Searches for glueballs at BESIII

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The search for glueballs – colorless bound states of gluons – is one of the most important tasks within the modern QCD. While parameters of glueballs are predicted under a wide range of models, their experimental observation is extremely difficult due to the possible mixing with the conventional mesons. Glueballs are predicted to be abundantly produced in glue-rich processes. In this paper we present results of searches for various glueball states performed using uniquely large datasets of charmonia decays obtained by the BESIII experiment.

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Introduction

Quantum Chromodynamics (QCD) has yielded many results in the past 50 years, but some of its predictions remain elusive. One of the most important task within QCD as of now is to search for the particles outside of the conventional quark model [1]. While conventional hadrons consist of either 2 or 3 valence quarks and/or antiquarks, QCD allow for other exotic states, such as tetraquarks, pentaquarks, hybrids and glueballs. The latter are colorless bound states of gluons which existence is made possible due to the non-Abelian nature of QCD and gluon self-interaction.

Glueball properties were predicted in a wide array of different models. In particular, glueball mass spectrum was modeled using many non-perturbative approaches, most important here being LQCD predictions [2–4]. While their exact predictions vary, all of the models in question agree that three lightest glueballs must be scalar ($1.5 - 2.0$ GeV/c^2), tensor ($1.8 - 2.7$ GeV/c^2) and pseudoscalar ($2.1 - 2.6$ GeV/c^2) states, with expected mass ranges shown in brackets.

Main processes which are used in glueball searches are $p\bar{p}$-annihilation, central production via the Pomeron-Pomeron fusion and radiative charmonia decays. All of these channels allow for creation of glue-rich environment, which should greatly increase production rate of glueballs [1]. Out of all these channels, charmonia decays have additional benefits. Firstly, the final state in charmonia decays is dominated by processes with $I = 0$, which applies isospin filter. Secondly, positive C-parity is required in charmonia decays, which applies an additional spin-parity filter. Thirdly and finally, e^+e^- colliders, which are often used to acquire data of charmonia decays, provide very clean environment. Due to the importance of charmonium decays for glueball searches, lattice QCD predictions for radiative yields of glueballs have been obtained in [5–7].

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BESIII at BEPCII

Detailed description of the experimental setup is contained in [8, 9], a brief description is provided below. The BESIII detector is a multi-purpose detector which records symmetric e^+e^- collisions provided by the BEPCII facility. The BEPCII collider allows for creating e^+e^- collisions with center-of-mass energy ranging from 1.84 GeV/c^2 to 4.95 GeV/c^2 and peak luminosity of 1.1×10^{33} cm^{-2}s^{-1} achieved at $\sqrt{s} = 3.773$ GeV/c^2.

The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber, a time-of-flight system, and a CsI(Tl) electromagnetic calorimeter, which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel.

The BESIII collaboration has obtained many different datasets, both for specific energy points and broad scans for XYZ stuides. Among them are largest datasets of J/ψ and $\psi(3686)$ decays, 10 billion [10] and 2.7 billion [11] events respectively. The size of these datasets make precise measurements utilising partial wave analysis methods possible. Such methods are necessary for the task of glueball search and for the precise determination of meson spectra due to the overlap of resonances.

Partial wave analysis formalism

Amplitude analyses, also called partial-wave analyses, or PWAs for short, are a standard part of the hadron spectroscopy toolkit (e.g., see Ref. [12]). Usage of the amplitude analysis is inevitable when trying to discern multiple overlapping resonances with their interference taken into account.

Main idea of the amplitude analysis is to decompose decay amplitude into a sum of partial waves with specific angular dependancies. Most commonly, the decay amplitude is factorised into an angular part and a dynamic part. The former can be provided in different bases and approaches depending on analysis in question, including LS coupling basis [13], helicity basis, and multipole radiative basis. The latter actually contains information about resonance production and decays, and interaction dynamics. This dynamic part could be parameterised under different models, depending on the studied spectrum. After the decay amplitude is parameterised, the likelihood function is constructed based on it and fitted to the data. Free parameters of the model used in the amplitude construction are obtained as a result of the fit.

