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Recent Highlights on Meson Spectroscopy at BESIII

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Abstract. Despite mesons being one of the longest known type of particles, there are still many open questions. Besides well understood states that can be clearly attributed to meson nonets, there are many candidates which could have an exotic nature instead. Such exotic particles e.g. glueballs, hybrids and tetraquarks can be favorably studied in clean, gluon rich environments. The BESIII experiment, which is in operation at the BEPCII electron-positron collider in Beijing since 2009, has collected world leading high statistic data samples in the charmonium region. This allows to study rare reactions that are considered to be suppressed. This offers unique possibilities to study exotic QCD states in the charmonium sector, but also the light meson spectrum which can be accessed via charmonium decays. Especially radiative J/ψ decays offer a gluon rich environment in which glueballs and hybrid states can be expected. Since these states are often hard to identify and disentangle, partial wave analysis are needed to determine the different contributions.

1 Introduction

Quantum Chromo Dynamics (QCD), the theory of the strong force, allows besides bound states of quarks also for bound states of gluons. Besides well understood $q\bar{q}$ states that can be clearly attributed to Meson nonets and are well understood, there are nowadays many particles that are often attributed to the light meson sector which could have an exotic nature instead. Such exotic particles are e.g. Glueballs that consist only of gluons, Hybrids which are $q\bar{q}$ states with additional gluonic degrees of freedom, and Tetraquarks or Molecules which are composed of four quarks in different binding configurations.
Due to the highly populated light meson spectrum, the description and identification of such candidates is experimentally challenging. In addition, since light mesons occur in the non-perturbative regime of QCD they also impose a huge theoretical challenge.
Especially radiative charmonium decays are an ideal place to study matter with explicit gluonic degrees of freedom, due to the gluon rich decay process (c.f. Fig. 1).

The BESIII experiment, has collected world leading high statistic data samples in the charmonium region since 2009 and has therefore excellent opportunities to explore the light meson regime. The following sections summarize the recent results of BESIII of amplitude analyses in radiative J/ψ decays and two-photon production.

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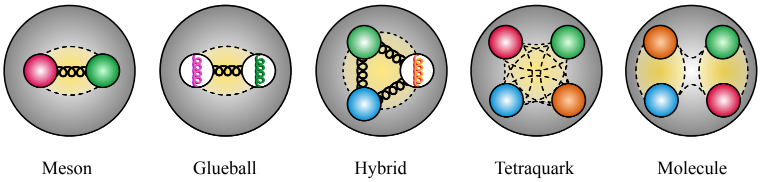

Figure 1: Schematic constituent picture of "ordinary" and exotic matter.

2 Observation of a State $X(2600)$ in the $\pi^+\pi^-\eta'$ System in the Process $J/\psi \to \gamma\pi^+\pi^-\eta'$

In 2003 [1] an interesting enhancement right at the $\bar{p}p$ threshold was observed by the BES collaboration and later confirmed by the CLEO [2] and BESIII [3] collaborations. The state was later called $X(1835)$ and the spin-parity quantum numbers were determined to be $J^{PC} = 0^{-+}$. The state was later also observed in other radiative J/ψ decays such as $3(\pi^+\pi^-)$, $K_S^0 K_S^0 \eta$, $\gamma\phi$ and $\pi^+\pi^-\eta'$ [4–8]. Here, an abrupt kink was observed at the $\bar{p}p$ threshold.
Due to the location of the $X(1835)$ right at the $\bar{p}p$ threshold, the inner structure and precise determination of the resonances pole position is particularly interesting. Two scenarios might be possible. It could be either a narrow state just below threshold which would correspond to a bound state, or it might be a broad state with strong coupling to an $\bar{p}p$ so-called molecular object. A line shape analysis found equally good descriptions for a Flatté and Breit-Wigner scenario [9] leaving the puzzle still unsolved. In order to reveal the inner structure of this object further studies and preferably a coupled-channel analysis should be performed. Besides the prominent $X(1835)$ state, the invariant $\pi^+\pi^-\eta'$ mass shows further structures at higher mass with increasing statistics, which led to the observation of the $X(2120)$ and the $X(2370)$ states. The evolution with increasing statistics is shown in Figure 2.

