed. In the subsequent analysis, two K_S^0 candidates are mixed randomly as they are indistinguishable.

Photon candidates are identified using showers in the EMC. Each shower is required to have deposited at least 25 MeV in the barrel and 50 MeV in the endcaps of the EMC. To suppress contamination from charged particles, the angle between the shower position and the extrapolated trajectory of any charged track at the EMC must be greater than 10° . The timing difference between the EMC shower and the event start time is required to be within $[0, 700]$ ns to suppress electronic noise and the energy deposits unrelated to the event. At least one good photon candidate is required.

To suppress the combinatorial background and improve the resolution, a four-constraint (4C) kinematic fit for the $\psi(3686) \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$ hypothesis is performed on the four-momenta of final-state particles in the lab frame. The combination with the smallest χ_{4C}^2 is retained for further analysis, and the χ_{4C}^2 of the kinematic fit is required to be less than 50. Contributions from $\chi_{c0,2} \rightarrow K_S^0 K_S^0$ are suppressed by requiring $M_{K_S^0 K_S^0} < 2.8 \text{ GeV}/c^2$, as shown in figure 1(b).

A total of 17,672 candidates survived the above selection criteria. The background contribution is estimated with the $\psi(3686)$ inclusive MC sample, yielding a total background

fraction from $\psi(3686)$ decays below 1%, dominated by the final state $\gamma K_S^0 K_S^0 \pi^0$. This simulated background is incorporated into the further amplitude analysis. The background from the continuum process is estimated using a (401.0 ± 4.0) pb⁻¹ data sample at $\sqrt{s} = 3.650$ GeV [24], resulting in only one surviving event, which corresponds to 10 events in the $\psi(3686)$ data sample with integrated luminosity (3877.0 ± 39.0) pb⁻¹ [24]. Consequently, the continuum background is ignored in the subsequent analysis.

4 Amplitude analysis

4.1 Amplitude

The covariant tensor amplitude cited from ref. [41] is used to describe the radiative decay $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$ in this work by assuming an isobar model. The amplitude is expressed as

$$\mathcal{A} = \psi_\mu(m_1) e_\nu^*(m_2) A^{\mu\nu} = \psi_\mu(m_1) e_\nu^*(m_2) \sum_i \Lambda_i U_i^{\mu\nu}, \quad (4.1)$$

where ψ and e denote the polarization vectors of $\psi(3686)$ and the photon, with polarizations m_1 and m_2 , respectively. The complex coupling constant Λ_i corresponds to the i -th amplitude component $U_i^{\mu\nu}$, whose explicit expressions are given in ref. [41]. Summing over the polarizations of $\psi(3686)$ and the photon, the amplitude squared is given by

$$|\mathcal{M}|^2 = \frac{1}{2} \sum_{m_1=1}^2 \sum_{m_2=1}^2 |\mathcal{A}|^2. \quad (4.2)$$

The Blatt-Weisskopf factor $B_L(Q, Q_0)$ has been incorporated into $U_i^{\mu\nu}$, where Q is the momentum of daughter particles in the rest frame of their mother, and $Q_0 = \frac{0.197321}{R}$ GeV/ c is a hadron “scale” parameter. Here, R denotes the radius of the centrifugal barrier in femtometers (fm). In the nominal fit, we take $R = 0.59$ fm, corresponding to 3 GeV⁻¹, which is the center of the expected range $[1, 5]$ GeV⁻¹ [37]. Corresponding uncertainties are considered by varying R in the systematic uncertainty.

The dynamic part $f^{(X)}$ for resonance X has also been included in the $U_i^{\mu\nu}$ following the convention of ref. [41]. The f_0 and f_2 waves are described with the K-matrix approach. Since only one decay channel $f_{0,2} \rightarrow K_S^0 K_S^0$ is considered in this work, our methodology does not fully satisfy the unitarity condition since coupled-channel effects are neglected. Nonetheless, it offers a more dependable depiction of overlapping resonance states with significant widths compared to a straightforward summation of Breit-Wigner functions. To incorporate the production amplitude $\psi(3686) \rightarrow \gamma f_{0,2}$ within the K-matrix framework, a prevalent method called \mathcal{P} -vector parameterization [42, 43] is used in this work. For the i -th production wave of $f_{0,2}$, corresponding dynamic part is written as

$$f_i^{(f_{0,2})} = n(1 - \mathcal{K}i\rho n^2)^{-1} \mathcal{P}_i, \quad (4.3)$$

where $n = Q^L B_L(Q, Q_0)$ and $\rho = Q/\sqrt{s}$ is the phase space factor of $f_{0,2} \rightarrow K_S^0 K_S^0$. The K-matrix \mathcal{K} is defined as $\mathcal{K} = \sum_a \frac{g_a^2}{m_a^2 - s} + b$, where m_a and g_a are the bare mass and coupling

to $K_S^0 K_S^0$ for pole a , respectively, and b accounts for the background contribution in the K-matrix. All parameters shown in \mathcal{K} are real-valued. The production vector \mathcal{P} is given as

$$\mathcal{P}_i = \sum_a \frac{\beta_a^i g_a}{m_a^2 - s} + \beta_{\text{bkg}}^i, \quad (4.4)$$

where the complex parameters β_a^i describes the i -th wave production strength for pole a and β_{bkg} models the non-resonant production. The β , m , and g are all free parameters in the fit. Since the production strengths have already been included in the P-vector, the complex coupling constant Λ_i in eq. (4.1) is fixed to one for both f_0 and f_2 components. The $K^*(892)$ resonance is described with a simple Breit-Wigner function $f^{(K^*)} = 1/(M_0^2 - s - iM_0\Gamma_0)$, where the resonance parameters M_0 and Γ_0 are fixed to the ‘‘charged only, hadroproduced’’ values provided by the PDG. Considering the $K_S^0 K_S^0$ pair has been symmetrized, the complex coupling constants Λ_i of the amplitudes of $K^*(892) \rightarrow K_{S1}^0 \gamma$ and $K^*(892) \rightarrow K_{S2}^0 \gamma$ are constrained to be the same in the fit.

