EPJ Web of Conferences **291**, 02001 (2024) https://doi.org/10.1051/epjconf/202429102001
MESON 2023

Light Meson Decays at BESIII

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Abstract. At the precision frontier of particle physics, light mesons decays play important roles in understanding strong interactions, quark Model, CP violations, and so on. They provide valuable laboratories for the testing Chiral Perturbative Theory predictions, studying the EM form factors and fundamental sysmmetries, and last but not least, probing new physics beyond the Standard Model. In this talk, we present the new results from BESIII about the η' and η decays based on large J/ψ datasets.

1 Introduction

As the neutral members of the ground state pseudoscalar nonet, both η and η' play an important role in understanding low energy quantum chromodynamics (QCD). In particular the η' meson, much heavier than the Goldstone bosons of broken chiral symmetry, plays a special role as the predominant singlet state arising from the strong axial *U(1)* anomaly. In addition, the decays of both mesons are used to search for processes beyond any considered extension of the Standard Model (SM) and to test fundamental discrete symmetries [1].

There are several experiments in the world which can provide source of η or η' events, including CLAS and GlueX at Jefferson Lab, Crystal Ball at BNL, WASA at COSY, KLOE-2 at INFN, and BESIII at IHEP. Among them, the BESIII is the one that had accumulated largest datasets of η and η' produced from J/ψ and ψ' decays, and will keep collecting data for more years. For example, with 10 billion J/ψ events, 1×10^7 and 4×10^6 of η mesons are produced from $J/\psi \to \gamma\eta$ and $J/\psi \to \phi\eta$, 5.2×10^7 and 2.5×10^6 of η' meson are produced, respectively.

The BESIII detector is installed on BEPCII accelerator and located in Beijing. It consistes of a helium-gas based drift chamber (MDC), a CsI(Tl) crystal calorimeter, a Time-of-Flight system, a 9-layer PRC-based muon chamber system, and a super-conducting solenoid megnet with a central field of 1.0 Tesla [2]. BESIII has performed a series of measurements on η and η' decays since data collection. In this talk, some new results on the light hadron decays from BESIII are presented.

2 $\eta' \to \pi^+\pi^- l^+ l^-$

The decays $\eta' \to \pi^+\pi^- l^+ l^-$ with ($l = e$ or μ) are especially interesting since these two decays may involve the box anomaly contribution [3]. Theoretically, these decays have been

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investigated with different models, including the effective meson theory, the chiral unitary approach, and the hidden gauge model. In previous analyses, the CLEO Collaboration [4] and BESIII analysis [5] have not observed $\eta' \to \pi^+\pi^-\mu^+\mu^-$ decays due to the virtual photon conversion to dimuon is significantly suppressed. The first experimental evidence of the decay $\eta' \to \pi^+\pi^-e^+e^-$ was obtained by the CLEO experiment [4]. Later, BESIII publised more precise result using 225 million J/ψ events [5].

Based on 1.3 billion J/ψ events at BESIII, the decay $\eta' \to \pi^+\pi^-\mu^+\mu^-$ is observed for the first time with a significance of 8σ. And the most precise branching ratio of $\eta' \to \pi^+\pi^-\mu^+\mu^-$ and $\eta' \to \pi^+\pi^-e^+e^-$ are measured as $B(\eta' \to \pi^+\pi^-e^+e^-) = (2.42\pm0.05_{stat.}\pm0.08_{syst.})\times10^{-3}$ [7] and $B(\eta' \to \pi^+\pi^-\mu^+\mu^-) = (1.97 \pm 0.33_{stat.} \pm 0.19_{syst.}) \times 10^{-5}$ [6], respectively. These results are consistent with current theoretical model predictions [8, 9].

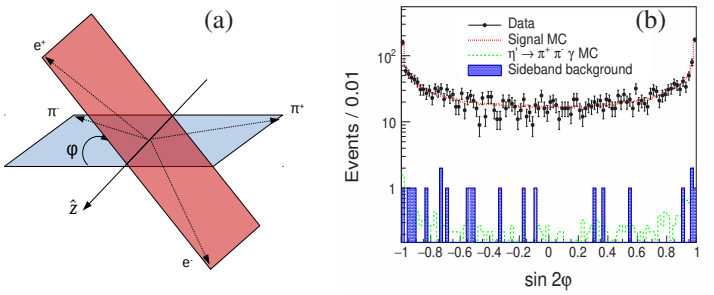

Figure 1. (a) Illustration of the decay plane angle φ in $\eta' \to \pi^+\pi^-e^+e^-$. (b) Distribution of $\sin 2\varphi$. Dots with error bars represent data, the dotted (red) histrogram represents the signal MC sample generated with a symmetric $\sin 2\varphi$ distribution, the dashed (green) histrogram represents the remaining background contribution.

