Light meson decays at BESIII

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Abstract. The BESIII experiment has accumulated the world's largest data samples of 1.3 billion J/ψ events and 0.45 billion $\psi(3686)$ events, which provide a unique opportunity to investigate light meson decays. The η and η' decays are sensitive tools for investigations of $\pi-\pi$ and $\eta-\pi$ interactions, symmetry breaking, and serve as a test of chiral perturbation theory. In recent years considerable results on η and η' decays were achieved at the BESIII experiment. In this proceeding, we present the significant progresses on amplitude analyses of Dalitz decays $\eta' \to 3\pi$, $\eta' \to \eta\pi\pi$, and radiative decay $\eta' \to \gamma\pi^+\pi^-$, $\eta' \to \gamma\gamma\pi^0$. Additionally, the $a_0^0(980)$-$f_0(980)$ mixing is an important probe to the nature of those two lightest scalar mesons. The first observation of $a_0^0(980)$-$f_0(980)$ mixing is also presented, which will help to improve the understanding of the nature of $a_0^0(980)$ and $f_0(980)$.

1 Introduction

Light meson decays play a crucial role in examining and understanding the Quantum Chromodynamics (QCD) theory in non-pertubative energy region. The η' meson is well established and its main decay modes are fairly well known [1]. However, η' decay dynamics remains a subject of extensive theoretical studies aiming at extensions of the chiral perturbation theory (ChPT).

In addition, the scalar mesons $a_0^0(980)$ and $f_0(980)$ are difficult to accommodate into the traditional quark-antiquark model [2]. In theory, they are explained as tetra-quarks [3], $K\bar{K}$ molecule [4], or quark-antiquark gluon hybrid [5] and so on. The mixing mechanism in the system of $a_0^0(980)$-$f_0(980)$, is thought to be an essential approach to clarify the nature of these two mesons.

The BESIII detector has accumulated the world's largest data samples of 1.3 billion J/ψ events and 0.45 billion $\psi(3686)$ events, which provides a unique opportunity to investigate light meson physics through J/ψ and $\psi(3686)$ decays. In this presentation, we will introduce some recent results from BESIII Collaboration that are related to light meson decays.

2 η' meson decays

2.1 Amplitude analysis of the decays $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$

The decays $\eta' \to \pi\pi\pi$ are isospin-violating processes, and can be used to determine the light quark mass difference, which is parameterized as the ratios of decay widths, $r_\pm = \mathcal{B}(\eta' \to$

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$\pi^+\pi^-\pi^0)/\mathcal{B}(\eta' \to \pi^+\pi^-\eta)$ and $r_0 = \mathcal{B}(\eta' \to \pi^0\pi^0\pi^0)/\mathcal{B}(\eta' \to \pi^0\pi^0\eta)$ [6, 7]. In addition, it is predicted that the $\eta' \to \rho^\pm\pi^\mp$ P-wave contribution should be large for $\eta' \to \pi^+\pi^-\pi^0$ [8]. However, there is no direct experimental evidence of an intermediate $\rho^\pm$ contribution to the decay $\eta' \to \pi^+\pi^-\pi^0$.

In this proceeding, an amplitude analysis combining $\eta' \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^0\pi^0\pi^0$ events originating from J/ψ radiative decays is presented [9]. Projections of the data and fit results are displayed in Fig. 1. The data are well described by three components: P wave ($\rho^\pm\pi^\mp$), resonant S wave ($\sigma\pi^0$), and phase-space S wave ($\pi\pi\pi$). The statistical significances of all three components are found to be larger than 24σ.