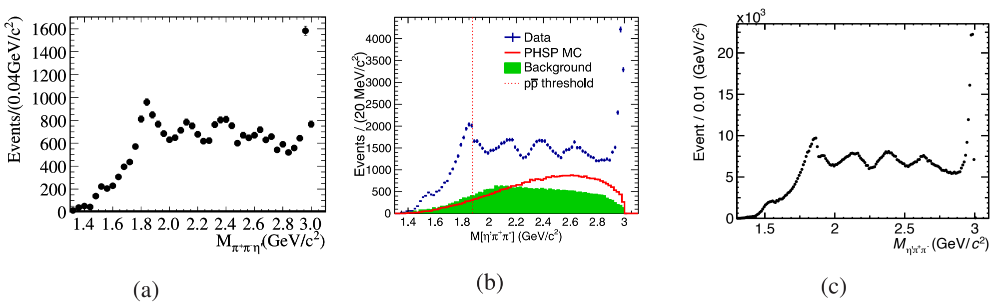

Figure 2: Evolution of the invariant $\pi^+\pi^-\eta'$ mass from $J/\psi \to \gamma\pi^+\pi^-\eta'$ using 225 million [8] (a), 1090 million [9] (b) and 10 billion [10] (c) J/ψ events.

In the most recent analysis, using the full J/ψ data sample including 10 billion events, a new state was observed at 2.6 GeV/c^2, called $X(2600)$ [10] with a significance of more than 20σ. The mass and width of the $X(2600)$ state are determined to be $2617.8 \pm 2.1^{+18.2}_{-1.9}$ MeV/c^2 and $200 \pm 8^{+20}_{-17}$ MeV, respectively. A simultaneous fit to the $\pi^+\pi^-$ and $\pi^+\pi^-\eta'$ systems showed a correlation between the $X(2600)$ and a non-trivial structure around 1.5 GeV/c^2 in the invariant $\pi^+\pi^-$ mass (see Figure 3). The $\pi^+\pi^-$ spectrum is described best with a $f_0(1500)$ contribution and an additional resonance (called $X(1540)$) at $1540\,\mathrm{MeV}/c^2$. It is noteworthy that the dip in the $\pi^+\pi^-$ spectrum occurs right at the $\eta\eta'$ threshold which might indicate a much more complicated interplay of the $X(2600)$ with the $\eta\eta'$ final state. Although, this final state has been analyzed several times and most recently taking advantage of best available statistics, many questions are still unanswered. Further studies, including more advanced theoretical models are hopefully able to answer them.

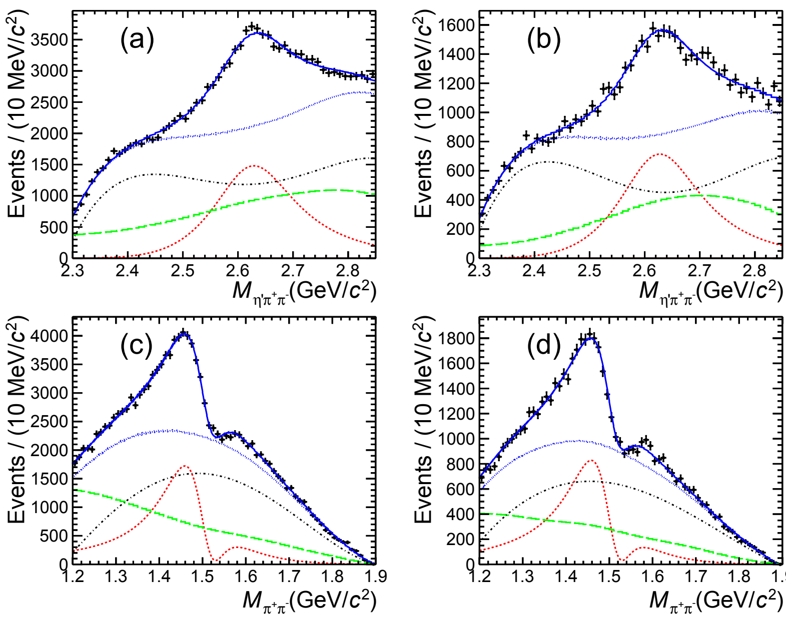

Figure 3: The $\pi^+\pi^-\eta'$ and $\pi^+\pi^-$ mass spectra distributions with the two decay channels of η', $\eta' \to \gamma\pi^+\pi^-$ and $\eta' \to \pi^+\pi^-\eta$, with the simultaneous fit results overlaid: (a) and (c) are fit results for $\eta' \to \gamma\pi^+\pi^-$ channel, (b) and (d) are fit results for the $\eta' \to \pi^+\pi^-\eta$ channel. The dots with error bar are data, the blue solid lines are the total fits, the red dashed lines describe the $X(2600)$ signal, all other lines describe different background sources.