4.2 Fit method

The complex coupling constants Λ and the parameters of the K-matrix shown in eqs. (4.1) and (4.3) are determined by an event-based maximum likelihood fit. The log-likelihood function is constructed as

$$\ln \mathcal{L} = \ln \mathcal{L}_{\text{dt}} - \ln \mathcal{L}_{\text{bg}}. \quad (4.5)$$

Here, $\ln \mathcal{L}_{\text{dt/bg}}$ sums over all the data/background events and is defined as

$$\ln \mathcal{L}_{\text{dt/bg}} = \sum_k^{N_{\text{dt/bg}}} \ln \left[\frac{|\mathcal{M}(\xi^k)|^2}{\int \epsilon(\xi) |\mathcal{M}(\xi)|^2 R_3(\xi) d\xi} \right], \quad (4.6)$$

where ϵ denotes the detection efficiency, R_3 is the three-body phase space factor, and ξ^k is the measurement of the k -th event, namely the four-momenta of the final state $\gamma K_S^0 K_S^0$. The background contribution is modeled with the inclusive MC simulation and directly subtracted from the data sample. The integral in the denominator is numerically calculated with a MC method as

$$\int \epsilon(\xi) |\mathcal{M}(\xi)|^2 R_3(\xi) d\xi \propto \sum_{k_{\text{MC}}}^{N_{\text{MC}}} |\mathcal{M}(\xi^{k_{\text{MC}}})|^2. \quad (4.7)$$

Here, N_{MC} is the number of simulated events uniformly distributed in the $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$ phase space after detector simulation and event selection, which is 25 times larger than the data sample.

Technically, the calculation of the log-likelihood is accelerated by the GPU. The minimization of $-\ln \mathcal{L}$ is executed with the MINUIT package [44].

4.3 Significance test

To determine which resonance states should be included in the nominal solution, several models M_j with different sets of resonances are tried based on the moment distributions

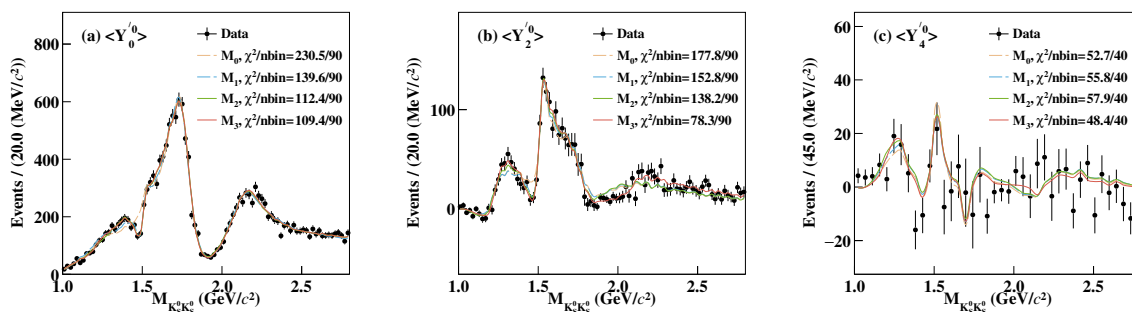


Figure 2. The moments of (a) $\langle Y_0^0 \rangle$, (b) $\langle Y_2^0 \rangle$, and (c) $\langle Y_4^0 \rangle$ without acceptance correction. The black dots with error bars are the data sample after subtracting the simulated background sample. The curves in various colors are fit projections of different models.

Model	Added Pole	N_{par}	$\ln \mathcal{L}$	Significance
M_0	—	26	0	—
M_1	$f_0(1500)$	30	56.8	10.0
M_2	$f_0(1370)$	34	77.8	5.6
M_3	$f_2(1950)$	42	133.9	9.3
Scan f_0	$f_0(X)$	46	137.5	< 3
Scan f_2	$f_2(X)$	50	139.4	< 3

Table 1. The numbers of float parameters N_{par} , log-likelihood values relative to the minimal model $\ln \mathcal{L}$, and the statistical significance of added poles. The poles included in the minimal model M_0 are $f_0(1710)$, $f_0(2020)$, $f_2(1270)$, and $f_2'(1525)$.

$\langle Y_l^0 \rangle$. Considering only the f_0 and f_2 contributions, the moments are related to the spin-0 (S) and spin-2 (D) amplitudes by [21]

$$\begin{aligned}
 \sqrt{4\pi} \langle Y_0^0 \rangle &= S_0^2 + D_0^2 + D_1^2 + D_2^2, \\
 \sqrt{4\pi} \langle Y_2^0 \rangle &= \frac{1}{7\sqrt{5}} (10D_0^2 + 5D_1^2 - 10D_2^2) + 2S_0 D_0 \cos \phi_{D_0}, \\
 \sqrt{4\pi} \langle Y_4^0 \rangle &= \frac{1}{7} (6D_0^2 - 4D_1^2 + D_2^2),
 \end{aligned} \tag{4.8}$$

where ϕ_{D_0} is the phase of the D -wave relative to the S -wave. The moments without acceptance correction $\langle Y_l^0 \rangle = \sum_i^{N_{\text{dt}}} P_l(\cos \theta_{K_S^0}^i)$ are extracted from data sample by re-weighting the mass spectrum $M_{K_S^0 K_S^0}$ with the l -th Legendre polynomials P_l after subtracting the simulated background sample, where $\theta_{K_S^0}$ is the opening angle between the opposite flight directions of $\psi(3686)$ and K_S^0 in the rest frame of the $K_S^0 K_S^0$ system. The determination of the nominal solution is described below and summarized in table 1.

- As shown in figure 2, several significant peaks in the $\langle Y_l^0 \rangle(M_{K_S^0 K_S^0})$ distributions are identified as $f_0(1710)$, $f_0(2020)$, $f_2(1270)$, and $f_2'(1525)$. Thus, the minimal model M_0 is chosen to include these four states. It should be noted that one can not control which resonances are included directly. However, by imposing start-parameter ranges

and parameters limits on the bare masses and couplings, the fitted pole positions do match the expected resonance well. Additionally, the f_0 background is added in the \mathcal{P} -vector to describe the non-resonant structures, while the f_0 background term in the K-matrix is found to be insignificant. The $K^*(892)^0 \rightarrow K_S^0 \gamma$ contribution is included, as suggested by the $M_{K_S^0 \gamma}$ spectra in figure 3. No evidence of $f_0(980)$ is observed near the $K\bar{K}$ threshold. The fit projection of M_0 is displayed in figure 2, revealing significant deviations around $1.5 \text{ GeV}/c^2$ in the $\langle Y_{0(2)}^{\prime 0} \rangle$ distributions.

