Light meson decays at BESIII

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Abstract

The world's largest sample of J/ψ events accumulated at the BESIII detector offers a unique opportunity to investigate η and η' physics via two body J/ψ radiative or hadronic decays. In recent years the BESIII experiment has made significant progresses in η/η' decays. A selection of recent highlights in light meson spectroscopy at BESIII are reviewed in this report, including the observation of $\eta' \to \pi^+\pi^-\mu^+\mu^-$, the study of $\eta' \to \pi^+\pi^-e^+e^-$, and search for CP-violation in this decay, search for the rare decays of $\eta' \to 4\pi^0$ and $\eta' \to \gamma\gamma\eta$, as well as the precision measurement of the branching fraction of η' decays.

1 Introduction

Because of the special role in understanding low energy quantum chromodynamics (QCD), η and η' mesons attract considerable theoretical and experimental attention. As a mixture of the lowest pseudoscale singlet and octet, η/η' have inspired a wide variety of physics issues, e.g., $\eta-\eta'$ mixing, the light quark masses, the fundamental discrete symmetries, as well as physics beyond the standard model (SM). In addition, η/η' decays offer unique opportunities to investigate decay dynamics and test different chiral perturbation theory (ChPT) and the vector meson dominance (VMD) models. Moreover, it is also possible to search for new phenomena in rare or forbidden η/η' decays.

The BESIII detector [1] is operated at BEPCII, an e^+e^- collider running at a center of mass energy of $2-4.9$ GeV. BESIII experiment accumulated 1.31 billion J/ψ events in the years 2009 and 2012. The results reported in this proceeding are based on this data sample. In 2018 and 2019, BESIII continue collected J/ψ events, makes the number of J/ψ increased to 10 billion in total. Copious η and η' mesons are produced via the radiative and hadronic decays of J/ψ.

Considering the radiative decays of J/ψ, $J/\psi \to \gamma\eta/\eta'$, the total J/ψ sample corresponds to 1.1×10^7 η mesons and 5.2×10^7 η' mesons, respectively, which allow to analysis specific decays with the unprecedented statistics and to search for rare and forbidden decays.

2 Observation of $\eta' \to \pi^+\pi^-\mu^+\mu^-$

The processes $\eta' \to \pi^+\pi^-l^+l^-$ (with $l = e$ or μ) are expected to have similar structure as $\eta' \to \pi^+\pi^-\gamma$, involving the box anomaly contribution, with the radiative γ replaced with an offshell one and decays into a lepton pair [2]. Therefore, different theoretical models are used to investigate those decays, including the hidden gauge model, the effective meson theory, and the chiral unitary approach. Due to the lower phase space of $\eta' \to \pi^+\pi^-\mu^+\mu^-$, the branching ratio is predicted about 2 orders of magnitude lower than for $\eta' \to \pi^+\pi^-e^+e^-$. In 2013, BESIII performed a study to search the processes $\eta' \to \pi^+\pi^-l^+l^-$ (with $l = e$ or μ) with a data sample of 225 million J/ψ events [6]. The branching fraction of $\eta' \to \pi^+\pi^-e^+e^-$ is determined to be $(2.11 \pm 0.12(stat) \pm 0.14(syst)) \times 10^{-3}$, while no obvious $\eta' \to \pi^+\pi^-\mu^+\mu^-$ signal was observed and an upper limit $\mathcal{B}(\eta' \to \pi^+\pi^-\mu^+\mu^-) < 2.9 \times 10^{-5}$ at 90% confidence level (CL) is set, which is the most stringent result to date.

