PROCEEDINGS OF SCIENCE

Light Meson decays at BESIII

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The BESIII experiment has accumulated the world's largest J/ψ sample, and its radiative or hadronic decays offer a unique opportunity to investigate physics in the low-energy region. This report presents the recent highlights in η/η' decays at BESIII, including evidence of the cusp effect in $\eta' \to \pi^0\pi^0\eta$, study of the chiral anomaly in $\eta' \to \pi^+\pi^-\pi^+\pi^-$ and form factor measurements with $\eta/\eta' \to \gamma e^+e^-$ and $\eta' \to \pi^+\pi^-l^+l^-$.

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1. Introduction

Because of the special role in understanding low energy quantum chromodynamics (QCD), η and η' mesons attract considerable theoretical and experimental attention, e.g., $\eta - \eta'$ mixing parameters, the light quark mass ratio, the hadronic contributions to the anomalous magnetic moment of the muon. In addition, η and η' decays offer unique opportunities to investigate their decay dynamics and test different chiral perturbation theory (ChPT) and the vector meson dominance (VMD) models.

The BESIII detector is operated at BEPCII, an e^+e^- collider running at a center of mass energy of 2-4.9 GeV. BESIII experiment has accumulated 10 billion J/ψ events. Copious η and η' mesons are produced via radiative and hadronic decays of J/ψ. Considering the radiative decays of $J/\psi \to \gamma\eta/\eta'$, the total J/ψ sample corresponding to 1.1×10^7 η mesons and 5.2×10^7 η' mesons, respectively, which allows to analysis specific decays with the unprecedented statistics.

2. Evidence of the Cusp Effect in $\eta' \to \pi^0\pi^0\eta$

The $\pi\pi$ interactions at low energies have been the subject of investigations for a few decades. 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 [1–6].

With a 10 billion J/ψ data sample, 4.3×10^5 $\eta' \to \eta\pi^0\pi^0$ events are selected with the BESIII detector. Using the unbinned maximum likelihood method, a fit based on the nonrelativistic effective field theory (NREFT) is performed on the Dalitz plot of $M^2(\pi^0\pi^0)$ versus $M^2(\eta\pi^0)$. The fit result is shown in the Fig. 1. The fit with tree level amplitude (Fit I) shows a discrepancy below the charged pion mass threshold, and the contribution of one- and two-loop level (Fit II Fit IV) can better describe the data of this region. The significance of the cusp effect is found to be around 3.5σ. The scattering length combination $a_0 - a_2$ is measured to be $0.226 \pm 0.060_{\text{stat}} \pm 0.013_{\text{syst}}$, which is in good agreement with theoretical calculation [7]. Observing 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.

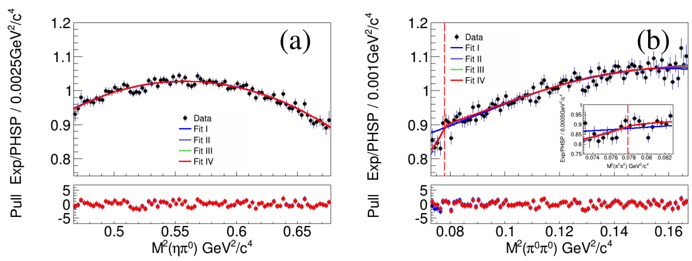

Figure 1: The fit result projections divided by phase space of (a)$M^2(\eta\pi^0)$ and (b)$M^2(\pi^0\pi^0)$.

3. Study of the Chiral Anomaly in $\eta' \to \pi^+\pi^-\pi^+\pi^-$

The η' meson, interpreted as a flavor singlet state arising from the axial U(1) anomaly, has attracted both theoretical and experimental attention due to its special role in helping to understand low-energy Quantum Chromodynamics (QCD). Its dominant radiative and hadronic decays have been observed and well measured, however the study of its rare decays is still an open field, and is of value for investigating the symmetry-breaking mechanisms. A theoretical combination of ChPT and VMD has calculated the anomalous decay of $\eta \to 2(\pi^+\pi^-)$ [8] to test the chiral anomalies of η' decays. The decay amplitude is described by $\mathcal{A}(\eta' \to \pi^+\pi^-\pi^+\pi^-) = \epsilon_{\mu\nu\alpha\beta} p_1^\mu p_2^\nu p_3^\alpha p_4^\beta \left\{ \left[\frac{s_{12}}{D_\rho(s_{12})} + \frac{s_{34}}{D_\rho(s_{34})} - \frac{s_{14}}{D_\rho(s_{14})} - \frac{s_{23}}{D_\rho(s_{23})} \right] + \alpha \left[\frac{M_\rho^2(s_{12}+s_{34})}{D_\rho(s_{12})D_\rho(s_{34})} - \frac{M_\rho^2(s_{14}+s_{23})}{D_\rho(s_{14})D_\rho(s_{23})} \right] \right\}$ and α corresponds to the individual parameters.