- Next, the $f_0(1500)$ is added into the model as M_1 . This significantly improves the description of the dip around $1.5 \text{ GeV}/c^2$. With the change in the log-likelihood value $\Delta(\ln \mathcal{L})$ and the number of free parameters ΔN_{par} relative to the previous model, the statistical significance of $f_0(1500)$ is calculated to be 10σ using the Wilk's theorem as an approximate estimation. However, some deviation around $1.3 \text{ GeV}/c^2$ in the $\langle Y_{0(2)}^{\prime 0} \rangle$ spectrum remains.
- To address this, $f_0(1370)$ is included in the model as M_2 , which provides a good description of the peak around $1.3 \text{ GeV}/c^2$. The statistical significance of $f_0(1370)$ is calculated to be 5σ .
- The discrepancy around $2.0 \text{ GeV}/c^2$ on the $\langle Y_2^{\prime 0} \rangle$ spectrum is attributed to the absence of a broad f_2 contribution. There are two potential sources: an additional f_2 pole or f_2 background. It is found that including an additional f_2 pole provides a significantly better fit than the f_2 background with $\Delta \ln \mathcal{L} = 40$. After adding one more f_2 pole around $2.0 \text{ GeV}/c^2$ as model M_3 , all three moments $\langle Y_L^{\prime 0} \rangle$ are well described. The determined pole position is consistent with $f_2(1950)$ in the PDG [37]. The statistical significance of this $f_2(1950)$ pole is determined to be 9σ .
- Finally, attempts are made to include an additional $f_{0,2}$ pole or f_4 resonance state into model M_3 by scanning its bare mass from 1.0 GeV to 2.5 GeV . Other parameters are kept to be float in this scan. None of them yields a statistical significance greater than 3σ . Therefore, the model M_3 is taken as the nominal solution.

4.4 Nominal solution

Figure 3 shows the fit projections of nominal solution on the two-body invariant mass spectra and several helicity angular distributions. In addition to the previously defined $\theta_{K_S^0}$, θ_γ represents the flight direction of γ in the rest frame of $\psi(3686)$; $\phi_{K_S^0}$ is the angle between the decay planes of $\psi(3686) \rightarrow \gamma f$ and $f \rightarrow K_S^0 K_S^0$ in the rest frame of $\psi(3686)$; and $\theta_{K_S^0 K_S^0}$ is the opening angle between the two K_S^0 flight directions in the rest frame of $\psi(3686)$. The nominal solution provides a good description of the data sample.

4.5 Pole positions

The pole positions are obtained by solving the complex function $(1 - \mathcal{K}i\rho n^2) = 0$ numerically in the unphysical sheet $\text{Im}(k) < 0$, where the k is the momentum of K_S^0 in the rest frame of $f_{0,2}$. The statistical uncertainty is accessed by generating 1000 sets of K-matrix parameters based on the corresponding covariance matrix and calculating the pole positions. The standard

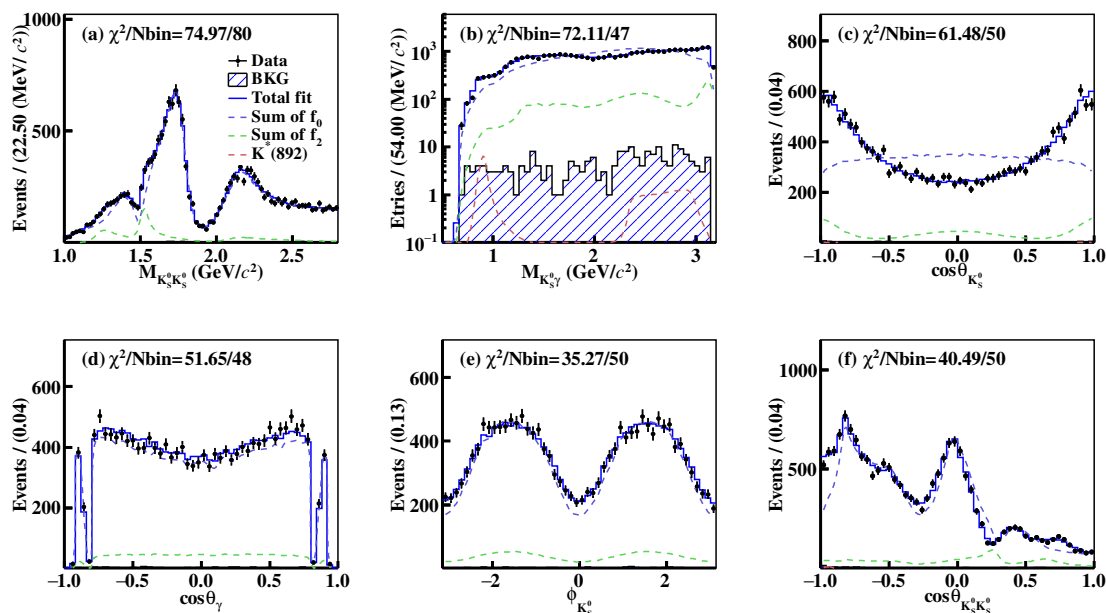


Figure 3. The fit projections of the nominal solution. The black dots with error bars are the data sample. The solid blue curve is the fit result. The hatched histogram is the background. The dashed lines with various colors are different components. The projections from the two identical K_S^0 mesons are merged in subplot (b).