The decay $\eta' \to \pi^+\pi^-e^+e^-$ allows for a test of CP-violation due to the interference between the dominating, CP-converving, magnetic transition, and a possible CP-violating electric dipole type transition [10]. Such an interference term is proportional to $\sin 2\varphi$, where φ is the angle between the decay planes of the e^+e^--pair and the $\pi^+\pi^-$-pair, as shown in Fig. 1 (a). Experimentally, the electric dipole transition will manifest itself as an asymmetry $\mathcal{A}_\varphi = \frac{N(\sin 2\varphi>0)-N(\sin 2\varphi<0)}{N(\sin 2\varphi>0)+N(\sin 2\varphi<0)}$, where $N(x)$ represents the acceptance-corrected number of events in the corresponding angular region. Based on the 1.3 billion J/ψ events, BESIII measured this observable as $\mathcal{A}_\varphi = (2.9 \pm 3.7_{stat.} \pm 1.1_{syst.})\%$ [7]. The distribution of $\sin 2\varphi$ from data is shown in Fig. 1 (b). This result is consistent with the SM prediction, and no CP violation is observed.

3 $\eta' \to l^+l^-l^+l^-$

The η' decays to four leptons are of great interest for understanding the pseudoscalar transition form factor (TFF) and the interactions between pseudoscalars and virtual photons. The TFF is necessary input to the pseudoscalar-meson-pole contributions to the hadronic light-by-light scattering, which causes the second largest uncertainty for $g-2$ of muon. By means of a data-driven approach based on the use of rational approximants applied to π^0, η and η' transition form factor experimental data in the space-like region, the branching ratios of double Dalitz decays are predicted [11]. However, there is no concrete experimental evidence yet.

Based on 10 billion J/ψ events, the double Dalitz decay $\eta' \to e^+e^-e^+e^-$ is observed for the first time, with a significance of 5.7σ with systematic uncertainties taken into consideration. Its branching fraction is determined to be $\mathcal{B}(\eta' \to e^+e^-e^+e^-) = (4.5 \pm 1.0_{stat.} \pm 0.5_{syst.}) \times 10^{-5}$, which is in reasonable agreement with theoretical predictions. This result provides new information for the studies about η' Timelike-Form-Factor (TFF) and the interactions between η' and virtual photons.

4 $\eta' \to \eta\pi^0\pi^0$

In $\pi\pi$ interaction, one of the prominent features is the loop contribution to the $\pi\pi$ scattering: the S-wave charge-exchange rescattering $\pi^+\pi^- \to \pi^0\pi^0$ causes a prominent cusp at the center of mass energy corresponding to the summed mass of two charged pions. The cusp effect can shed light on the fundamental properties of QCD at low energies, by determining the strength of the S-wave $\pi\pi$ interaction [13–17]. This effect was firstly observed in $K^+ \to \pi^0\pi^0\pi^+$ in 2006 by NA48/2 experiment. While not been seen in $\eta \to 3\pi^0$ or $\eta' \to \eta\pi^0\pi^0$ channels even there are theoretical predictions.

Based on 10 billion J/ψ events at BESIII, a dedicated study on $J/\psi \to \gamma\eta'$, $\eta' \to \eta\pi^0\pi^0$ is performed. From the invariant mass distribution of $\pi^0\pi^0$, a clear cusp effect appears. Using an unbinned maximum likelihood method, a fit is performed on the Dalitz plot of $M^2(\pi^0\pi^0)$ versus $M^2(\eta\pi^0)$ within the frame work of nonrelativistic effective field theory (NREFT) [18]. The fit result is shown in Fig. 2. The amplitude provides a good description of the structure around the charged pion mass threshold and the statistical significance is found to be around 3.5σ. The scattering length combination $a_0 - a_2$ is measured to be $0.226 \pm 0.060_{stat.} \pm 0.013_{syst.}$, which is in good agreement with the theoretical value of 0.2644 ± 0.0051 [19] within the uncertainties. The observation of the evidence of the cusp effect in $\eta' \to \eta\pi^0\pi^0$ decay demonstrates the excellent potential to investigate the underlying dynamics of light mesons at the BESIII experiment.