Using a sample of 1.31×10^9 J/ψ events, BESIII searched this decay [7] recently via the process $J/\psi \to \gamma\eta'$. Clear η' signal with a significance of 8σ is observed for the first time in the invariant mass of $\pi^+\pi^-\mu^+\mu^-$, as the right peak in Fig. 1 shown. A global fit to the $\pi^+\pi^-\mu^+\mu^-$ mass spectrum yields 53 ± 9 signal events. The corresponding branching fraction is determined to be $(1.97 \pm 0.33 \pm 0.19) \times 10^{-5}$, where the first uncertainty is statistical and the second systematical. The result is in good agreement with theoretical predictions, which are predicted in the range of $(1.5 - 2.5) \times 10^{-5}$ [3–5].
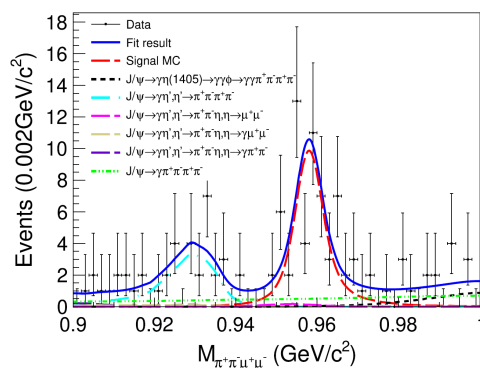
Figure 1: The $\pi^+\pi^-\mu^+\mu^-$ invariant mass spectrum around the η' mass. The dots with error bars represent the data, the red line is signal MC, and the blue line is the total fit result. The other dotted lines represent different backgrounds. The plot is reproduced from Ref [7] under the Creative Commons Attribution 4.0 International license.

3 The study of $\eta' \to \pi^+\pi^-e^+e^-$

As described in Sec. 2, this process is expected to proceed through an intermediate virtual photon $\eta' \to \pi^+\pi^-\gamma^* \to \pi^+\pi^-e^+e^-$. By comparing the precision measurement of the branching ratio of $\eta' \to \pi^+\pi^-e^+e^-$ with the predictions from different theoretical approaches, such as

VMD and ChPT models, it is possible to probe the electromagnetic structure of η' meson.

Using a data sample of 1.31 billion J/ψ events, BESIII performed the study of $\eta' \to \pi^+\pi^-e^+e^-$ recently [8] via the process $J/\psi \to \gamma\eta'$. Clean η' signal is observed in the invariant mass of $\pi^+\pi^-e^+e^-$, as shown in the left panel of Fig. 2. The background contamination ratio is around 2%, mainly from $\eta' \to \pi^+\pi^-\gamma$. A global fit to the $\pi^+\pi^-e^+e^-$ mass spectrum yields 2584 ± 52 signal events, corresponds to $\mathcal{B}(\eta' \to \pi^+\pi^-e^+e^-) = (2.42 \pm 0.05(stat) \pm 0.08(syst)) \times 10^{-3}$. The result is consistent with but about one standard deviation higher than the predictions from various theoretical approach, including the hidden gauge model [$(2.17\pm0.21)\times10^{-3}$] and the modified VMD model [$(2.27 \pm 0.13) \times 10^{-3}$] in reference [5], and the unitary chiral perturbation theory approach [$(2.13^{+0.17}_{-0.31}) \times 10^{-3}$] in reference [4].

A new aspect of this decay is the possibility of a new CP-violating mechanism [9], which is analogy to the studies in $K^0_L \to \pi^+\pi^-e^+e^-$ [10,11]. The CP-violation effect could be induced from the interference between the parity-conserving magnetic transition and a possible parity-violating electric dipole type transition. Then can be extracted by an asymmetry A_ϕ in the angle ϕ between the electrons and pions decay planes in the η' rest frame, i.e.