Resonance	Pole position	$ \mathcal{R}_{E_1} ^2$	$ \mathcal{R}_{M_2} ^2$	$ \mathcal{R}_{E_3} ^2$	$ \mathcal{R}_{\text{sum}} ^2$
$f_0(1370)$	$(1297.4 \pm 56.9) - i(125.8 \pm 71.5)$	$19.1^{+45.6}_{-12.1}$	—	—	$19.1^{+45.6}_{-12.1}$
$f_0(1500)$	$(1487.8 \pm 7.7) - i(46.1 \pm 8.6)$	$11.9^{+9.7}_{-4.9}$	—	—	$11.9^{+9.7}_{-4.9}$
$f_0(1710)$	$(1770.7 \pm 5.1) - i(84.7 \pm 3.8)$	$274.2^{+40.2}_{-29.9}$	—	—	$274.2^{+40.2}_{-29.9}$
$f_0(2100)$	$(2141.9 \pm 17.2) - i(138.8 \pm 10)$	$137.3^{+24.5}_{-22.0}$	—	—	$137.3^{+24.5}_{-22.0}$
$f_2(1270)$	$(1226.2 \pm 8.6) - i(78.9 \pm 7.5)$	$7.4^{+2.0}_{-2.4}$	$9.3^{+2.2}_{-2.7}$	$3.3^{+1.9}_{-1.0}$	$20.1^{+3.9}_{-4.4}$
$f_2(1525)$	$(1515.7 \pm 4.3) - i(33.7 \pm 3.8)$	$3.4^{+1.8}_{-1.6}$	$3.2^{+1.1}_{-1.2}$	$0.7^{+1.0}_{-0.4}$	$7.3^{+2.6}_{-2.1}$
$f_2(1950)$	$(2069.9 \pm 22.2) - i(130 \pm 26)$	$25.5^{+17.1}_{-11.5}$	$5.5^{+5.5}_{-3.1}$	$2.6^{+3.9}_{-1.5}$	$33.5^{+20.7}_{-12.7}$

Table 2. The solved pole positions in MeV and corresponding squared modulus of residues $|\mathcal{R}|^2$ in ($\times 10^{-4}$). Here, the uncertainty is statistical only.

deviations of the calculated pole positions are taken to be statistical uncertainties. The results are summarized in table 2. The reliability of statistical uncertainties are further validated with the bootstrap method [45] by performing fits to alternative data samples obtained by sampling with replacement from original data sample by 100 times. All of the alternative samples share the same statistics as the original one. The standard deviations of the resultant distributions of pole positions obtained from fits to alternative data samples, are found to be consistent with the statistical uncertainties obtained in the nominal approach.

4.6 Pole residues

The contributions of individual $f_{0,2}$ poles a in the decay $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$ are quantified with the residue of $f_i^{(f_{0,2})} = n(1 - \mathcal{K}i\rho n^2)^{-1} \mathcal{P}_i$ in the complex- s plane at their pole positions s_a . The residues are proportional to the product of the production and decay strength, hence the combined branching fraction of $\psi(3686) \rightarrow \gamma f_{0,2}, f_{0,2} \rightarrow K_S^0 K_S^0$ is given as

$$\mathcal{B}(\psi(3686) \rightarrow \gamma f_{0,2}, f_{0,2} \rightarrow K_S^0 K_S^0) \propto |\mathcal{R}|^2, \quad (4.9)$$

where the residue \mathcal{R} is defined as

$$\begin{aligned} \mathcal{R}(s_a) &= \frac{1}{2\pi i} \oint \sqrt{\rho_{\psi \rightarrow \gamma f}(s_a)} \times f_i^{(f_{0,2})}(s_a) \times \sqrt{\rho_{f \rightarrow K_S^0 K_S^0}(s_a)} ds \\ &= \frac{1}{2\pi i} \int_0^{2\pi} \sqrt{\rho_{\psi \rightarrow \gamma f}(s_a + re^{i\theta})} \times f_i^{(f_{0,2})}(s_a + re^{i\theta}) \times \sqrt{\rho_{f \rightarrow K_S^0 K_S^0}(s_a + re^{i\theta})} ire^{i\theta} d\theta. \end{aligned} \quad (4.10)$$

Here, we use $ds = d(s_a + re^{i\theta}) = ire^{i\theta} d\theta$ and r should be small enough to ensure only one pole s_a in this circle contour $s_a + re^{i\theta}$. This integral is calculated numerically via

$$\mathcal{R}(s_a) \simeq \frac{1}{2\pi i} \sum_{n=1}^N \sqrt{\rho_{\psi \rightarrow \gamma f}(s_n)} \times f_i^{(f_{0,2})}(s_n) \times \sqrt{\rho_{f \rightarrow K_S^0 K_S^0}(s_n)} \times ire^{in\Delta\theta} \times \Delta\theta, \quad (4.11)$$

where $\Delta\theta = 2\pi/N$ and $s_n = s_a + re^{in\Delta\theta}$. However, it should be noted the covariant tensor amplitudes used in the amplitude fit are not well normalized and orthogonal. Therefore, the obtained residues $\mathcal{R}_{\text{cov}}^{f_{0,2}}$ in covariant tensor amplitude are further converted to the residues $\mathcal{R}_{\text{E1/M2/E3}}^{f_{0,2}}$ in helicity amplitude in multi-pole basis, which is written as [17]

$$\begin{aligned} I &= \sum_{\lambda_\psi = \lambda_\gamma = \pm 1} |h_0(\theta_{K_S^0}) d_{1,1}^1(\theta_\gamma) e^{\pm i\phi_{K_S^0}} + h_1(\theta_{K_S^0}) d_{1,0}^1(\theta_\gamma) + h_2(\theta_{K_S^0}) d_{1,-1}^1(\theta_\gamma) e^{\mp i\phi_{K_S^0}}|^2 \\ &+ \sum_{\lambda_\psi = -\lambda_\gamma = \pm 1} |h_0(\theta_{K_S^0}) d_{1,-1}^1(\theta_\gamma) e^{\mp i\phi_{K_S^0}} - h_1(\theta_{K_S^0}) d_{1,0}^1(\theta_\gamma) + h_2(\theta_{K_S^0}) d_{1,1}^1(\theta_\gamma) e^{\pm i\phi_{K_S^0}}|^2, \end{aligned} \quad (4.12)$$

where the $h_{0,1,2}$ is defined as

$$\begin{aligned} h_0(\theta_{K_S^0}) &= \sqrt{3}\alpha_{01} + \sqrt{\frac{3}{2}}(\alpha_{21} + \sqrt{5}\alpha_{22} + 2\alpha_{23})d_{0,0}^2(\theta_{K_S^0}) \\ h_1(\theta_{K_S^0}) &= \frac{\sqrt{2}}{2}(3\alpha_{21} + \sqrt{5}\alpha_{22} - 4\alpha_{23})d_{1,0}^2(\theta_{K_S^0}) \\ h_2(\theta_{K_S^0}) &= (3\alpha_{21} - \sqrt{5}\alpha_{22} + \alpha_{23})d_{2,0}^2(\theta_{K_S^0}). \end{aligned} \quad (4.13)$$

