Light QCD exotics at BESIII

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Summary. — Using the world's largest samples of J/ψ and $\psi(3686)$ events produced in e^+e^- annihilation, BESIII is uniquely positioned to study light hadrons in radiative and hadronic charmonium decays. In particular, exotic hadron candidates including multiquark states, hybrid mesons and glueballs can be studied in high detail. Recent highlights on the light exotics searches, including the observation of an isoscalar spin-exotic 1^{-+} state $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$, the observation of $X(2600)$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$ and a PWA of $J/\psi \to \gamma K^0_S K^0_S \pi^0$ are presented.

1. – Introduction

The Beijing Electron Spectrometer III (BESIII) detector [1] is a general purpose magnetic spectrometer installed at the Beijing Electron Positron Collider II (BEPCII) [2]. BEPCII is a double-ring e^+e^- collider hosted at the Institute of High Energy Physics with a beam energy tuneable in a range from 1.0 GeV to 2.45 GeV. The BESIII detector has a geometrical acceptance of 93% of 4π solid angle and it consists of four main subsystems: a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight (TOF) system, a CsI(Tl) electromagnetic calorimeter (EMC) and a resistive plate muon chamber. The first three subdetectors are enclosed in a superconductive solenoidal magnet which generates a magnetic field of about 1 T. More details can be found in [1].

The BESIII experiment has accumulated more than 1.3×10^9 J/ψ events and about 450 million of $\psi(3686)$ events, which provide a clean laboratory to study light hadron physics and search for light exotic hadron states below the open charm threshold, such as multiquark states, glueballs and hybrids.

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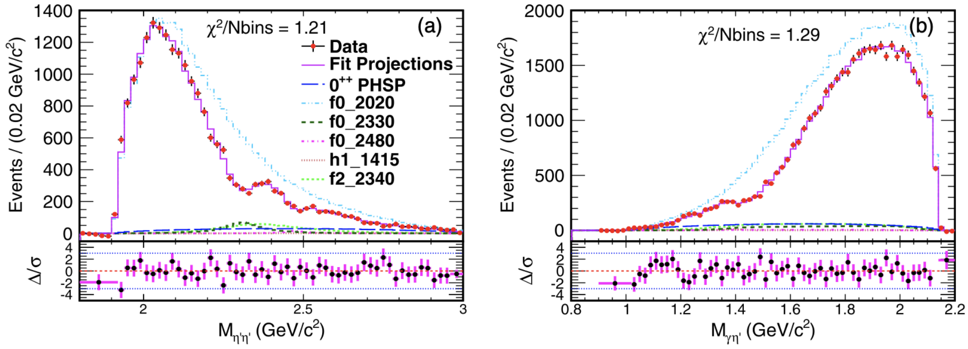

Fig. 1. – Comparison of data and combined PWA fit projection for (a) invariant mass distribution of $M_{\eta'\eta'}$ and (b) $M_{\gamma\eta'}$

2. – Search for glueballs and exotic states

The existence of glueballs has been predicted by QCD. According to Lattice QCD calculation [3, 4, 5], the mass of the ground state glueball with quantum number $J^{PC} = 0^{++}$, should be in the range [1.6-1.7] GeV/c^2, while the mass of the first excited state (with $J^{PC} = 2^{++}$) should be around 2.3 GeV/c^2. These mass ranges are accessible at the BESIII experiment. In addition, the radiative J/ψ decay is a gluon rich process and is therefore regarded as one of the most promising hunting grounds for glueballs.

A partial wave analysis (PWA) of the process $J/\psi \to \gamma\eta'\eta'$ was recently performed using the full J/ψ data set collected with the BESIII detector [6]. The two η' are reconstructed using their decays to $\gamma\pi^+\pi^-$ or $\eta\pi^+\pi^-$, with $\eta \to \gamma\gamma$. The PWA is performed in order to disentangle the intermediate structures present in such decays using the GPUPWA framework [7], and the quasi two-body decay amplitude are constructed using the covariant tensor amplitude described in Ref. [8]. The comparison of PWA fit projection and data on the invariant mass distributions of $\eta'\eta'$ and $\gamma\eta'$ are shown in Figure 1. All components with significance greater that 5σ are retained in the baseline model and are summarized in [6]. The $f_0(2020)$, $f_0(2330)$, and $f_2(2340)$ are observed for the first time in the $\eta'\eta'$ decay mode. The production of $f_0(2020)$ in this decay mode is compatible with that of $f_0(2100)$ in the $J/\psi \to \gamma\eta\eta$ [9] and $f_0(2200)$ $J/\psi \to \gamma K^0_S K^0_S$ [10]. If those scalars are assigned to one resonance, its large production rate in the radiative J/ψ decay suggests that it has a large overlap with scalar glueball, even if its mass is lower than the mass from LQCD prediction [3, 4, 5].