$$A_\phi = \frac{N(\sin 2\phi > 0) - N(\sin 2\phi < 0)}{N(\sin 2\phi > 0) + N(\sin 2\phi < 0)}, \tag{1}$$

where $N(x)$ is the acceptance-corrected number of events in the corresponding angular region. The asymmetry is measured to be $A_\phi = (2.9\pm3.7_{stat}\pm1.1_{syst})$%, which is extracted for the first time and consistent with 0 within uncertainties. The right panel of Fig 2 shows the distribution of the $\sin 2\phi$.
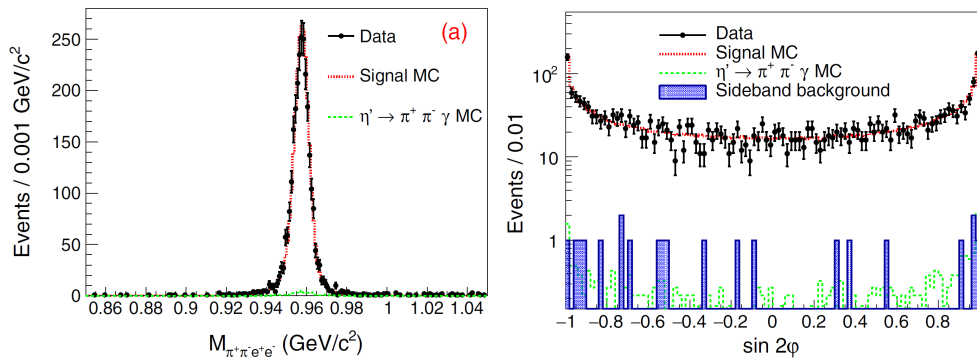
Figure 2: The $\pi^+\pi^-e^+e^-$ invariant mass spectrum around η' mass (left) and the $\sin 2\phi$ distribution in the signal region (right). The dots with error bars are data, the red histograms are signal MC, and other histograms are representing for backgrounds. The plot is reproduced from Ref [8] under the Creative Commons Attribution 4.0 International license.

4 The rare decay of $\eta' \to \pi^0\pi^0\pi^0\pi^0$

The S-wave in $\eta' \to \pi^0\pi^0\pi^0\pi^0\pi^0$ violates CP invariance, which is induced by the CP-violating QCD θ-term and the contribution is expected at the level of 10^{-23} [12,13]. The D-wave CP-conserving effect through the pion-pion charge-exchange rescattering loop predicts the branching fraction to be $\sim 4 \times 10^{-8}$ [14] based on ChPT and VMD model but not strictly. An alternative mechanism through two f_2 tensor mesons is found to be completely negligible in

comparison [14]. The most stringent upper limit 3.2×10^{-4} at 90% CL was from the GAMS-4π Collaboration [15].

Using a data sample of 1.31 billion J/ψ events, BESIII Collaboration performed the search for this decay via the radiative decay of J/ψ [16]. The invariant mass spectrum of $\pi^0\pi^0\pi^0\pi^0$ is shown in Fig. 3, and no significant η' signal is observed. With a Bayesian approach, the upper limit on the branching fraction is determined to be $\mathcal{B}(\eta' \to \pi^0\pi^0\pi^0\pi^0) < 4.94 \times 10^{-5}$ at 90% CL, which is still far to reach the theoretical predication with a level of 10^{-8}. Further studies with 10 billion J/ψ events are still necessary to search for the process $\eta' \to 4\pi^0$.
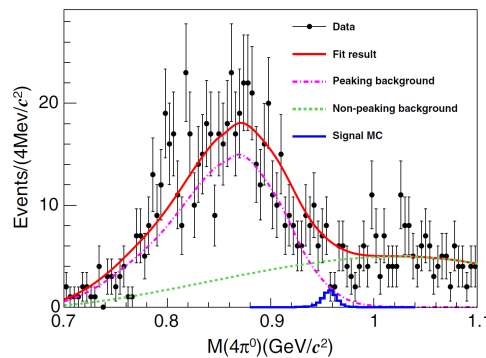
Figure 3: $\pi^0\pi^0\pi^0\pi^0$ invariant mass spectrum in η' signal region. The black dots with error bars are data, the red line is fit result without signal, the blue histogram is the excepted signal contribution shown with arbitrary normalization, the other lines represent contributions from different backgrounds. The plot is reproduced from Ref [16] under the Creative Commons Attribution 4.0 International license.