Here, α_{01} is the complex coefficient of E1 transition of 0^{++} ; α_{21} , α_{22} , and α_{23} are the complex coefficients of E1, M2, and E3 transitions of 2^{++} , respectively. Following refs. [17, 46], the conversion relationship for $\psi(3686) \rightarrow \gamma f_0$ reads $\mathcal{R}_{\text{E1}}^{f_0} = \sqrt{\frac{1}{6}} \mathcal{R}_{\text{cov}}^{f_0}$ and the relationship for $\psi(3686) \rightarrow \gamma f_2$ reads

$$\begin{bmatrix} \mathcal{R}_{\text{E1}}^{f_2} \\ \mathcal{R}_{\text{M2}}^{f_2} \\ \mathcal{R}_{\text{E3}}^{f_2} \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{3}{2}} & \sqrt{\frac{15}{2}} & 2\sqrt{\frac{3}{2}} \\ 3\sqrt{\frac{1}{2}} & \sqrt{\frac{5}{2}} & -2\sqrt{2} \\ 3 & -\sqrt{5} & 1 \end{bmatrix}^{-1} \times \frac{2\sqrt{2}}{3} Q_{K_S^0}^2 \times \begin{bmatrix} -1 & -2\frac{E_\gamma^2}{m_{f_2}^2} M_\psi^2 & 0 \\ -\sqrt{3}\frac{E_{f_2}}{m_{f_2}} & 0 & \sqrt{3}\frac{E_\gamma^2}{m_{f_2}} M_\psi \\ -\sqrt{6} & 0 & 0 \end{bmatrix} \times \begin{bmatrix} \mathcal{R}_{\text{cov},1}^{f_2} \\ \mathcal{R}_{\text{cov},2}^{f_2} \\ \mathcal{R}_{\text{cov},3}^{f_2} \end{bmatrix}, \quad (4.14)$$

Pole property		Hadron scale	Fit bias	$M_{K_S^0 K_S^0}$ calibration	$M_{K_S^0 K_S^0}$ cut	Helix corr	Add pole	\mathcal{P} -vector BG	Sum
Real	$f_0(1370)$	4.3	20.4		11.3	3.1	8.3	14.8	29.4
	$f_0(1500)$	0.5	0.2		1.5	0.6	2.3	0.7	3.7
	$f_0(1710)$	0.1	0.0		2.2	0.7	2.1	1.7	4.2
	$f_0(2020)$	1.5	3.0	2.2	9.8	3.9	11.1	8.3	17.9
	$f_2(1270)$	6.9	1.4		3.0	0.2	0.3	3.8	8.8
	$f_2(1525)$	1.0	2.1		0.3	0.2	0.7	0.2	3.3
	$f_2(1950)$	3.7	13.4		5.6	2.1	3.0	8.3	17.6
Imag	$f_0(1370)$	2.1	2.0	0.1	19.5	5.3	15.3	35.9	44.0
	$f_0(1500)$	0.7	4.2	0.1	1.9	0.5	3.5	3.2	6.6
	$f_0(1710)$	0.6	0.3	0.1	0.2	0.2	4.0	2.4	4.7
	$f_0(2020)$	0.7	3.1	0.1	4.6	0.3	0.6	13.3	14.4
	$f_2(1270)$	11.1	1.5	0.1	2.4	0.8	2.3	0.4	11.7
	$f_2(1525)$	0.4	3.3	0.2	0.6	1.4	1.6	1.0	4.1
	$f_2(1950)$	18.7	0.7	0.1	2.2	0.7	4.0	1.5	19.3
$ \mathcal{R} ^2$	$f_0(1370)$	0.7	0.4		17.1	1.6	14.4	14.4	26.7
	$f_0(1500)$	0.5	3.6		2.8	0.1	3.2	3.8	6.8
	$f_0(1710)$	1.1	5.9		17.3	3.2	19.6	4.7	27.4
	$f_0(2020)$	0.6	2.7		13.6	0.2	10.1	33.0	37.1
	$f_2(1270), E_1$	3.1	0.0		1.1	0.2	0.7	1.3	3.6
	$f_2(1270), M_2$	2.2	0.8		0.8	0.3	0.5	1.3	2.9
	$f_2(1270), E_3$	0.8	0.3		0.2	0.0	1.0	0.4	1.4
	$f_2(1270), \text{Sum}$	6.1	0.4	—	1.8	0.5	2.2	3.0	7.4
	$f_2(1525), E_1$	0.7	0.0		0.2	0.2	0.7	0.0	1.1
	$f_2(1525), M_2$	0.1	0.4		0.1	0.2	0.8	0.3	1.0
	$f_2(1525), E_3$	0.1	0.1		0.1	0.2	0.3	0.1	0.4
	$f_2(1525), \text{Sum}$	0.7	0.3		0.3	0.5	1.8	0.4	2.1
	$f_2(1950), E_1$	7.0	0.1		5.2	0.4	7.3	3.4	11.9
	$f_2(1950), M_2$	2.0	2.0		0.1	0.3	2.0	0.8	3.6
	$f_2(1950), E_3$	0.8	0.6		0.7	0.1	0.7	0.4	1.5
$f_2(1950), \text{Sum}$	9.8	2.3		5.0	0.8	10.0	4.6	15.8	

Table 3. The systematic uncertainties for pole positions in MeV and pole residue $|\mathcal{R}|^2$ in $(\times 10^{-4})$.

where the E_{γ, f_2} are defined in the $\psi(3686)$ rest frame and $Q_{K_S^0}$ is the momentum of K_S^0 in the $K_S^0 K_S^0$ rest frame. All the kinematic variables shown in eq. (4.14) are calculated at the pole masses of the f_2 states $m_{K_S^0 K_S^0} = m_{f_2}$. The total contribution of f_2 state $|\mathcal{R}_{\text{sum}}|^2$ is calculated with $|\mathcal{R}_{E_1}|^2 + |\mathcal{R}_{M_2}|^2 + |\mathcal{R}_{E_3}|^2$. The obtained results are also summarized in table 2.