With 10 billion J/ψ data samples, 1.7×10^3 $\eta' \to \pi^+\pi^-\pi^+\pi^-$ events are selected collected with the BESIII detector [9]. Using the unbinned maximum likelihood method, the amplitude analysis fit gives $\alpha = 1.22 \pm 0.33_{\text{stat.}} \pm 0.04_{\text{syst.}}$, where fit results to the mass spectra of different $\pi^+\pi^-$ combinations are illustrated in Fig. 2. Since the high statistical uncertainties of fit result, we cannot make a conclusion about which chiral anomaly is dominant.

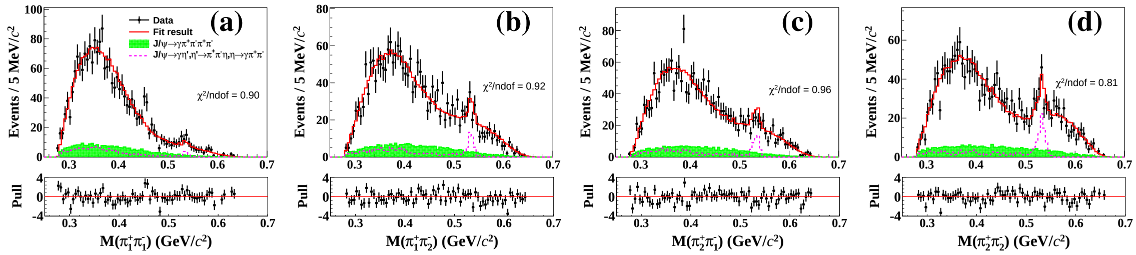

Figure 2: The fitted projections to the invariant mass of four $\pi^+\pi^-$ combinations, where $\pi_1^{+(-)}$ and $\pi_2^{+(-)}$ are sorted in ascending order of their energy.

4. Measurement of the Form Factors in $\eta/\eta' \to \gamma e^+e^-$

In the Dalitz decays $\eta/\eta' \to \gamma l^+l^-(l = e, \mu)$, the lepton pair is formed through the internal conversion of an intermediate virtual photon. These decays are of special interest since their decay rates are sensitive to the electromagnetic structure arising at the vertex of the transition. Deviations of the measured quantities from their quantum electrodynamics (QED) predictions are usually described in terms of a timelike transition form factor, which sheds light on the meson's structure [10]. In addition, these Dalitz decays also play an important role in the evaluation of the hadronic light-by-light contribution to the muon anomalous magnetic moment [11]. Modifications to the QED decay rate due to the inner structure of the mesons are incorporated in the transition form factor (TFF) $F(q^2)$, where q is the momentum transferred to the lepton pair.

The single-pole TFF is written as $1/(1 - q^2/\Lambda^2)$ of η decays. In the case of the η', the pole is expected to lie within the kinematic boundaries of the decay. A widely used expression for the multi-pole form factor is $\frac{\Lambda^2(\Lambda^2+\gamma^2)}{(\Lambda^2-q^2)^2+\Lambda^2\gamma^2}$. The parameter to be experimentally determined is the slope of the form factor b.

With 10 billion J/ψ data sample, 2.3×10^4 $\eta\to\gamma e^+e^-$ events and 7.6×10^3 $\eta'\to\gamma e^+e^-$ events are selected collected with the BESIII detector [12]. Using the unbinned maximum likelihood method, fits are performed on the invariant mass of e^+e^-. The results are illustrated in Fig. 3. The parameters Λ_η, $\Lambda_{\eta'}$, and $\gamma_{\eta'}$ are determined to be $(0.749\pm0.027\pm0.008)$ GeV$/c^2$, $(0.802\pm0.007\pm0.008)$ GeV$/c^2$ and $(0.113\pm0.010\pm0.002)$ GeV$/c^2$, respectively, in good agreement with previous works.