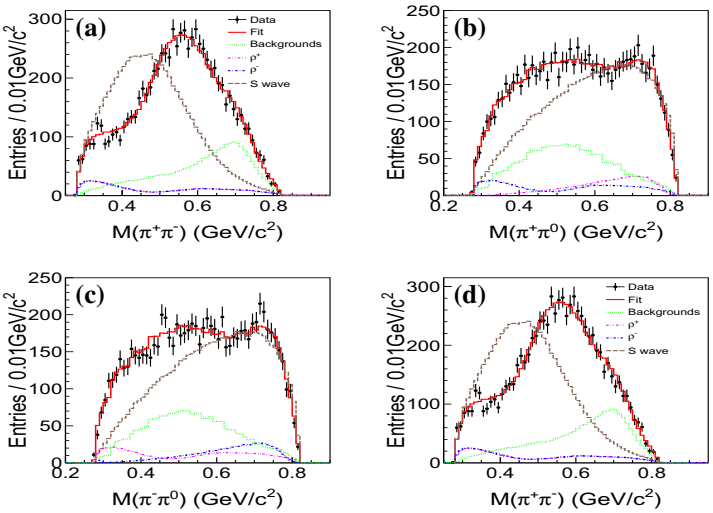

Figure 1. Comparison of the invariant mass distributions of (a) $\pi^+\pi^-$, (b) $\pi^+\pi^0$, (c) $\pi^-\pi^0$, and (d) $\pi^0\pi^0$ between data (dots with error bars) and the fit result projections (solid histograms). The dotted, dashed, dash-dotted, and dash-dot-dotted histograms show the contributions from background, S wave, ρ^-, and ρ^+, respectively.

With the branching fractions of $\eta' \to \pi\pi\eta$ taken from the PDG [1], $r_\pm$ and r_0 are calculated to be $(8.77 \pm 1.19) \times 10^{-3}$ and $(15.86 \pm 1.33) \times 10^{-3}$, respectively. The observed substantial P- and S-wave resonant contributions have to be properly considered by theory before attempting to determine light quark masses from $r_\pm$ and r_0.

2.2 Measurement of the matrix elements for the decays $\eta' \to \eta\pi\pi$

The two dominant hadronic decays, $\eta' \to \eta\pi^+\pi^-$ and $\eta' \to \eta\pi^0\pi^0$, are believed to be an ideal place to study $\pi\pi$ and $\eta\pi$ scattering [10, 11]. The matrix elements for $\eta' \to \eta\pi^+\pi^-$ have been studied by the CLEO [12], VES [13] and BESIII [14] Collaborations. The most recent measurement of $\eta' \to \eta\pi^0\pi^0$ is from the GAMS-4π experiment [15], complementing older results reported by the GAMS-2000 Collaboration [16].

In this proceeding, the most precise measurements of the matrix element for the $\eta' \to \eta\pi^+\pi^-$ and $\eta' \to \eta\pi^0\pi^0$ decays are presented based on J/ψ radiative decay [17]. Both the general and the linear representations are used to determine the Dalitz plot parameters, the fit results are shown in Fig. 2. The Dalitz plot parameters for both decays are in reasonable agreement and more precise than the previous measurements [12–15].

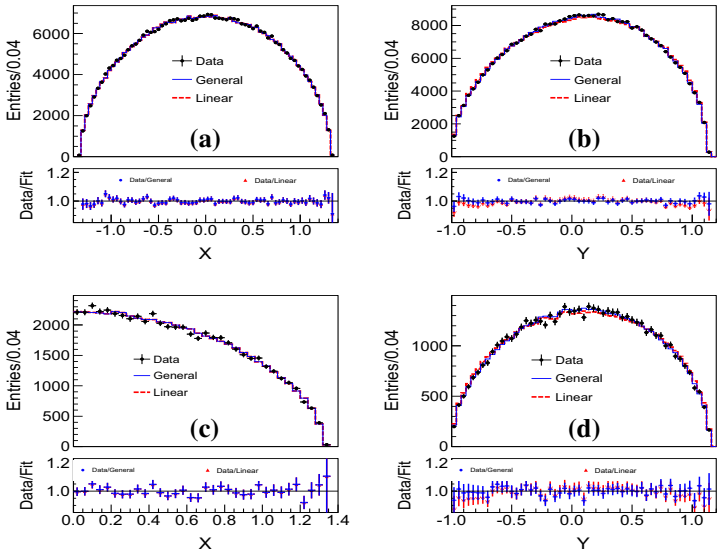

Figure 2. Projections of the fit results onto (a) X and (b) Y for $\eta' \to \eta\pi^+\pi^-$, (c) X and (d) Y for $\eta' \to \eta\pi^0\pi^0$ in the general (solid histograms) and linear (dashed histograms) representations, where the dots with error bars represent data.

