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Overview of most recent BESIII results

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Abstract. Since 2009, the BESIII experiment has been colliding e^+e^- beams in the energy range between 2.0 and 4.9 GeV. This allowed the BESIII Collaboration to collect three of the largest data sets of charmonium resonances (J/ψ, $\psi(2S)$, and $\psi(3770)$) in the world as well as other data sets at the centre-of-mass energies above 3.8 GeV. These datasets allow BESIII to deepen the knowledge of the properties of charmonia; investigate the light hadrons spectra; probe the decay and production mechanism of charmed mesons; search for the exotic XYZ hadrons and to understand their nature; perform precision Quantum ChromoDynamics measurements (such as R-value measurements and Form Factors estimations). Some of the most recent and noteworthy results from the BESIII collaboration are presented.

1 Introduction

The BESIII (BEijing Spectrometer III) detector records symmetric e^+e^- collisions provided by the BEPCII (Beijing Electron Positron Collider II) storage ring, which operates in the centre-of-mass energy ($\sqrt{s}$) range from 2.0 to 4.9 GeV. The machine is hosted at the Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences (CAS) in Beijing, People's Republic of China. Details on the sub-detectors and their performance can be found in Ref. [1]. Typically referred to as a τ-charm factory, BESIII physics programme [2] covers charmonium(-like) and light hadrons spectroscopy, charmed mesons and baryons decays, τ studies, Quantum ChromoDynamics (QCD) measurements, and new physics searches.

Being BEPCII a leptonic collider, BESIII can profit from the direct production of vector states ($J^{PC} = 1^{--}$). This allowed the collaboration to gather the biggest datasets of the J/ψ, $\psi(2S)$, and $\psi(3770)$ resonances in the world. Owing to the statistics of these data sets and those at $\sqrt{s} > 3.8$ GeV, BESIII can probe a plethora of QCD features, ranging from the charmonium potential model to precision tests of QCD fundamental properties.

A compendium of the latest results of the BESIII collaboration is presented to give a glimpse of what the same can provide.

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2 Charmonium(-like) States

Charmonium ($c\bar{c}$) resonances are located in the transition region of perturbative and non-perturbative QCD and are thus an optimal benchmark for probing strong interaction phenomenological features. Despite conventional charmonia fitting fairly well potential model predictions, non-vector states are still not entirely known (e.g., the $h_c(1^1P_1)$) [3]. Moreover, the $c\bar{c}$ spectrum features supernumerary (XYZ) states, which do not fit potential model predictions, show strong couplings to hidden charm states, and can exhibit a non-zero charge [4].

2.1 The Latest Addition... the $Z_{cs}(3985)^0$ Resonance

Using 5 data sets with an integrated luminosity ($\mathcal{L}_{\rm Int}$) of 3.8 fb^{-1} at $\sqrt{s}$ = [4.628, 4.699] GeV, Ref. [5] reports the evidence of a near-threshold structure with a significance of 4.6σ in the $e^+e^- \to K^0_S(D^-_s D^{*+} + D^{*-}_s D^+)$ reaction.
To increase the final event tagging efficiency, a partial reconstruction technique is employed and only the neutral kaon and the non-excited charmed meson (either the D^-_s or the D^+) are identified. So, to tag the event, the $KK\pi$, $K^0_S K$, $KK\pi\pi^0$, $K^0_S K\pi\pi$, and $\eta'\pi$ decays are used to reconstruct the D^-_s mesons; while the $K\pi\pi$, $K^0_S\pi$, and $K^0_S\,3\pi$ channels are used to form the D^+ states. All the K^0_S states are reconstructed through their charged pions decay. Moreover, to select the signal events, each D-meson signal candidate is requested to have its reconstructed mass within 15 MeV/c^2 of its established [3] mass. Before analysing the K^0_S recoil mass, the RQ(DK^0_S) variable[1] is requested not to lay beyond 20 MeV/c^2 (10 MeV/c^2) of the D^{*+} (D^{*-}_s). Finally, the K^0_S recoil mass distributions for the 5 energy points are obtained and fitted with a simultaneous unbinned maximum likelihood fit. The signal is described by a combination of two Breit-Wigner functions (taking into account the two possible decay modes, $D^-_s D^{*+}/D^{*-}_s D^+$) properly smeared taking into account the detector resolution and the mass-dependent efficiency; the background is modelled from MC samples (for the non-resonant process and higher excited mesonic channels) and using signal sidebands (for simulating the combinatorial background).