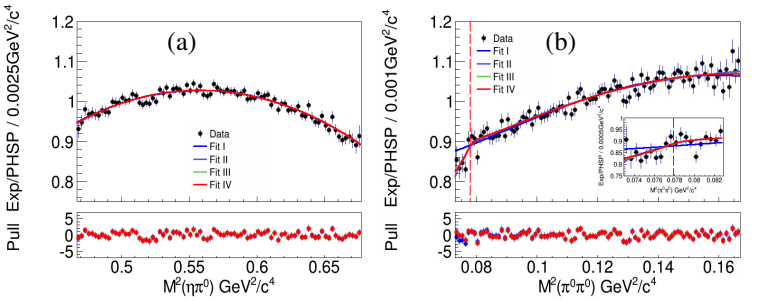

Figure 2. The fit result projections divided by phase space of different models to variable (a) $M^2(\eta\pi^0)$ and (b) $M^2(\pi^0\pi^0)$.

5 Updated results on $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^0\pi^0\pi^0$

The decay of η meson into 3π violates isospin symmetry and is related to the difference of light-quark masses. Therefore, this decay offers a unique way to determine the quark mass. With 10 billion J/ψ events, about 0.6 million events of $\eta \to \pi^+\pi^-\pi^0$ and 0.27 million $\eta \to \pi^0\pi^0\pi^0$ have been collected and analyzed with Dalitz analysis method [20].

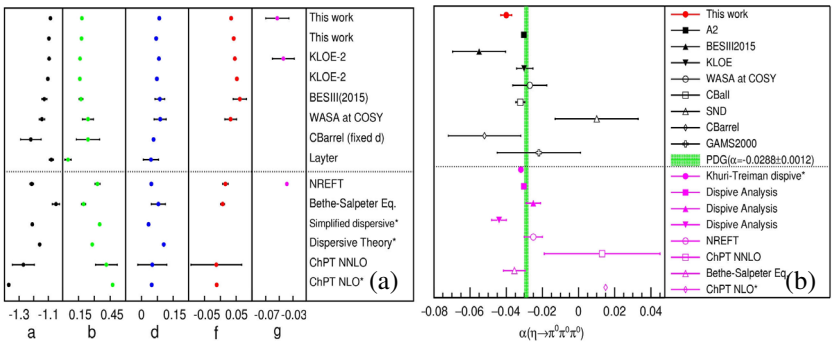

Figure 3. Comparison of the experimental measurements and theoretical calculations for (a) $\eta \to \pi^+\pi^-\pi^0$ and (b) $\eta \to \pi^0\pi^0\pi^0$. No uncertainties were reported for theoretical predictions and marked by $*$ in the legend.

The matrix elements for both channels are in reasonable agreement with previous measurements. The results comparing with previous experimental results and various theoretical predictions are shown in Fig. 3 for both channels. For the charged channel (left plot), the decay parameter results are compared with experimental results from KLOE-2 [21], BESIII in 2015 [22], WASA at COSY [23], CBarrel [24], Layter [25], and theoretical calculations from NREFT [26], Bethe-Salpeter [27], Simplified dispersive [28], Dispersive Theory [29], ChPT NNLO and ChPT NLO [30]. For the neutral channel (right plot), the α parameter is compared with experimental results from A2 [31], BESIII [22], KLOE [32], WASA at COSY [33], CBall [34], SND [35], CBarrel [36], GAMS2000 [37] and average value from PDG [38], and theoretical calculations from Khuri-Treiman dispive [39], Dispive Analysis [40, 41], NREFT [26], ChPT NNLO [30], Bethe-Salpeter [27], and ChPT NLO [28]. A nonzero gX^2Y term for the decay mode $\eta \to \pi^+\pi^-\pi^0$ is confirmed, as reported by the KLOE Collaboration, while the other higher-order terms are found to be insignificant. Dalitz plot asymmetries in the $\eta \to \pi^+\pi^-\pi^0$ decay are also explored and found to be consistent with charge conjugation invariance. In addition, a cusp effect is investigated in the $\eta \to \pi^0\pi^0\pi^0$ decay, and no obvious structure around the $\pi^+\pi^-$ mass threshold is observed.

6 Summary

We present the recent results on the light meson decays in this talk, such as the η or η' hadronic decays, leptonic decays, and rare decays. The huge J/ψ dataset from BESIII offers a unique place for the light meson study and make the high precision measurement possible. We are expecting that more results, *i.e.*, more precise result of η or η' Dalitz decays, rare and forbidden decays, form factors and so on will come in the future.

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