There are two main approaches to the parameterisation of the dynamic part of the amplitude. The first one is to provide parameterisation using some underlying model; such approach is often called model-dependent, or MD for short. An example of the parameterisation could be a sum of Breit-Wigner functions used to parameterise a coherent sum of resonances. Model-dependent analyses has a clear benefit that the model parameters, which are

a direct result of the fitting procedure, are directly tied to the properties of the scattering amplitude in the complex s-plane. The main drawback of analyses of this sort, however, is that numerical results obtained by them have very limited usability outside of the chosen model assumptions.

The second approach is to measure the dynamic part as a function of the invariant mass of selected final state particles. An independent fitting procedure is performed in each narrow invariant mass bin while making minimal model assumptions. Within such approach, which is called model-independent, or MI for short, dynamic part of the amplitude is simply taken as a constant for each partial wave in each invariant mass bin. This approach makes it possible to perform an amplitude analysis even in the situations when commonly used parameterisations end up insufficient, particularly in the case of the light hadron spectra. The results obtained in the MI manner allow for subsequent development of more complex models and could be studied in conjunction with results from other decay channels, thus resulting in a coupled-channel analyses. The disadvantage of such approach is that fit parameters by themselves are difficult to interpret directly and instead have to be used to obtain partial wave intensities first.

Both of these approaches were used extensively in the BESIII studies and yielded a lot of results in searches for the glueball candidates.

Scalar glueball search

The scalar sector exhibits an abundance of overlapping states, making it challenging to discern specific resonances. Multiple amplitude analyses were performed at BESIII with an aim of studying the light hadron spectrum in general and scalar sector in particular.

The first is the study of $J/\psi \to \gamma X \to \gamma\eta\eta$ radiative decays [14]. This is the MD analysis utilising covariant formalism approach for angular dependancies and Breit-Wigner functions for the intermediate resonance parameterisation. Among other states, three scalar states were observed in fit results in the mass range predicted for the scalar glueball: $f_0(1500)$, $f_0(1710)$ and $f_0(2100)$. The mass projection is shown on the left plot in Fig. 1.

The second is the study of $J/\psi \to \gamma X \to \gamma\pi^0\pi^0$ decays [15], which was the first of many MI analyses performed by the BESIII Collaboration. While in this analysis itself no interpretations for the light hadron spectrum were provided, its results were integral for subsequent coupled-channel analyses which are discussed later. The mass spectrum of selected events is shown on the middle plot in Fig. 1.

The third is the study of $J/\psi \to \gamma X \to \gamma K_S K_S$ decays [15]. Both MD and MI approaches were used, with MI results used in subsequent coupled-channel analyses. In the MD results, multiple scalar states were observed in the mass region of interest: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ and $f_0(1790)$. The mass projection is shown on the right plot in Fig. 1.

The final one among single-channel studies is the study of $J/\psi \to \gamma X \to$

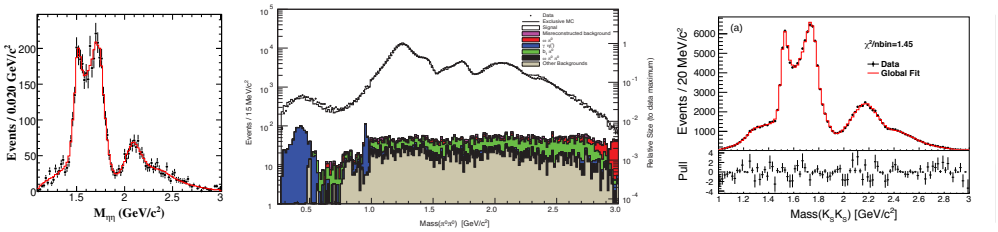

Fig. 1. Left - mass projection for $J/\psi \to \gamma\eta\eta$ study, middle - mass spectrum for $J/\psi \to \gamma\pi^0\pi^0$ study, right - mass projection for $J/\psi \to \gamma K_S K_S$ study.

$\gamma\eta\eta^{'}$ decays [16, 17]. While the main result of this MD analysis is an observation of $\eta_1(1855)$ exotic state, an additional upper limit on the ratio of branching fractions $\mathcal{B}(f_0(1710) \to \eta\eta^{'})/\mathcal{B}(f_0(1710) \to \pi\pi)$ was determined to be 1.61×10^{-3} at 90% CL. This lends support to the hypothesis that $f_0(1710)$ has a large glueball component due to the fact that single glueball decays to the $\eta\eta^{'}$ final state are suppressed because of gauge duality.