5 Systematic uncertainties

The systematic uncertainties of the amplitude analysis are summarized in table 3. They are estimated as follows. The total systematic uncertainty is obtained by adding the individual ones in quadrature.

The systematic uncertainty associated with the choice of the hadron “scale” parameter Q_0 is estimated by performing scan on Q_0 value. The difference between the nominal solution with $Q_0 = 3 \text{ GeV}^{-1}$ and alternative fit with the best $Q_0 = 2.2 \text{ GeV}^{-1}$ is taken as the systematic uncertainty.

The systematic uncertainty due to fit bias is estimated with a toy MC study. A total of 100 sets of signal MC samples are generated based on the nominal solution with the background contribution mixed. The same amplitude fits are performed on these pseudo-data samples, and any observed fit biases are assigned as the systematic uncertainty.

The systematic uncertainty of the mass calibration is studied by performing a 1D fit to the $M_{K_S^0 K_S^0}$ distribution of the data sample around the χ_{c0} mass region. The resolution and mass shift of $M_{K_S^0 K_S^0}$ are determined to be $\sigma = 7.3 \text{ MeV}/c^2$ and $\Delta M = 2.2 \text{ MeV}/c^2$, respectively. As a conservative estimation, the corresponding impacts on the pole positions $\Re - i\Im$ are assigned as $\Delta\Re = 2.2 \text{ MeV}/c^2$ and $\Delta\Im = (\sqrt{(\Im^2 + (\sigma/2)^2}) - |\Im|)$.

The uncertainty caused by the cut $M_{K_S^0 K_S^0} < 2.8 \text{ GeV}/c^2$ is estimated by varying the cut range to $M_{K_S^0 K_S^0} < 2.7 \text{ GeV}/c^2$ and $2.9 \text{ GeV}/c^2$ and performing alternative fits. The maximum changes on pole positions are taken as the systematic uncertainties.

The systematic uncertainty associated with the 4C kinematic fit is studied by performing an alternative amplitude fit with a phase space MC sample after helix correction [47]. The difference between this alternative fit and nominal fit is taken as the systematic uncertainty.

The systematic uncertainty due to additional $f_{0,2,4}$ state is assigned as the largest difference between the fit results of nominal solution and the solution with the largest improvement on $\ln \mathcal{L}$ in the scan of additional $f_{0,2}$ pole and f_4 resonance state.

The systematic uncertainty due to background modeling in \mathcal{P} vector is estimated by using the first-order polynomial background term as $\mathcal{P}_i = \sum_a \frac{\beta_a^i g_a}{m_a^2 - s} + \beta_{\text{bkg}}^{i,0} + \beta_{\text{bkg}}^{i,1} \times s$ in alternative fit. The difference in pole positions between nominal and alternative fit is taken as the systematic uncertainty.

6 The branching fractions of individual poles

The branching fractions of individual poles are calculated as

$$\mathcal{B}(\psi(3686) \rightarrow \gamma R, R \rightarrow K_S^0 K_S^0) = \sigma_a / \sigma_{\text{tot}} \times \mathcal{B}'(\psi(3686) \rightarrow \gamma K_S^0 K_S^0). \quad (6.1)$$

Here, $\mathcal{B}'(\psi(3686) \rightarrow \gamma K_S^0 K_S^0)$ is the total branching fraction with $M_{K_S^0 K_S^0} < 2.8 \text{ GeV}/c^2$; σ_a and σ_{tot} are the total decay rates of pole a and the process, respectively. The total decay rate σ_{tot} is calculated in a numerical approach as

$$\sigma_{\text{tot}} = \int |\mathcal{M}|^2 d\Phi_3 \simeq |\bar{\mathcal{M}}|^2 \times \Phi_3, \quad (6.2)$$

where $|\bar{\mathcal{M}}|^2$ is the averaged amplitude squared of phase space MC sample without detector efficiency and Φ_3 is the three-body phase space factor of $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$ with $M_{K_S^0 K_S^0} < 2.8 \text{ GeV}/c^2$. The Φ_3 is calculated with

$$\Phi_3 = \int_{4M_{K_S^0}^2}^{2.8^2} \rho_{\psi(3686) \rightarrow \gamma a}(s) \times \rho_{a \rightarrow K_S^0 K_S^0}(s) ds, \quad (6.3)$$

where ρ indicates corresponding two-body phase space factor. For the decay rate of pole a , one can not intuitively separate the contribution of individual pole from the total amplitude. Therefore, as an approximate approach, a Breit-Wigner function $\mathcal{R}_{\text{sum}}^a / (s - M_a^2 + iM_a\Gamma_a)$,

which yields exactly the same pole position $M_a - i\Gamma_a/2$ and residue $\mathcal{R}_{\text{sum}}^a$, is used to model the contribution from individual pole $|\mathcal{M}_a|^2$. The decay rate of such a Breit-Wigner function is calculated to be

$$\sigma_a = \int_{4M_{K_S^0}^2}^{2.8^2} \left| \frac{\mathcal{R}_{\text{sum}}^a}{s - M_a^2 + iM_a\Gamma_a} \right|^2 ds \simeq \int_0^\infty \left| \frac{\mathcal{R}_{\text{sum}}^a}{s - M_a^2 + iM_a\Gamma_a} \right|^2 ds = \frac{\pi |\mathcal{R}_{\text{sum}}^a|^2}{M_a\Gamma_a}. \quad (6.4)$$

Here, the narrow width assumptions [48] are used and it should be noted that the phase space factor has been included in the residue following eq. (4.10).