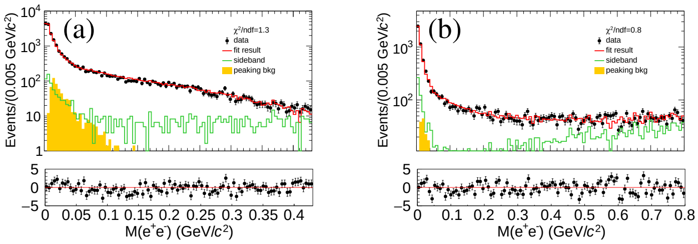

Figure 3: The fits to the $\eta^{(\prime)}$ form factors for (a) $\eta\to\gamma e^+e^-$ and (b) $\eta'\to\gamma e^+e^-$.

5. Measurement of the Form Factors in $\eta'\to\pi^+\pi^-l^+l^-$

The $\eta'\to\pi^+\pi^-l^+l^-$ (with $l=e$ or μ) decays are of great interest in both theoretical and experimental research as they involve contributions from the box-anomaly of quantum chromodynamics (QCD), and can be used to probe TFFs [13]. The TFF is of utmost importance because it determines the size of hadronic quantum corrections in the calculation of the anomalous magnetic moment of the muon, $(g-2)_\mu$ [11]. Theoretically, the $\eta'\to\pi^+\pi^-l^+l^-$ decays have been investigated with different models, including the hidden gauge model [13], the chiral unitary approach [14] and the VMD models [13].

The TFF of this article is derived from the VMD model with finite-width corrections as [15] $\mathrm{VMD}(s_{\pi\pi},s_{ll})=1-\frac{3}{4}(c_1-c_2+c_3)+\frac{3}{4}(c_1-c_2-c_3)\times\frac{m_V^2}{m_V^2-s_{ll}-im_V\Gamma(s_{ll})}+\frac{3}{2}c_3\frac{m_{V,\pi}^2}{m_{V,\pi}^2-s_{\pi\pi}-im_{V,\pi}\Gamma(s_{\pi\pi})}\times\frac{m_V^2}{m_V^2-s_{ll}-im_V\Gamma(s_{ll})}$. Here m_V and $m_{V,\pi}$ are the masses of the vector meson $V(V\to l^+l^-)$ and $V_\pi(V_\pi\to\pi^+\pi^-)$, respectively. The parameters c_{1-3} are model dependent and determine the contributions of the different interaction terms. Γ is its total width [16].

Unbinned maximum likelihood fits to the l^+l^- and $\pi^+\pi^-$ mass spectra are performed to determine the fit parameters in the VMD factor. The fit results is illustrated in Fig. 4. We calculate a weighted average of $b_{\eta'}=1.30\pm0.19$ (GeV$/c^2)^{-2}$ for $\eta'\to\pi^+\pi^-e^+e^-$ and $\eta'\to\pi^+\pi^-\mu^+\mu^-$ combined [17], where the uncertainty is obtained by combining statistical and systematic uncertainties. The value of $b_{\eta'}$ measured in this work is consistent with the VMD theoretical calculations and the previous results.

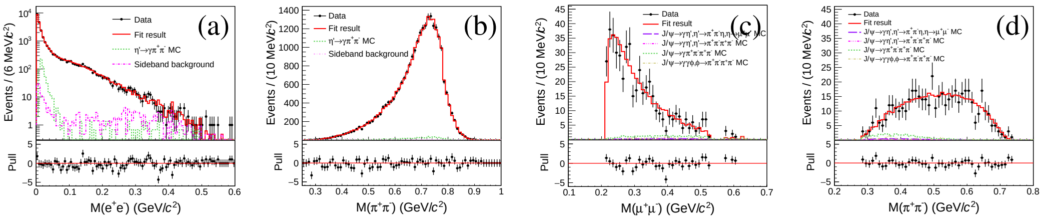

Figure 4: Fits to the invariant mass distributions of (a) e^+e^- and (b) $\pi^+\pi^-$ for $\eta' \to \pi^+\pi^-e^+e^-$, (c) $\mu^+\mu^-$ and (d) $\pi^+\pi^-$ for $\eta' \to \pi^+\pi^-\mu^+\mu^-$.

6. Summary

We present the recent results on the light meson decays in this talk, mainly focused on the decay mechanisms and form factors measurements of η and η'. The comparison of the η/η' form factors between different experiments and theoretical calculations is illustrated in Fig. 5. The huge J/ψ data set from BESIII offers a unique place for the light meson study and make the high precision measurement possible. We are expecting more results, i.e., more precise results of η or η' rare decays and forbidden decays.