5 Search for the rare decay of $\eta' \to \gamma\gamma\eta$

Within the frame works of the VMD model and linear σ model, the branching fractions of $\eta' \to \gamma\gamma\pi^0$ and $\eta' \to \gamma\gamma\eta$ are predicted to be $2.91(21) \times 10^{-3}$ and $1.17(8) \times 10^{-4}$, respectively [17]. The branching fraction of $\eta' \to \gamma\gamma\pi^0$ was determined to be $(32.0 \pm 0.7 \pm 2.3) \times 10^{-4}$ [18] by BESIII experiment, while the $\eta' \to \gamma\gamma\eta$ decay has not been observed to date. The most stringent upper limit 8×10^{-4} at the 90% CL was from GAMS-4π Collaboration [19].

Using a data sample of 1.31 billion J/ψ events, a search for the doubly radiative decay $\eta' \to \gamma\gamma\eta$ is performed by BESIII experiment via the radiative decay of J/ψ, $J/\psi \to \gamma\eta'$ [20]. A global fit to the $\gamma\gamma\eta$ invariant mass spectrum, shown in Fig. 4, yields 24.9 ± 10.3 $\eta' \to \gamma\gamma\eta$ events, with a statistical significance of 2.6σ, and the branching fraction is calculated to be $(8.25 \pm 3.41 \pm 0.72) \times 10^{-5}$, which need to be confirmed with higher statistics. Here the first error is statistical and the second systematical. An upper limit of the branching fraction is also set as 1.3×10^{-4} at 90% CL, which is consistent with a recent theoretical prediction of 2×10^{-4} [17] within the frame work of the linear σ model and the VMD model.

6 Precision measurement of the branching fractions of η' decays

Due to the difficulty of tagging η' inclusive decays, the exclusive branching fractions (BFs) of η' in the Particle Data Group (PDG) [21] are all relative measurements. In a recent analysis of BESIII [23], the Collaboration developed an approach to tag the η' inclusive decays
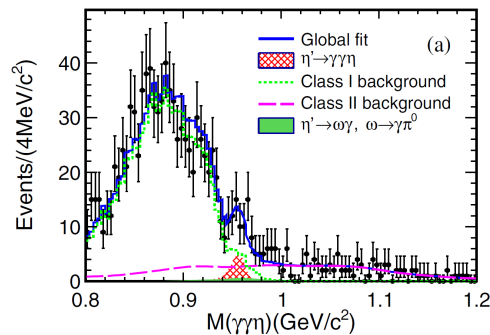
Figure 4: $\gamma\gamma\eta$ invariant mass distribution in η' signal region. The black dots with error bars are data, the blue line is the global fit result, the shaded histogram is signal, and the others are backgrounds. The plot is reproduced from Ref [20] under the Creative Commons Attribution 4.0 International license.

and then to measure the absolute BF of $J/\psi \to \gamma\eta'$ and exclusive BFs of η' for the first time. Taking advantage of the excellent momentum resolution of charged tracks in the main drift chamber (MDC), the η' inclusive decays can be well reconstructed by requiring the radiative photon from J/ψ converted into e^+e^- pairs in the beam pipe or MDC inner wall. The BF of $J/\psi \to \gamma\eta'$ is determined to be $(5.27 \pm 0.03(stat) \pm 0.05(syst)) \times 10^{-3}$ by analyzing the converted events. The result is consistent with the world average value and with a significantly improved precision. Then samples of five dominant decays of η', $\eta' \to \gamma\pi^+\pi^-$, $\eta\pi^+\pi^-$, $\eta\pi^0\pi^0$, $\gamma\omega$, and $\gamma\gamma$ are selected via J/ψ decays to $\gamma\eta'$ with the radiative photon detected by the electromagnetic calorimeter. Together with the η' sample tagged by photon conversion, the absolute BFs for those decay channels are determined and presented in Table 1, which is the first independent measurements. Furthermore, Table 1 also shows the relative BFs for η' decays, which are in agreement with CLEO's result [22] within two standard deviations but with improved precision.