2.3 Precision study of $\eta' \to \gamma\pi^+\pi^-$ decay dynamics

In the vector meson dominance (VMD) model [18], the radiative decay $\eta' \to \gamma\pi^+\pi^-$ is dominated by the decay $\eta' \to \gamma\rho(770)$. In the past, the dipion mass distribution was studied by several experiments [19–22]. A peak shift of about +20 MeV/c^2 for the ρ^0 meson with respect to the expected position was observed. This discrepancy could be attributed to a higher term of the Wess-Zumino-Witten anomaly, known as the box anomaly, in the chiral perturbation theory (ChPT) Lagrangian [23].

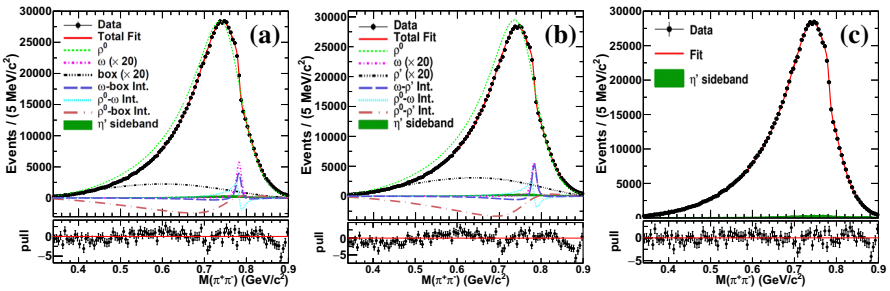

Figure 3. (a) Model-dependent fit results in case ρ^0-ω-box anomaly; (b) model-dependent fit results in case ρ^0-ω-ρ'; (c)model-independent fit with ω interference. Dots with error bars represent data, the green shaded histograms are the background from η' sideband events, the red solid curves are the total fit results, and others represent the separate contributions as indicated.

In this proceeding, we present a precision measurement of the dipion mass distribution for the $\eta' \to \gamma\pi^+\pi^-$ process originating from the radiative decays $J/\psi \to \gamma\eta'$ [24]. Both model-dependent and model-independent approaches are used to investigate the decay dynamics,

the fit results are shown in Fig. 3. The ω contribution is observed for the first time in the dipion mass spectrum. The model-dependent fit indicates that only the components of ρ^0 and ω as well as the corresponding interference fail to describe the data, and an extra significant contribution, *i.e.* the box anomaly or ρ^+, is found to be necessary. The model independent approach provides a satisfactory parametrization of the dipion invariant mass spectrum.

2.4 Observation of the doubly radiative decay $\eta' \to \gamma\gamma\pi^0$

Recently, the doubly radiative decay $\eta' \to \gamma\gamma\pi^0$ was studied in the frameworks of the linear σ model (LσM) [25] and the VMD model [26], which demonstrated that the contributions from the VMD are dominant. Experimentally, only an upper limit of the nonresonant branching fraction of $\mathcal{B}(\eta' \to \gamma\gamma\pi^0)_{\rm NR} < 8 \times 10^{-4}$ at the 90% confidence level has been determined by the GAMS-2000 experiment [27].