In addition to the single-channel analyses, two coupled-channel analyses were performed utilising previously obtained MI results. The first one analysed radiative decays of J/ψ into $\eta\eta^{'}$, $\pi\pi$, $K\bar{K}$, $\eta\eta$ and $\omega\phi$ final states [18]. Additionally, data on $\pi\pi$ collisions and $\bar{p}N$ annihilation at rest was used in simultaneous fit. The model used to parameterise dynamic part of the amplitude is K-matrix and Breit-Wigner functions plus additional modifications to take the final state rescattering into account. This analysis resulted in the observation of the peak structure with mass $M_G \approx 1865$ MeV$/c^2$ and width $\Gamma_G \approx 370$ MeV$/c^2$, which was interpreted as a scalar glueball mixing with six different scalar mesons [19].

However, this is not the only possible interpretation of available MI results. A separate study was done, this time utilising only data of J/ψ radiative decays into $\pi\pi$ and $K_S K_S$ [20], with no restrictions for the two-meson rescattering amplitude being applied. The same enhancement as in the previous analysis was not observed in the fit, but $f_0(1710)$ state is still proposed to have sizeable glueball component.

Tensor glueball search

The tensor glueball candidates were studied almost exclusively in the single-channel MD analyses. While no clear candidate has been proposed, some potential candidates were observed with masses consistent with LQCD predictions for the tensor glueball mass.

Two out of three analyses were already discussed, these are studies of radiative decays of J/ψ to $\eta\eta$ [14] and $K_S K_S$ [21] systems. In both of them, tensor state $f_2(2340)$ was observed with noticeable yield.

The last analysis which should be discussed is the study of $J/\psi \to \gamma X \to \gamma\phi\phi$ decays [22]. In this study, three tensor states with masses above 2 GeV$/c^2$ were observed with noticeable yields: $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$. The mass projection is shown on the left plot in Fig. 2.

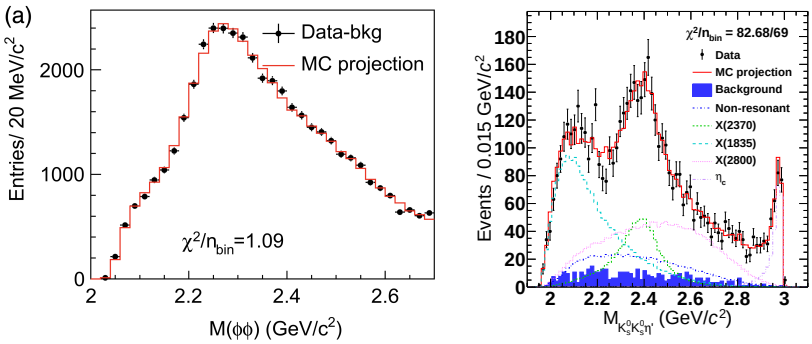

Fig. 2. Left – mass projection for $J/\psi \to \gamma\phi\phi$ study, right – mass projection for $J/\psi \to \gamma K_S^0 K_S^0 \eta^{'}$ study.

Currently, the $f_2(2340)$ state looks like the most promising tensor glueball candidate. Its mass is consistent with LQCD predictions for the tensor glueball and it has substantial yield observed in $\eta\eta$, $\phi\phi$ and $K_S K_S$ final states. However, it is important to note that currently observed yield of $f_2(2340)$ is two orders of magnitude smaller than the yield of the tensor glueball in radiative J/ψ decays predicted by LQCD [6].

Pseudoscalar glueball search

The main candidate for the pseudoscalar glueball at the moment is the $X(2370)$ state. Its first observation was made in the study of $J/\psi \to \gamma\pi^+\pi^-\eta^{'}$ decays [23]. Additional confirmation of this state's existence was obtained in the study of $J/\psi \to \gamma K\bar{K}\eta^{'}$ decays [24]. Finally, in the recent study of $J/\psi \to \gamma K_S^0 K_S^0 \eta^{'}$ decays an updated J/ψ dataset was used [25]. Due to its size, it became possible to determine quantum numbers of the $X(2370)$ state, which turned out to be a pseudoscalar with $J^{PC} = 0^{-+}$. The mass projection is shown on the right plot in Fig. 2. Currently, there are no observations which contradict the hypothesis of the $X(2370)$ state being a pseudoscalar glueball.