In addition to the glueball states, QCD also allows the existence of hybrid mesons, $q\bar{q}$ states with gluonic degree of freedom. Models and LQCD predict that the exotic $J^{PC} = 1^{-+}$ nonet hybrid mesons is the lightest, with a mass around 1.7−2.1 GeV/c^2 [11]. To date, there are evidence of three isovector 1^{-+} states ($\pi_1(1400)$, $\pi_1(1600)$, and $\pi_1(2015)$) [12, 13, 14, 15]. Finding an isoscalar 1^{-+} hybrid state is critical for establishing the hybrid multiplet. Based on a sample of $(10.09 \pm 0.04) \times 10^9$ J/ψ events collected by BESIII, a PWA of $J/\psi \to \gamma\eta\eta'$ to search for 1^{-+} and investigate the decay property of $f_0(1710)$ was performed [16, 17]. An isoscalar state with exotic quantum number 1^{-+}, denoted as $\eta_1(1855)$, has been observed for the first time with a statistical significance larger than 19σ. Its mass and width are measured to be $(1855 \pm 9^{+6}_{-1})$ MeV/c^2 and $(188 \pm 18^{+3}_{-8})$ MeV [17], in agreement with LQCD calculation [18]. In addition, the

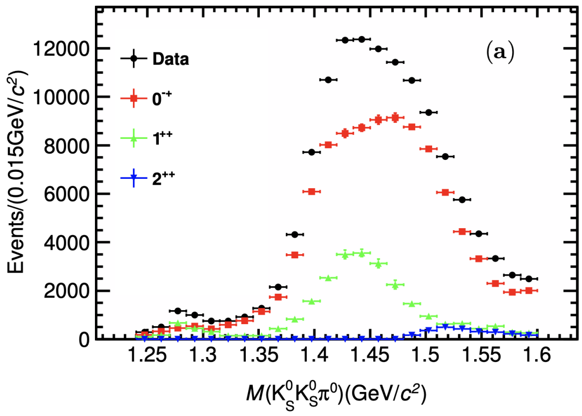

Fig. 2. – $K_S^0 K_S^0 \pi^0$ intensity spectra for the dominant spin-parity components obtained from MI PWA results. Only statistical uncertainty are reported for data, while the uncertainties on the others are obtained from PWA in each bin.

decay $J/\psi \to \gamma f_0(1500) \to \gamma\eta\eta'$ has also been observed with a statistical significance larger that 30σ, while the $J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta'$ is found to be negligible. The suppressed decay rate of the $f_0(1710)$ into $\eta\eta'$ supports the hypothesis that the $f_0(1710)$ has a large overlap with the scalar glueball, and the $f_0(1710)/f_0(2020)$ might be interpreted as flavor singlet [19].

Radiative J/ψ decay can also been used to investigate the nature of the pseudoscalar structure around 1.4 GeV/c^2, which is often interpreted as the combination of two isoscalar resonant state, i.e., the $\eta(1405)$ and $\eta(1475)$. From a theoretical point of view, the pseudoscalar nonet of ground state is well established, and the $\eta(1295)$ and $\eta(1475)$ are generally assigned to be the first radial excitation of the ground state η and η' [20], and hence it became very difficult to accomodate additional pseudoscalar states. Therefore, the possibility of an additional unconventional state has been widely discussed. To investigate the $\eta(1405/1475)$ nature, BESIII Collaboration performed a PWA analysis of the decay $J/\psi \to \gamma K_S^0 K_S^0 \pi^0$ using the full J/ψ data set, where both mass dependent (MD) and mass independent (MI) approach are performed [21]. In particular, to extract the contributions from different components, a MI PWA is performed: the intermediate states in the $K_S^0 K_S^0 \pi^0$ invariant mass spectrum are parameterized by a separate complex constant in 24 bins of 15 MeV/c^2 width in the region $M(K_S^0 K_S^0 \pi^0) < 1.6$ GeV/c^2 (bin-by-bin analysis). Taking into account the spin-parity, charge conjugation and isospin conservation, all possible decay mode candidates are evaluated, and the $K_S^0 K_S^0 \pi^0$ invariant mass spectra obtained from the MI PWA results are shown in Figure **2**. The fit results confirm that the dominant contribution comes from the pseudoscalar component; axial vector component also contribute (peaking at 1.28 GeV/c^2 and 1.42 GeV/c^2); and there is also a small tensor component decaying into $K^*(892)^0 K_S^0$ around 1.52 GeV/c^2 observed for the first time in this decay mode. A mass dependent PWA is also performed, and the results are summarized in Ref. [21]. The nominal solution is in good agreement with the MI PWA results, and it includes two pseudoscalar state, the $\eta(1405)$ and the $\eta(1475)$, two axial vector states, the $f_1(1285)$ and the $f_1(1425)$, and a tensor state, the $f_2(1525)$.