3 Observation of an Isoscalar Resonance with Exotic $J^{PC} = 1^{-+}$ Quantum Numbers in $J/\psi \to \gamma\eta\eta'$

Exotic quantum numbers such as 1^{-+} are a smoking gun for exotic matter, since they can not be reached by pure $\bar{q}q$ states. Currently there are three isovector states handled as hybrid states, the $\pi_1(1400/1600)$, and the $\pi_1(2025)$. The $\pi_1(1400)$ and $\pi_1(1600)$ where formerly treated as two individual states, where the lighter was only seen in the decay to $\pi\eta$ and the heavier in the decay to $\pi\eta'$. Recent analyses of the JPAC and Bochum group showed in advanced partial wave analyses that it is possible to describe both structures by only one pole which couples to both final states [11, 12]. This is also supported by lattice QCD calculations which predict only one state below $2\,\mathrm{GeV}/c^2$ [13]. Besides identifying the isovector hybrid states, finding also an isoscalar 1^{-+} hybrid state would be crucial for the understanding of a hybrid multiplet. A recent partial wave analysis (PWA) of the $J/\psi \to \gamma\eta\eta'$ process has been performed based on $(10.09 \pm 0.04) \cdot 10^9$ J/ψ events collected with the BESIII detector

[14–16]. In the PWA all kinematically allowed resonances listed in the PDG were considered in the $\eta\eta'$ and $\gamma\eta^{(\prime)}$ systems. An additional exotic 1^{-+} contribution in the $\eta\eta'$ system was needed in the final fit hypothesis. The overall fit result and the different contributions can be seen in Figure 4. The mass and width where determined to be $M = (1855 \pm 9^{+6}_{-1})\,\mathrm{MeV}/c^2$ and $\Gamma = (199 \pm 18^{+3}_{-8})\,\mathrm{MeV}$, respectively. The so-called $\eta_1(1855)$ was observed for the first time and might be the isoscalar partner of the $\pi_1(1600)$. Since the PWA model is based on Breit-Wigner descriptions for the different resonances, further studies including more sophisticated dynamical descriptions could help to determine the resonance properties in a less model dependent approach. Future studies, including other production mechanisms and decay modes will help to clarify the nature of the $\eta_1(1855)$.

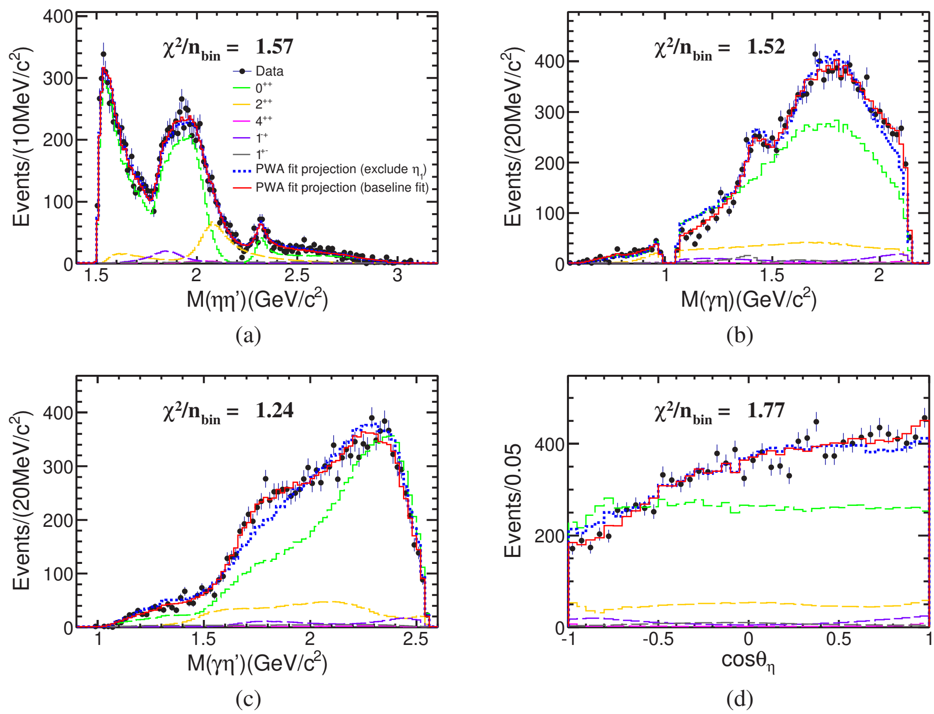

Figure 4: Background-subtracted data (black points) and the PWA fit projections (lines) for (a,b,c) the invariant mass distributions of (a) $\eta\eta'$, (b) $\gamma\eta$, and (c) $\gamma\eta'$, and (d) the distribution of $\cos\theta_\eta$, where θ_η is the angle of the η momentum in the $\eta\eta'$ helicity coordinate system.