Table 1: Summary of the measured BFs for η' decays.

Decay mode	$\mathcal{B}(\eta' \to X)(\%)$		$\mathcal{B}/\mathcal{B}(\eta' \to \eta\pi^+\pi^-)$	
	BESIII [23]	PDG [21]	BESIII [23]	CLEO [22]
$\eta' \to \gamma\pi^+\pi^-$	$29.90 \pm 0.03 \pm 0.55$	28.9 ± 0.5	$0.725 \pm 0.002 \pm 0.010$	$0.677 \pm 0.024 \pm 0.011$
$\eta' \to \eta\pi^+\pi^-$	$41.24 \pm 0.08 \pm 1.24$	42.6 ± 0.7	-	-
$\eta' \to \eta\pi^0\pi^0$	$21.36 \pm 0.10 \pm 0.92$	22.8 ± 0.8	$0.518 \pm 0.003 \pm 0.021$	$0.555 \pm 0.043 \pm 0.013$
$\eta' \to \gamma\omega$	$2.489 \pm 0.018 \pm 0.074$	2.62 ± 0.13	$0.0604 \pm 0.0005 \pm 0.0012$	$0.055 \pm 0.007 \pm 0.001$
$\eta' \to \gamma\gamma$	$2.331 \pm 0.012 \pm 0.035$	2.22 ± 0.08	$0.0565 \pm 0.0003 \pm 0.0015$	$0.053 \pm 0.004 \pm 0.001$

7 Conclusion

The BESIII collaboration has produced fruitful results related with light meson decays, including the studies of the decay dynamics, tests of discrete symmetries, searches for rare decays, and many other interesting results not covered in this proceeding. The BESIII experiment has accumulated 10 billion J/ψ events in total, which is a unique worldwide sample, allows to study the light mesons with unprecedented statistics. Ongoing analyses will produce more precise results in the next years.

References

[1] M. Ablikim et al. (BESIII Collaboration), *Design and Construction of the BESIII Detector*, Nucl. Instrum. Meth. A **614**, 345 (2010), doi:10.1016/j.nima.2009.12.050.

[2] E. Witten, *Global Aspects of Current Algebra*, Nucl. Phys. B **223**, 422 (1983), doi:10.1016/0550-3213(83)90063-9.

[3] A. Faessler, C. Fuchs and M. I. Krivoruchenko, *Dilepton spectra from decays of light unflavored mesons*, Phys. Rev. C **61**, 035206 (2000), doi:10.1103/PhysRevC.61.035206.

[4] B. Borasoy and R. Nissler, η, $\eta' \to \pi l^+ l^-$ *in a chiral unitary approach*, Eur. Phys. J. A **33**, 95 (2007), doi:10.1140/epja/i2007-10396-3.

[5] T. Petri, *nomalous decays of pseudoscalar mesons*, arXiv:1010.2378.

[6] M. Ablikim et al. (BESIII Collaboration), *Measurement of $\eta' \to \pi^+\pi^- e^+ e^-$ and $\eta' \to \pi^+\pi^- \mu^+\mu^-$* Phys. Rev. D **87**, 092011 (2013), doi:10.1103/PhysRevD.87.092011.

[7] M. Ablikim et al. (BESIII Collaboration), *Observation of $\eta' \to \pi^+\pi^- \mu^+\mu^-$*, Phys. Rev. D **103**, 072006 (2021), doi:10.1103/PhysRevD.103.072006.

[8] M. Ablikim et al. (BESIII Collaboration), *Measurement of the branching fraction of and search for a CP-violating asymmetry in $\eta' \to \pi^+\pi^- e^+ e^-$ at BESIII* Phys. Rev. D **103**, 092005 (2021), doi:10.1103/PhysRevD.103.092005.