The $Z_{cs}(3985)^0$ coupling to $D^-_s D^{*+}/D^{*-}_s D^+$ suggests a minimum quark content of $c\bar{c}s\bar{d}$. Following Ref. [6], which predicts the Z^+_{cs} [7] to have a neutral isospin partner, the $Z_{cs}(3985)^0$ mass is found to be consistent with predictions (m($Z_{cs}(3985)^0$) > m(Z^+_{cs})) and the Born cross-sections ($\sigma^{\rm Born}$) multiplied by the decays branching fraction found to be compatible with the charged partner.

2.2 Y and ψ States

2.2.1 Y Resonances

Using 28 energy points at $\sqrt{s}$ = [4.127, 4.600] GeV with a $\mathcal{L}_{\rm Int}$ = 15.6 fb^{-1}, Ref. [8] studies the $e^+e^- \to K^+K^-J/\psi$ line-shape employing a partial reconstruction technique to increase the event selection efficiency. Only the most energetic kaon and the J/ψ ($\to \ell\ell$) resonance are identified. Signal yields (i.e., number of $e^+e^- \to K^+K^-J/\psi$ events) are then obtained from the 28 background-subtracted invariant J/ψ distributions. A maximum likelihood fit is then applied to the dressed cross-sections (i.e., $\sigma^{\rm Born}$ but including vacuum polarization effects), with the fit function being parameterized as a coherent sum of two relativistic

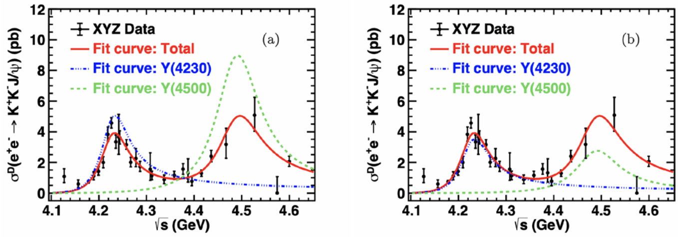

Figure 1. Fit solutions to the dressed cross-section of the $e^+e^- \to K^+K^-J/\psi$ channel. (a) corresponds to Solution I, (b) corresponds to Solution II.

Breit-Wigner distributions.

As Fig. 1 shows, both the solutions of the fit predict two resonances. The low-mass state is consistent with the $Y(4230)$ one, making it the first time this state is observed (at a significance of 29σ) in the K^+K^-J/ψ channel. The other resonance has no corresponding observed state, as such it is named $Y(4500)$. It is the first observation of this exotic Y-state with a significance of 8σ. The mass $Y(4500)$ is such that this state can be consistent with the 5S-4D mixing scheme [9], with the hadronic molecule model [10], or with a hidden-charm hidden-strange state [11].

2.2.2 ψ States

Similarly to the analysis presented in Sec. 2.2.1, Ref. [12] studies the $e^+e^- \to \pi^+\pi^-\psi_2(3823)$ cross-section using 20 energy points at $\sqrt{s}$ = [4.230, 4.700] GeV ($\mathcal{L}_{\rm Int}$ = 11.3 fb^{-1}). To increase the signal events yield, the $\psi_2(3823)$ is partially reconstructed through its $\gamma\chi_{c1,c2} \to \gamma\ (\gamma J\psi) \to \gamma\ (\gamma\ (\ell\ell)\ )$ decay, allowing one-missing-photon events. For each energy point, the $\pi^+\pi^-$ recoil mass (RM($\pi^+\pi^-$)) is then fitted to extrapolate the number of $e^+e^- \to \pi^+\pi^-\psi_2(3823) \to \pi^+\pi^-\gamma\chi_{c1,c2}$ events and the $\psi_2(3823)$ mass. This strategy allows estimating the most precise $\psi_2(3823)$ mass value up to date $3823.12 \pm 0.43 \pm 0.13$ MeV/c^2 (cf., Ref. [3]).

No signal above the 3σ significance is found for the $\gamma\chi_{c1,c2} \to$ channel, hence, only the $e^+e^- \to \pi^+\pi^-\psi_2(3823) \to \pi^+\pi^-\gamma\chi_{c1}$ cross-section is fitted. Two structures are found, one corresponding to the $Y(4360)$ state and the other to the $Y(4660)$ resonance. With a significance greater than 5σ, this is the first observation of Y-states decaying to a D-wave charmonium resonance. Moreover, the sizeable observation of the $Y(4660)$ in this channel challenges both its $f_0(980)\psi(2S)$ hadron molecule interpretation [13] and the extended baryonium one [14], as the absence or at most a weak coupling to other non-$\psi(2S)$ charmonium states is essential for these two models.