4 Coupled-Channel Analysis of Two-Photon Data at BESIII

Besides gluon rich processes, e^+e^- collider also provide access to two-photon reactions which are considered to be gluon poor. Since photons couple only to charge in first order, the production of exotic states with explicit gluonic degrees of freedom, such as glueballs or hybrids, is expected to be suppressed. Therefore, two-photon reactions act as anti-glueball filter and measuring the production strength of a state in two-photon production, offers direct information on the inner structure. Here, a coupled-channel PWA of the channels $\gamma\gamma \to \pi^0\pi^0$, $\pi^0\eta$ and K^+K^- has been performed for the first time [17].
All available data samples in the beam energy range between $\sqrt{s} = 3.7 - 4.7\,\mathrm{GeV}$,

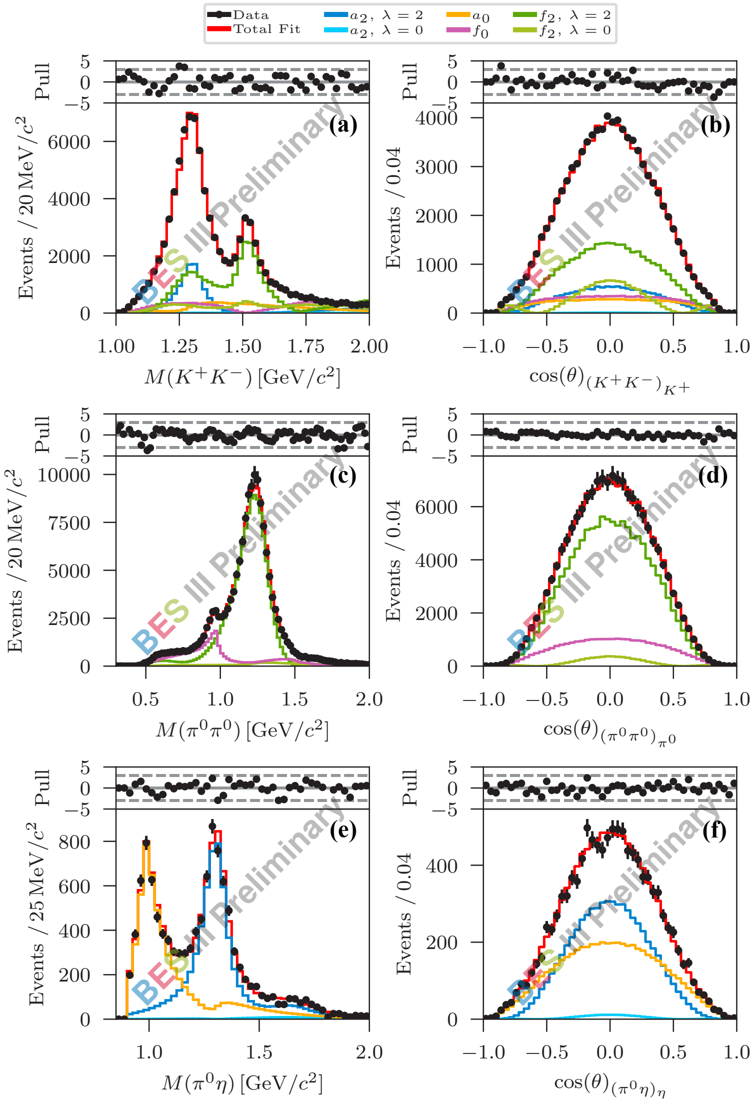

Figure 5: Contributions obtained from the best fit result for the invariant K^+K^- mass distribution (a), helicity angle of one kaon in the K^+K^- rest frame (b). And similar for the $\pi^0\pi^0$ system in Figures (c) and (d) and the $\pi^0\eta$ system in Figures (e) and (f). The residues and error bars are based on the statistical uncertainties obtained by the bootstrapping.

corresponding to an integrated luminosity of 21.7 fb^{-1} collected by the BESIII experiment, were used. By applying event-based background rejection methods, very pure data samples have been selected. In this event based background subtraction, for every event a weight is determined from fits to the p_T distribution of the two-photon system, in which signal and background have significantly different shapes, which corresponds to the probability that

a specific event is a signal event. The data were described using the K-matrix formalism under the P-vector approach and the resonance parameters were fixed to a parameterization obtained form a recent coupled-channel analysis [12].
The obtained fit result for all three final states is shown in Figure 5. The final results of this analysis, including a publication, is foreseen in the near future.

5 Summary

In this report a subset of the most recent highlights in the field of meson spectroscopy at BESIII was summarized. The results show that radiative J/ψ decays provide an excellent laboratory to study exotic matter in the light meson regime. In particular, the 10 billion of J/ψ data collected by BESIII provide leading precision and will allow for further studies of even rarer processes. The results on the two-photon production show furthermore that BESIII can also provide state of the art results using the collection of data samples beyond on resonance data samples. This rich data base will play an important role in the future, together with state of the art PWA techniques, to answer long standing open question in the light meson regime. Many new results are expected in the near future!

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