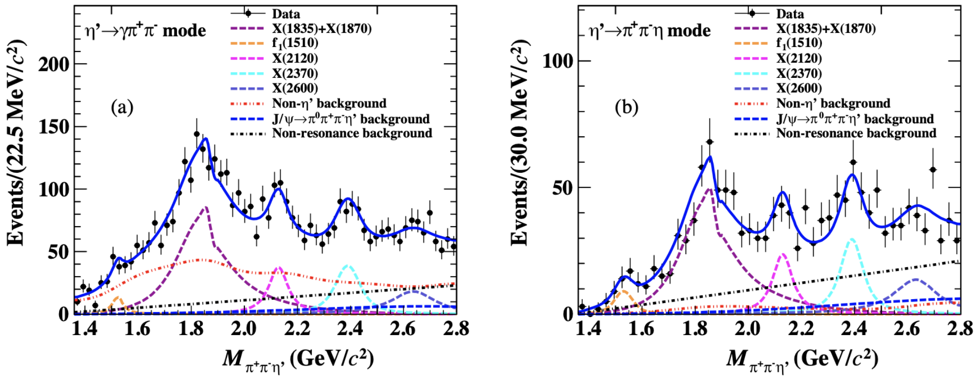

Fig. 3. – Invariant mass distribution $M_{\pi^+\pi^-\eta'}$ for (a) $\eta' \to \gamma\pi^+\pi^-$ decay mode, and (b) for $\eta' \to \pi^+\pi^-\eta$ decay modes.

3. – Enhancement at $p\bar{p}$ threshold and X states observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$

Radiative J/ψ decay into $\eta'\pi^+\pi^-$ decay mode is mainly used to search for a pseudoscalar glueball. In particular, the ground state of the 0^{-+} glueballs has predicted to have a mass around $2.3-2.6$ GeV/c^2 [3, 4]. Therefore, the search of all possible mesons in this region is crucial. At BESIII, several exotic states in the process $J/\psi \to \gamma\eta'\pi^+\pi^-$ have been observed. The $X(1835)$ resonances, observed first by the BES Collaboration [22], was confirmed with a statistical significance larger that 20σ [23] using the J/ψ data collected at BESIII, and its spin parity is determined to be 0^{-+} in the process $J/\psi \to \gamma K^0_S K^0_S \eta$ [24]. The $X(2120)$ and $X(2370)$ resonances where observed with a statistical significance of 7.2σ and 6.4σ [23], and the measured mass of $X(2370)$ is found to be consistent with LQCD prediction for pseudoscalar glueball [26]. Further studies of the process $J/\psi \to \gamma\eta'\pi^+\pi^-$ are important in order to shed light on the nature of the observed X states in this energy region. Using a sample of about 10×10^{10} J/ψ event collected at BESIII, a resonance, denoted as $X(2600)$, is observed in the $\eta'\pi^+\pi^-$ invariant mass spectrum with a significance larger than 20σ [27]. Its mass and width are determined to be $2618.3 \pm 2.0^{+16.3}_{-1.4}$ MeV/c^2 and $195 \pm 5^{+26}_{-17}$ MeV, respectively. In the same analysis, a structure around 1.5 GeV/c^2 is observed in the $\pi^+\pi^-$ invariant mass spectrum. This structure is described taking into account the interference between the $f_0(1500)$ and an additional resonance, denoted as $X(1540)$. Both the $f_0(1500)$ and $X(1540)$ resonances are observed with a significance larger than 20σ [27].

The unprecedented J/ψ sample available at BESIII, allows to study the electromagnetic (EM) Dalitz decay $J/\psi \to e^+e^-\eta'\pi^+\pi^-$ and search for the $X(1835)$, $X(2120)$, $X(2370)$, and $X(2600)$ [28]. Figure **3** shows the invariant mass spectra of the $\eta'\pi^+\pi^-$ candidates for the $\eta' \to \gamma\pi^+\pi^-$ and $\eta' \to \eta\pi^+\pi^-$ decay modes. In the fit, the line shape near the $p\bar{p}$ threshold is described assuming the interference between the $X(1835)$ and a narrow resonance, $X(1870)$, near the threshold.

The EM Dalitz decay $J/\psi \to e^+e^-X(1835)$ gives access to the EM transition form factors (TFFs) between the J/ψ and the $X(1835)$. The q^2-dependent TFF $|F(q^2)|^2$, where q^2 is the square of the invariant mass of the e^+e^- pair, is measured by dividing the $M_{e^+e^-}$ invariant mass distribution into five intervals. The $|F(q^2)|^2$ values are then obtained as the ratios of the branching fractions measured by means of the fit method mentioned above and described in [28], and those predicted by QED in each interval The measured values of $|F(q^2)|^2$ for the $J/\psi \to e^+e^-X(1835)$ process deviate significantly from the pointlike particle assumption [29]. Using a simple pole approximation, the pole mass parameter $\Lambda = [1.75 \pm 0.29(\mathrm{stat}) \pm 0.05(\mathrm{syst})]$ GeV/c^2 was extracted, and it can be used as input parameter to improve theoretical calculations.

4. – Conclusion

In this report, we have explored a selection of the latest BESIII results on light QCD exotic states, highlighting the potential provided by the J/ψ decays for the investigation of light meson spectroscopy and the study of unconventional states. Thanks to the 10 billion of J/ψ data collected at BESIII, more analyses and extensive research efforts will be paved.

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