2.3 Back to the Origins... Rediscovering the $h_c(1^1P_1)$

Despite extensive studies of the charmonium system, knowledge of the singlet state $h_c(1^1P_1)$ is sparse. Only nine decay modes have been observed, with the electromagnetic $h_c \to \gamma\eta_c$

[1]Essentially DK^0_S recoil mass, corrected by the difference between the reconstructed invariant mass of the signal D candidate, and its known PDG mass.

(E1) decay being the predominant one [3]. Refs. [15, 16] pursued the search for this state's non-E1 decays.

Using a $\mathcal{L}_{\mathrm{Int}} = 11.3\ \mathrm{fb}^{-1}$ ($\sqrt{s} = [4.189, 4.437]$ GeV) via the $e^+e^- \to \pi^+\pi^- h_c$ production channel, Ref. [15] searched for the hadronic transition $h_c \to \pi^0 J/\psi$ without finding any significant signal.

On the other hand, Ref. [16] searched for pure hadronic decay channels using the BESIII's 448 million of $\psi(2S)$ events via the $\psi(2S) \to \pi^0 h_c$. This study found evidence (4.9σ) for the $h_c \to \mathrm{p\bar{p}}\pi^+\pi^-\pi^0$ decay and observed (5.1σ) the $h_c(1^1P_1)$ state decaying into $\mathrm{p\bar{p}}\eta$ ($\eta \to \pi^+\pi^-\pi^0/\gamma\gamma$).

Using the $h_c(1^1P_1)$ state E1 decay and exploiting BESIII's $\psi(2S)$ data set, it is possible to provide another measurement of this state's mass and width. Ref. [17], using the $\psi(2S) \to \pi^0 h_c \to \pi^0$ ($\gamma\eta_c$), gives, with an increased precision with respect to Ref. [3], the second measurement only of this state's width. This work increased the precision of the production and the decay branching fraction estimates, by a factor of two and three times concerning the PDG measurement [3]. Furthermore, with the $h_c(1^1P_1)$ state mass estimate, Ref. [17] provides the mass splitting between the pseudo-vector state and the centre-of-gravity mass of the three $\chi_{cJ}(1^3P_J)$ ones, finding it to be consistent to 0 at leading-order [18].

3 Light Hadrons

Despite the Naïve Quark Model describing conventional hadrons containing two or three quarks, QCD predicts an additional plethora of exotic states (hybrids, glueballs, mesonic molecules, etc.).
Indeed, also below the $c\bar{c}$ spectrum many supernumerary XYZ-like states are experimentally observed. Also here, in the light quarks regime, the nature of these exotic states is hard to determine, as they have overlapping masses with "regular" states.
Radiative J/ψ (i.e., $\to \gamma$ + had) decays are gluon-rich processes, ideal for studying light glueballs and hybrids. Owing to its statistics, the BESIII collaboration plays a fundamental role in the searches for these states.

3.1 A New Incognita... The $X(2600)$ State

Using the 10 billion J/ψ data set, Ref. [19] studies the radiative $J/\psi \to \gamma\pi^+\pi^-\eta'$ decay, reconstructing the η' meson from its $\gamma\pi^+\pi^-$ and η ($\to \gamma\gamma$) $\pi^+\pi^-$ main [3] decays. In said analysis, the invariant $\pi^+\pi^-\eta'$ mass ($\mathrm{M}(\pi^+\pi^-\eta')$) is obtained and confronted to the $\pi^+\pi^-$ one ($\mathrm{M}(\pi^+\pi^-)$). In the $\mathrm{M}(\pi^+\pi^-\eta')$ distribution, apart from the already observed $X(1835)$, $X(2120)$, $X(2370)$, and η_c states, a new structure around 2.6 GeV/c^2 is found and is seen to be correlated with another one in the $\mathrm{M}(\pi^+\pi^-)$ spectrum at 1.5 GeV/c^2.
To study the parameters and significance of this structure, a simultaneous fit, to the invariant $\pi^+\pi^-\eta'$ and $\pi^+\pi^-$ mass distributions is performed. The $X(2600)$, as this structure is called by Ref. [19], is found for the first time with a significance of more than 20σ, and its partner structure in the $\mathrm{M}(\pi^+\pi^-)$ spectrum is described as an interference between the $f_0(1500)$ resonance and an $X(1540)$ state. Considering the $X(2600) \to f_0(1500)/X(1540)$ decay, the spin parity of the $X(2600)$ state is 0^{-+} or 2^{-+}. With these spin-parity assignments, the $X(2600)$ state can be a radial excitation of the η meson [20] or an exotic hadron.