The total branching fraction $\mathcal{B}'(\psi(3686) \rightarrow \gamma K_S^0 K_S^0)$ is measured to be

$$\mathcal{B}'(\psi(3686) \rightarrow \gamma K_S^0 K_S^0) = \frac{N_{\text{sig}}}{N_{\psi(3686)} \times \epsilon \times \mathcal{B}^2(K_S^0 \rightarrow \pi^+\pi^-)} = (5.91 \pm 0.05) \times 10^{-5}, \quad (6.5)$$

where $N_{\text{sig}} = 17567 \pm 134$ is the signal number obtained by counting; $N_{\psi(3686)} = (2712 \pm 15) \times 10^6$ is the total $\psi(3686)$ number [24]; $\epsilon = (22.92 \pm 0.03)\%$ is the detection efficiency determined with signal MC sample generated based on the amplitude fit result; $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-) = (69.20 \pm 0.05)\%$ is quoted from PDG [37]. The systematic uncertainties of branching fraction $\mathcal{B}'(\psi(3686) \rightarrow \gamma K_S^0 K_S^0)$ include the following sources

- $\psi(3686)$ number: the systematic uncertainty of $\psi(3686)$ number is 0.6% [24].
- Photon reconstruction: the systematic uncertainty due to photon reconstruction efficiency is studied with the control sample $e^+e^- \rightarrow \gamma\mu^+\mu^-$, which is found to be 0.5% per photon.
- K_S^0 reconstruction: the systematic uncertainty associated with the K_S^0 reconstruction efficiency is studied with the control samples $J/\psi \rightarrow K_S^0 K^+\pi^- + c.c.$ and $J/\psi \rightarrow \phi K_S^0 K^+\pi^- + c.c.$, which is found to be 0.5% per K_S^0 .
- MC statistics: the systematic uncertainty caused by MC statistic $\sqrt{\frac{1-\epsilon}{N \cdot \epsilon}} = 0.1\%$.
- Helix correction: the systematic uncertainty associated with 4C kinematic fit is studied by performing helix correction to the signal MC sample. The variation on the signal efficiency 2.2% is assigned as this uncertainty.
- The quoted $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)$: the systematic uncertainty due to quoted $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-) = (69.20 \pm 0.05)\%$ is 0.1%.

The total systematic uncertainty are obtained to be 2.5% by summing all sources quadratically.

The branching fraction $\mathcal{B}'(\psi(3686) \rightarrow \gamma K_S^0 K_S^0)$ is finally calculated as $(5.91 \pm 0.05 \pm 0.02) \times 10^{-5}$. The branching fractions of individual poles are summarized in table 5.

7 Summary

By analyzing $(2712 \pm 14) \times 10^6$ $\psi(3686)$ events, we have performed the first amplitude analysis of $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$. Based on a one-channel K-matrix approach for the dynamics description, the data sample is well described with four poles for the f_0 -wave and three poles for the f_2 -wave.

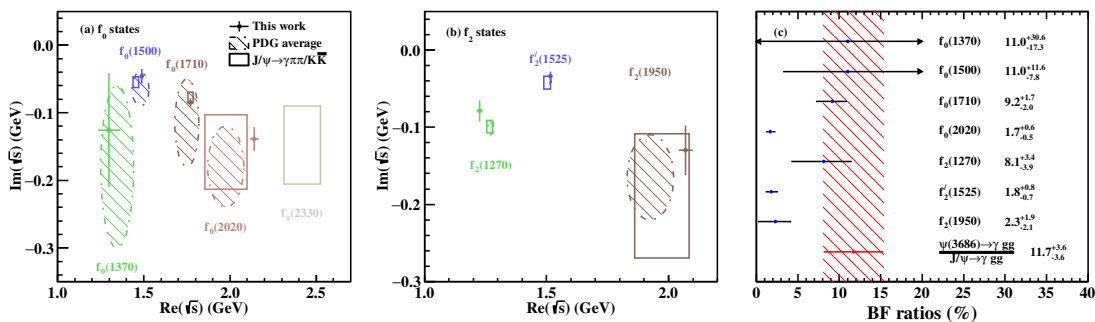


Figure 4. The pole positions of (a) f_0 and (b) f_2 states measured in this work, given by the PDG average, and $J/\psi \rightarrow \gamma\pi\pi/K\bar{K}$ [49]. The dots with error bars are obtained in this work. The hatched ellipses with dashed lines are the PDG values. The boxes with solid lines are cited from the 3-channel results of $J/\psi \rightarrow \gamma\pi\pi/K\bar{K}$ [49], where $f_0(2330)$ could only be identified with the 4π channel included. (c) The branching fraction ratios $\mathcal{B}(\psi(3686) \rightarrow \gamma f_{0,2})/\mathcal{B}(J/\psi \rightarrow \gamma f_{0,2})$ and their comparison with $\mathcal{B}(\psi(3686) \rightarrow \gamma gg)/\mathcal{B}(J/\psi \rightarrow \gamma gg)$ [37].

The determined pole positions are summarized in table 4, all of which match the well-known resonance states listed in the PDG as shown in figure 4. A further comparison is made with the combined analysis of $J/\psi \rightarrow \gamma\pi^0\pi^0/K_S^0K_S^0$ [49] as displayed in figure 4. The observations of $f_0(1500)$, $f_0(1710)$, $f_2'(1525)$, and $f_2(1950)$ are in good agreement between the two studies. For the $f_0(1370)$, the determined pole position in this work is not stable, and no pole is identified as $f_0(1370)$ in ref. [49]. The observed f_0 pole above 2 GeV is assigned as $f_0(2020)$, the mass of which is slightly higher than the corresponding averaged value in PDG. This possibly be due to the fact that PDG assigns the pole with higher mass as $f_0(2100/2200)$, which may be the same state as $f_0(2020)$. The pole $f_0(2330)$ is not observed in this work, nor in the 2-channel fit in ref. [49], but it is observed when including an additional 4π channel [49]. The pole position of $f_2(1270)$ slightly deviates from the previous measurements potentially due to the absence of $\pi\pi$ couple-channel effect in this analysis. This comparison suggests that the produced $f_{0,2}$ poles in the $\psi(3686)$ radiative decay are in agreement with these in J/ψ radiative decay.

The production behaviors of f_0 and f_2 poles in $\psi(3686) \rightarrow \gamma K_S^0 K_S^0$ are qualified with their residues in the multipole basis of helicity amplitude. The combined branching fractions $\mathcal{B}(\psi(3686) \rightarrow \gamma f_{0,2}, f_{0,2} \rightarrow K_S^0 K_S^0)$ are also calculated with residues under narrow width assumption. No significant violation of the relationship $E_1 > M_2 > E_3$, which is predicted by the conventional quark model [49] and confirmed in $J/\psi \rightarrow \gamma f_2$, is seen for $\psi(3686) \rightarrow \gamma f_2$ in current statistics. The branching fraction ratios $\mathcal{B}(\psi(3686) \rightarrow \gamma f_{0,2})/\mathcal{B}(J/\psi \rightarrow \gamma f_{0,2})$ are also listed in table 5 and shown in figure 4. By comparing the ratios with $\frac{\mathcal{B}(\psi(3686) \rightarrow \gamma gg)}{\mathcal{B}(J/\psi \rightarrow \gamma gg)} = (11.7 \pm 3.6)\%$, this work provides crucial experimental inputs on the internal structure of the $f_{0,2}$ states, especially their potential mixing with glueball components.