Preliminary results of $\psi(3686) \to \gamma\pi^0\pi^0$ study

In 2021, available dataset of $\psi(3686)$ decays size was greatly increased, now reaching 2.7×10^9 events. This allows for precise amplitude analyses of $\psi(3686)$ decays to be performed.

Such analyses, despite working with smaller statistic than that of J/ψ, have two important benefits. The first is that $\psi(3686)$ decays allow for study of higher invariant mass region. And the second is that in such analysis, less restrictions are applied due to the available phase space volume.

The MI analysis of $\psi(3686) \to \gamma\pi^0\pi^0$ radiative decays has been performed. Only 0^{++} and 2^{++} available intermediate states were taken into account, resulting in full intensity having contributions from four different partial waves. Judging from the MI results alone, tensor waves above 2.0 GeV/c^2

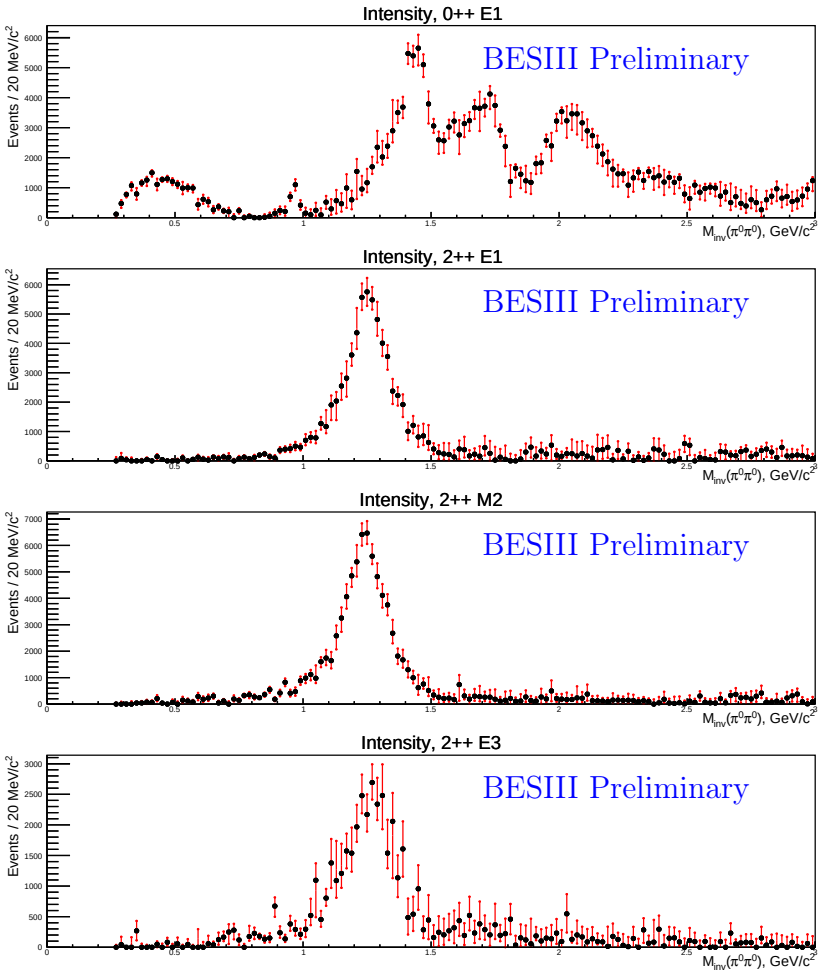

Fig. 3. Partial wave intensities. Black dots – results of the fit, red bars – 1σ confidence intervals.

are consistent with zero in almost all bins and no evidence for tensor glueball can be observed directly from MI results.

Summary

The BESIII Collaboration has made significant progress in searches for glueball states, leveraging unprecedented datasets of J/ψ and $\psi(3686)$ decays. These datasets allow for precise measurements utilising amplitude analysis methods. While J/ψ studies has already yielded great results in scalar, tensor and pseudoscalar sectors, subsequent studies of $\psi(3686)$ studies would be of great interest for further searches for glueball states, especially for tensor and pseudoscalar ones.

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Conflict of Interest

The author of this work declares that he has no conflicts of interest.

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