3.2 Partial Wave Analyses on J/ψ Decays

Owing to its huge statistics (the aforementioned 10 billion J/ψ data set), the BESIII Collaboration can study with high precision gluon-rich processes (such as $J/\psi \to \gamma\eta\eta'$ and $J/\psi \to \gamma\eta'\eta'$) also via the Partial Wave Analysis (PWA) technique. Following the isobar model [21], the total amplitude of a decay is parameterised as a sum of sequential quasi-two-body processes and its intermediate resonances contributions are studied.

Ref. [22] studies the $J/\psi \to \gamma\eta\eta'$ decay. After event selection, the four-momenta of the reconstructed $\gamma\eta\eta'$ are used to perform the PWA fit by constructing the quasi-two-body decay amplitudes in the sequential $J/\psi \to \gamma X, X \to \eta\eta'$ and $J/\psi \to \eta' X, X \to \gamma\eta$ processes. Hence, the $\eta\eta'$ and $\gamma\eta$ spectra are first fitted using all the allowed resonances from Refs. [3, 23, 24]; then, the fit is re-performed using all those resonances which have a statistical significance larger than 5σ from the first iteration. Finally, a search is performed for additional resonances by individually adding them to the second iteration solution. It is found that only a resonance with $J^{PC} = 1^{-+}$ around 1.9 GeV/c^2 in the $\eta\eta'$ spectrum has a significant contribution (i.e., bigger than 20σ). This state, observed for the first time and called $\eta_1(1855)$, is an isoscalar resonance with exotic quantum numbers, and its parameters are consistent with LQCD calculations for the 1^{-+} hybrid [25]. Moreover, the absence of any $f_0(1710)$ resonance contribution in the PWA fit, supports the hypothesis that the $f_0(1710)$ meson overlaps with the ground state scalar glueball [26].

Ref. [27] focuses on the $J/\psi \to \gamma\eta'\eta'$ channel. Similarly to Ref. [22] , a PWA fit is performed to the $J/\psi \to \gamma\eta'\eta'$ radiative transition. In this study, the $f_0(2480)$ meson, a new scalar resonance (i.e., with $J^{PC} = 0^{++}$), is observed for the first time with a significance bigger than 5σ.

4 Charm Mesons for QCD

The BESIII collaboration can also probe the light hadron spectrum via the hadronic and semi-leptonic D_s decays. On these channels, Amplitude Analyses (AA) [21] are performed to study the intermediate resonance contributions to the decays. Moreover, to measure branching fractions, Single Tag (ST) - Double Tag (DT) analysis methods are employed. In the branching fraction estimation, the ST sample is used as a normalising factor, for this data set one of two D_s mesons is reconstructed from a specific hadronic decay; on the other hand, to ensure high signal purity, in the DT sample the D_s "signal" meson is reconstructed through the searched decay, while the other D_s (so-called "tag"), is reconstructed through several hadronic decays. The synergy of these two techniques allows to estimate SU(3) multiplets couplings and shine a light on their nature.

4.1 Back to the $f_0(1710)$

Using a $\mathcal{L}_{\text{Int}} = 6.32$ fb^{-1} ($\sqrt{s}$ = [4.178, 4.226] GeV), Ref. [28] searches for the $D_s^+ \to K_S^0 K_S^0 \pi^+$ decay in the $e^+e^- \to D_s^* D_s \to \gamma D_s D_s$ process. An AA is performed on the $K_S^0 K_S^0$ and $K_S^0 \pi^+$ invariant masses, reconstructed through a DT sample. The AA allows identifying a structure around 1.7 GeV/c^2 in the $K_S^0 K_S^0$ spectrum; this structure, referred to as $S(1710)$, is modelled as an admixture of the $f_0(1710)$ meson and its $a_0(1710)$ isovector partner. Using the ST sample, it is possible to estimate the $D_s^+ \to S(1710)\pi^+ \to K_S^0 K_S^0 \pi^+$ branching fraction, which is found consistent with Ref. [29], implying the existence of an isovector partner [30] of the $f_0(1710)$ meson and a constructive interference between them when decaying to neutral kaons.