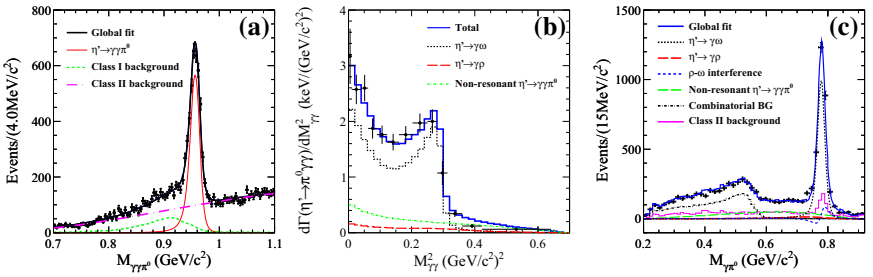

Figure 4. (a) Results of the fit to $M_{\gamma\gamma\pi^0}$ for the selected inclusive $\eta' \to \gamma\gamma\pi^0$ signal events; (b) partial width (in keV) versus $M^2_{\gamma\gamma}$ for the inclusive $\eta' \to \gamma\gamma\pi^0$ decay; (c)distribution of the invariant mass $M_{\gamma\pi^0}$ and fit results in the η' mass region.

The invariant mass of $M_{\gamma\gamma\pi^0}$ and the $M^2_{\gamma\gamma}$ dependent partial widths are shown in Fig. 4 (a) and (b), respectively. The branching fraction of the inclusive decay is measured for the first time to be $\mathcal{B}(\eta' \to \gamma\gamma\pi^0)_{\rm Incl.} = (3.20 \pm 0.07(\text{stat}) \pm 0.23(\text{sys})) \times 10^{-3}$. In addition, the branching fraction for the nonresonant decay is determined to be $\mathcal{B}(\eta' \to \gamma\gamma\pi^0)_{\rm NR} = (6.16 \pm 0.64(\text{stat}) \pm 0.67(\text{sys})) \times 10^{-4}$, which agrees with the upper limit measured by the GAMS-2000 experiment [27]. The invariant mass of $M_{\gamma\pi^0}$ is shown as in Fig. 4 (c), and the product branching fraction with the omega intermediate state involved is obtained to be $\mathcal{B}(\eta' \to \gamma\omega) \cdot \mathcal{B}(\omega \to \gamma\pi^0) = (2.37 \pm 0.14(\text{stat}) \pm 0.18(\text{sys})) \times 10^{-3}$. These results are useful to test QCD calculations on the transition form factor, and provide valuable inputs to the theoretical understanding of the light meson decay mechanisms.

3 Observation of $a_0^0(980)$-$f_0(980)$ mixing

The nature of the scalar mesons $a_0^0(980)$ and $f_0(980)$ have been controversial for several decades. In theory, these two states are difficult to accommodate in the traditional quark-antiquark model [2], and many alternative formulations have been proposed to explain their internal structure, including tetra-quarks [2, 3], $K\bar{K}$ molecule [4], or quark-antiquark gluon hybrid [5].

The mixing mechanism of $a_0^0(980)$-$f_0(980)$, which was first proposed in the late 1970s [28], is thought to be an essential approach to clarify the nature of these two mesons. The mixing mechanism predicts a narrow peak of about 8 MeV/c^2 in width between the charged and neutral $K\bar{K}$ mass thresholds, while the normal widths of $a_0^0(980)$ and $f_0(980)$

should be 50 – 100 MeV/c^2 [1]. The mixing intensities, ξ_{fa} and ξ_{af}, are important experimental probes for the nature of $a_0^0(980)$ and $f_0(980)$, as they are sensitive to the coupling constants in the processes of $a_0^0(980) \to K\bar{K}$ and $f_0(980) \to K\bar{K}$, respectively. A direct measurement of the mixing intensities would provide crucial constraints in models of $a_0^0(980)$ and $f_0(980)$ internal structure.

In this proceeding, we present a study of $a_0^0(980)$-$f_0(980)$ mixing with the decays of $J/\psi \to \phi\eta\pi^0$ ($\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$, $\phi \to K^+K^-$) and $\psi(3686) \to \gamma\chi_{c1} \to \gamma\pi^0\pi^+\pi^-$ [29]. The signals of $a_0^0(980)$-$f_0(980)$ mixing are observed with a statistical significance of larger than 5σ for the first time, and the corresponding branching fractions and mixing intensities are summarized in Table 1.