[9] D.-N. Gao, *The CP-violating asymmetry in $\eta \to \pi^+\pi^- e^+ e^-$*, Mod. Phys. Lett. A **17**, 1583 (2002), doi:10.1142/S0217732302007739.

[10] A. Alavi-Harati et al. (KTeV Collaboration), *Observation of CP Violation in $K_L \to \pi^+\pi^- e^+ e^-$ Decays*, Phys. Rev. Lett. **84**, 408 (2000), doi:10.1103/PhysRevLett.84.408.

[11] L. Iconomidou-Fayard et al. (NA48 Collaboration), *Results on CP Violation from the NA48 experiment at CERN*, Int. J. Mod. Phys. A **17**, 3012 (2002), doi:10.1142/S0217751X02012569.

[12] A. Pich and E. de Rafael, *Strong CP-violation in an effective chiral lagrangian approach*, Nucl. Phys. B **367**, 313 (1991), doi:10.1016/0550-3213(91)90019-T.

[13] K. Ottnad, B. Kubis, U. G. Meissner and F. K. Guo, *New insights into the neutron electric dipole moment*, Phys. Lett. B **687**, 42 (2010), doi:10.1016/j.physletb.2010.03.005.

[14] F.-K. Guo, B. Kubis and A. Wirzba, *Anomalous decays of η' and η into four pions*, Phys. Rev. D **85**, 014014 (2012), doi:0.1103/PhysRevD.85.014014.

[15] S. V. Donskov et al. (GAMS-4π Collaboration), *A search for decay $\eta' \to 4\pi^0$ with GAMS-4π setup*, Mod. Phys. Lett. A **29**, 1450213 (2014), doi:10.1142/S0217732314502137.

[16] M. Ablikim et al. (BESIII Collaboration), *Search for the rare decay $\eta' \to \pi^0\pi^0\pi^0\pi^0$ at BESIII*, Phys. Rev. D **101**, 032001 (2020), doi:10.1103/PhysRevD.101.032001.

[17] R. Escribano, S. Gonzàlez-Solís, R. Jora and E. Royo, *Theoretical analysis of the doubly radiative decays $\eta^{(')} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$*, Phys. Rev. D **102**, 034026 (2020), doi:10.1103/PhysRevD.102.034026.

[18] M. Ablikim et al. (BESIII Collaboration), *Observation of the doubly radiative decay* $\eta' \to \gamma\gamma\pi^0$, Phys. Rev. D **96**, 012005 (2017), doi:10.1103/PhysRevD.96.012005.

[19] S. V. Donskov (GAMS-4π Collaboration), $\eta' \to \pi^0\gamma\gamma$ *and* $\eta' \to \eta\gamma\gamma$ *at the GAMS-4π setup*, Phys. Atom. Nucl. **78**, 1043 (2015), doi:0.1134/S1063778815090070.

[20] M. Ablikim et al. (BESIII Collaboration), *Search for the decay* $\eta' \to \gamma\gamma\eta$, Phys. Rev. D **100**, 052015 (2019), doi:10.1103/PhysRevD.100.052015.

[21] P. A. Zyla et al., *Review of Particle Physics*, Progr. Theor. Exp. Phys. 083C01 (2020), doi:10.1093/ptep/ptaa104.

[22] T. K. Pedlar et al., *Charmonium decays to* $\gamma\pi^0$, $\gamma\eta$, *and* $\gamma\eta'$, Phys. Rev. D **79**, 111101 (2009), doi:10.1103/PhysRevD.79.111101.

[23] M. Ablikim et al. (BESIII Collaboration), *Precision Measurement of the Branching Fractions of* η' *Decays*, Phys. Rev. Lett. **122**, 142002 (2019), doi:10.1103/PhysRevLett.122.142002.