4.2 The $f_0(1710)$... Glueball, Molecule, or Scalar Meson?

Using the same data set and process as Ref. [28], Ref [31] studies the $D_s^+ \to K_S^0 K^+ \pi^0$ decay. Using a DT sample, an AA is performed on the $K_S^0 K^+$, $K_S^0 \pi^0$, and $K^+\pi^0$ invariant masses. The AA allows identifying a structure around 1.7 GeV/c^2 in the $K_S^0 K^+$ spectrum. The mass and width of this structure are measured and it is identified in the charged partner of the isovector state $a_0(1710)$ (i.e., $a_0(1710)^+$). Despite this, the mass value of the $a_0(1710)^+$ meson is found to be in tension (at a significance of 5σ) with the BaBar collaboration's one [32]. Using the ST sample, it is possible to estimate the $D_s^+ \to a_0(1710)^+$ branching fraction, which is found consistent with Ref. [33] predicting the $f_0(1710)$ being a $K\bar{K}^*$ molecule. Moreover, another possible interpretation comes from Ref. [34] suggesting this structure to be the isovector partner of the $X(1812)$ [35] scalar observed in $\omega\phi$ decay channel by the BES collaboration.

5 Baryon Studies

Finally, the BESIII collaboration can probe the perturbative regime of QCD by performing high-precision measurements such as R-value and Form Factors estimations.

5.1 R-Value Estimation

The R-value, which is the ratio between the $e^+e^- \to$ *hadrons* cross-section and the $e^+e^- \to \mu^+\mu^-$ one, allows the BESIII collaboration to probe the physics beyond the standard model, as it is fundamental for the determination of the anomalous muon magnetic moment, and to test quantum electrodynamics, as it enters in the running coupling constant calculations.

Using 14 energy points centre-of-mass energies between 2.2324 GeV and 3.6710 GeV, Ref. [36] provides the respective R-values. For such a measurement, good charged hadronic tracks are selected, while rejecting QED-related background. The trigger efficiency and the event selection are the least contributing uncertainties, thus, granting the most precise up-to-date measurement of the R-value for the aforementioned 14 energy points. Reaching an accuracy of 2.6% at $\sqrt{s} < 3.1$ GeV and 3.0% at $\sqrt{s} > 3.1$ GeV, the results are consistent with KEDR ones [37] and QCD predictions [38].

5.2 ElectroMagnetic Form Factors

An example of how the BESIII collaboration can perform regarding the form factors is represented in Ref. [39]. In this study, the $e^+e^- \to \Sigma^0\bar{\Sigma}^0$ Born cross-section at 7 centre-of-mass energies ($\sqrt{s}$ = [2.3864, 3.0200] GeV) is measured, providing the 7 corresponding Σ^0 effective form factors [Rev. Mod. Phys. 35, 335 (1963)]. For the data sets at $\sqrt{s} > 2.3960$ GeV, the process is reconstructed via Single Tag method, in which the Σ^0 baryon is completely reconstructed from its $\Sigma^0 \to \gamma\Lambda^0$, $\Lambda^0 \to p\pi^-$ decay chain. For the two energy points below 2.3960 GeV (i.e., near the $\Sigma^0\bar{\Sigma}^0$ production threshold), the soft-$\pi^\pm$ and the $\bar{p}$ annihilation products are reconstructed to identify the process.
The results are in agreement with the BaBar collaboration's ones [40], but with improved precision of a factor of 2. Moreover, following Ref. [41], an asymmetry in the effective form factors ($\mathrm{G_{Eff}}$) of Σ-triplet is observed confirming that $\mathrm{G_{Eff}}$ is proportional to the squared sum of the valence quarks' charge.

6 Summary

The BESIII collaboration started taking data in 2008, and, since then, its physics reach has spanned a plethora of topics. The main focus of this review is the most recent results of the BESIII collaboration in the QCD field, ranging from charmonium(-like) studies, in which both conventional and exotic states are under investigation; to light hadrons spectroscopy and decays, used to probe the nature of the light hybrids, glueballs, and mesonic molecules; to open charm physics, which in synergy with light hadrons studies, investigate the light exotic states; to the precision QCD measurements of which the R-value measurements or the EMFFs are just two examples.

The BESIII collaboration can also provide useful insights outside of the QCD environment such as probing BSM physics or studying the electroweak sector.

Finally, new data sets (e.g., $\sim 3 \times 10^9$ of $\psi(2S)$ or $\sim$20 fb^{-1} of $\psi(3770)$) are currently being taken and analysed, hence more studies and analyses will help the community to shed light on the mysteries of QCD.

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