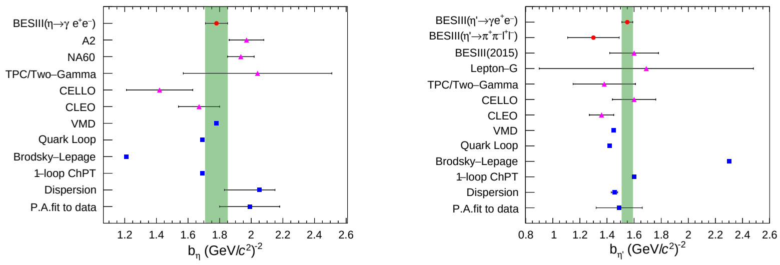

Figure 5: Slope parameters of the η(left) and η'(right) TFFs extracted from different experiments and calculated by different theoretical models. The points refer to experiments [18–24] (purple triangles), theoretical calculations [10, 25–29] (blue squares) and the BESIII measurements [12, 17] (red dots).

References

[1] U.-G. Meissner, G. Muller, and S. Steininger, Phys. Lett. B **406**, 154 (1997), [Erratum: Phys.Lett.B 407, 454 (1997)].

[2] N. Cabibbo, Phys. Rev. Lett. **93**, 121801 (2004).

[3] N. Cabibbo and G. Isidori, JHEP **03**, 021 (2005).

[4] G. Colangelo, J. Gasser, B. Kubis, and A. Rusetsky, Phys. Lett. B **638**, 187 (2006).

[5] E. Gamiz, J. Prades, and I. Scimemi, Eur. Phys. J. C **50**, 405 (2007).

[6] M. Bissegger, A. Fuhrer, J. Gasser, B. Kubis, and A. Rusetsky, Nucl. Phys. B **806**, 178 (2009).

[7] B. Kubis and S. P. Schneider, Eur. Phys. J. C **62**, 511 (2009).

[8] F.-K. Guo, B. Kubis, and A. Wirzba, Phys. Rev. D **85**, 014014 (2012).

[9] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **109**, 032006 (2024).

[10] L. G. Landsberg, Phys. Rept. **128**, 301 (1985).

[11] T. Aoyama *et al.*, Phys. Rept. **887**, 1 (2020).

[12] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **109**, 072001 (2024).

[13] T. Petri, *Anomalous decays of pseudoscalar mesons*, Other thesis (2010), arXiv:1010.2378 [nucl-th] .

[14] B. Borasoy and R. Nissler, Eur. Phys. J. A **33**, 95 (2007).

[15] G. J. Gounaris and J. J. Sakurai, Phys. Rev. Lett. **21**, 244 (1968).

[16] Z.-Y. Zhang, L.-Q. Qin, and S.-S. Fang, Chin. Phys. C **36**, 926 (2012).

[17] M. Ablikim *et al.* (BESIII Collaboration), JHEP **07**, 135 (2024).

[18] P. Adlarson *et al.*, Phys. Rev. C **95**, 035208 (2017).

[19] R. Arnaldi *et al.* (NA60 Collaboration), Phys. Lett. B **757**, 437 (2016).

[20] H. Aihara *et al.* (TPC/Two Gamma Collaboration), Phys. Rev. Lett. **64**, 172 (1990).

[21] H. J. Behrend *et al.* (CELLO Collaboration), Z. Phys. C **49**, 401 (1991).

[22] J. Gronberg *et al.* (CLEO Collaboration), Phys. Rev. D **57**, 33 (1998).

[23] R. I. Dzhelyadin *et al.*, Phys. Lett. B **88**, 379 (1979).

[24] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **92**, 012001 (2015).

[25] C. Hanhart, A. Kupść, U. G. Meißner, F. Stollenwerk, and A. Wirzba, Eur. Phys. J. C **73**, 2668 (2013).

[26] L. Ametller, J. Bijnens, A. Bramon, and F. Cornet, Phys. Rev. D **45**, 986 (1992).

[27] R. Escribano, P. Masjuan, and P. Sanchez-Puertas, Phys. Rev. D **89**, 034014 (2014).

[28] S. Holz, C. Hanhart, M. Hoferichter, and B. Kubis, Eur. Phys. J. C **82**, 434 (2022), [Addendum: Eur.Phys.J.C 82, 1159 (2022)].

[29] L. Ametller, L. Bergstrom, A. Bramon, and E. Masso, Nucl. Phys. B **228**, 301 (1983).