Table 1. The branching fractions ($\mathcal{B}$) and the intensities (ξ) of the $a_0^0(980)$-$f_0(980)$ mixing. The first uncertainties are statistical, the second ones are systematic, and the third are related to parameterization of $a_0^0(980)$ and $f_0(980)$.

Channel	$f_0(980) \to a_0^0(980)$		$a_0^0(980) \to f_0(980)$
	Solution I	Solution II	
$\mathcal{B}$(mixing) (10^{-6})	$3.18 \pm 0.51 \pm 0.38 \pm 0.28$	$1.31 \pm 0.41 \pm 0.39 \pm 0.43$	$0.35 \pm 0.06 \pm 0.03 \pm 0.06$
$\mathcal{B}$(EM) (10^{-6})	$3.25 \pm 1.08 \pm 1.08 \pm 1.12$	$2.62 \pm 1.02 \pm 1.13 \pm 0.48$	—
$\mathcal{B}$(total) (10^{-6})	$4.93 \pm 1.01 \pm 0.96 \pm 1.09$	$4.37 \pm 0.97 \pm 0.94 \pm 0.06$	—
ξ (%)	$0.99 \pm 0.16 \pm 0.30 \pm 0.09$	$0.41 \pm 0.13 \pm 0.17 \pm 0.13$	$0.40 \pm 0.07 \pm 0.14 \pm 0.07$

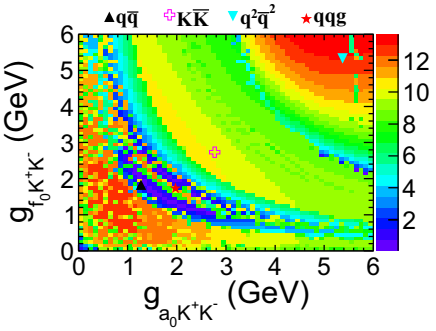

Figure 5. The statistical significance of the signal scanned in the two-dimensional space of $g_{a_0K^+K^-}$ and $g_{f_0K^+K^-}$. The regions with higher statistical significance indicate larger probability for the emergence of the two coupling constants. The markers indicate predictions from various illustrative theoretical models.

Since $a_0^0(980)$-$f_0(980)$ mixing is sensitive to the coupling constants of $a_0^0(980) \to K\bar{K}$ and $f_0(980) \to K\bar{K}$, we obtain the statistical significance of the mixing signal by scanning the two coupling constants $g_{a_0K^+K^-}$ and $g_{f_0K^+K^-}$. The statistical significance of the signal scanned in the two-dimensional space of $g_{a_0K^+K^-}$ and $g_{f_0K^+K^-}$ is shown in Fig. 5. For the distribution, the regions with higher statistical significance indicate larger probability for the emergence of the two coupling constants. The predicted coupling constants from various models [30] are displayed as well (color markers), but the theoretical uncertainties on the models are not considered here.

4 Summary

With the largest data samples of 1.3 billion J/ψ events and 0.45 billion $\psi(3686)$ events, the BESIII Collaboration has made significant progresses on light meson decays. Firstly, η'

hadronic Dalitz decays $\eta' \to 3\pi$, $\eta' \to \eta\pi\pi$, and η' radiative decays $\eta' \to \gamma\pi^+\pi^-$ as well as the double radiative decay $\eta' \to \gamma\gamma\pi^0$ are investigated, which deepen our knowledge about η' decay dynamics. Secondly, the $a_0^0(980)$-$f_0(980)$ mixing is observed with the statistical significance of large than 5σ for the first time. The corresponding branching fractions and mixing intensities are measured. The constraint regions on the coupling constants, $g_{a_0K^+K^-}$ and $g_{f_0K^+K^-}$, are also estimated. The results will help to improve the understanding of the nature of $a_0^0(980)$ and $f_0(980)$.

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