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Resonance	This work	PDG	$J/\psi \rightarrow \gamma\pi\pi/K\bar{K}$ [49]
$f_0(1370)$	$(1297.4 \pm 56.9 \pm 29.4) - i(125.8 \pm 71.5 \pm 44.0)$	$(1250 - 1440) - i(60 - 300)$	—
$f_0(1500)$	$(1487.8 \pm 7.7 \pm 3.7) - i(46.1 \pm 8.6 \pm 6.6)$	$(1430 - 1530) - i(40 - 90)$	$(1437 - 1471) - i(46 - 63)$
$f_0(1710)$	$(1770.7 \pm 5.1 \pm 4.2) - i(84.7 \pm 3.8 \pm 4.7)$	$(1680 - 1820) - i(50 - 180)$	$(1756 - 1785) - i(69 - 85)$
$f_0(2020)$	$(2141.9 \pm 17.2 \pm 17.9) - i(138.8 \pm 10.0 \pm 14.4)$	$(1870 - 2080) - i(120 - 240)$	$(1955 - 2098) - i(103 - 213)$
$f_2(1270)$	$(1226.2 \pm 8.6 \pm 8.8) - i(78.9 \pm 7.5 \pm 11.7)$	$(1260 - 1283) - i(90 - 110)$	$(1256 - 1279) - i(91 - 107)$
$f_2'(1525)$	$(1515.7 \pm 4.3 \pm 3.3) - i(33.7 \pm 3.8 \pm 4.1)$	$(1515 - 1520) - i(40 - 46)$	$(1488 - 1517) - i(34 - 50)$
$f_2(1950)$	$(2069.9 \pm 22.2 \pm 17.6) - i(130.0 \pm 26.0 \pm 19.3)$	$(1830 - 2020) - i(110 - 220)$	$(1862 - 2084) - i(108 - 269)$

Table 4. The pole positions determined in this work, cited from the PDG, and extracted from the 3-channel results of $J/\psi \rightarrow \gamma\pi\pi/K\bar{K}$ [49]. For this work, the first uncertainties are statistical and the second systematic. It should be noted that the PDG averaged values of some resonances have included ref. [49] hence there are some correlations.

$ \mathcal{R} ^2$	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$	$f_0(2020)$	$f_2(1270)$	$f_2(1525)$	$f_2(1950)$
E_1	$19.1^{+45.6}_{-12.1} \pm 26.7$	$11.9^{+9.7}_{-4.9} \pm 6.8$	$274.2^{+40.2}_{-29.9} \pm 27.4$	$137.3^{+24.5}_{-22.0} \pm 37.1$	$7.4^{+2.0}_{-2.4} \pm 3.6$	$3.4^{+1.8}_{-1.6} \pm 1.1$	$25.5^{+17.1}_{-11.5} \pm 11.9$
M_2	—	—	—	—	$9.3^{+2.2}_{-2.7} \pm 2.9$	$3.2^{+1.1}_{-1.2} \pm 1.0$	$5.5^{+5.5}_{-3.1} \pm 3.6$
E_3	—	—	—	—	$3.3^{+1.9}_{-1.0} \pm 1.4$	$0.7^{+1.0}_{-0.4} \pm 0.4$	$2.6^{+3.9}_{-1.5} \pm 1.5$
Sum	$19.1^{+45.6}_{-12.1} \pm 26.7$	$11.9^{+9.7}_{-4.9} \pm 6.8$	$274.2^{+40.2}_{-29.9} \pm 27.4$	$137.3^{+24.5}_{-22.0} \pm 37.1$	$20.1^{+3.9}_{-4.4} \pm 7.4$	$7.3^{+2.6}_{-2.1} \pm 2.1$	$33.5^{+20.7}_{-12.7} \pm 15.8$
$\mathcal{B}_{\psi(3686)} (\times 10^{-6})$	$1.2^{+2.8}_{-0.7} \pm 1.6$	$1.7^{+1.4}_{-0.7} \pm 1.0$	$18.3^{+2.7}_{-2.0} \pm 1.8$	$4.6^{+0.8}_{-0.7} \pm 1.3$	$2.1^{+0.4}_{-0.5} \pm 0.8$	$1.4^{+0.5}_{-0.4} \pm 0.4$	$1.2^{+0.8}_{-0.5} \pm 0.6$
$\mathcal{B}_{J/\psi} (\times 10^{-5})$	$1.1^{+0.1+0.4}_{-0.1-0.3}$	$1.6^{+0.2+0.2}_{-0.2-0.6}$	$20.0^{+0.3+3.1}_{-0.2-1.0}$	$27.2^{+0.8+1.7}_{-0.6-4.7}$	$2.6^{+0.1+0.6}_{-0.1-0.2}$	$8.0^{+0.0+0.7}_{-0.0-0.5}$	$5.5^{+0.3+3.8}_{-0.4-1.5}$
$\mathcal{B}_{\psi(3686)}/\mathcal{B}_{J/\psi} (\%)$	$11.0^{+30.6}_{-17.3}$	$11.0^{+11.6}_{-7.8}$	$9.2^{+1.7}_{-2.0}$	$1.7^{+0.6}_{-0.5}$	$8.1^{+3.4}_{-3.9}$	$1.8^{+0.8}_{-0.7}$	$2.3^{+1.9}_{-2.1}$

Table 5. The squared modulus of residues $|\mathcal{R}|^2$ and branching fractions $\mathcal{B}_{\psi(3686)}$ of $\psi(3686) \rightarrow \gamma R, R \rightarrow K_S^0 K_S^0$ for poles R obtained in this work, as well as the branching fractions $\mathcal{B}_{J/\psi}$ of individual resonances R in $J/\psi \rightarrow \gamma R, R \rightarrow K_S^0 K_S^0$ [18]. Here, the first uncertainty is statistical and the second is systematic.

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