

Physics with Charmonium - A few recent highlights of BESIII

Johan Messchendorp* for the BESIII Collaboration

KVI, University of Groningen, Zernikelaan 25, 9747 AA Groningen, The Netherlands.

E-mail: messchendorp@kvi.nl

Despite the successes of the standard model, the non-perturbative dynamics of the strong interaction are not fully understood yet. Charmonium spectroscopy serves as an ideal tool to shed light on the dynamics of the strong interaction such as quark confinement and the generation of hadron masses. The BESIII collaboration studies extensively the strong interaction and various aspects that could shed light on physics beyond the standard model via copious e^+e^- collisions at the BESIII/BEPCII facility in Beijing, China, in the charmonium mass regime. I present a few of the recent results with the emphasis on charmonium spectroscopy and decay studies using 106×10^6 $\psi(3686)$ events.

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*Speaker.

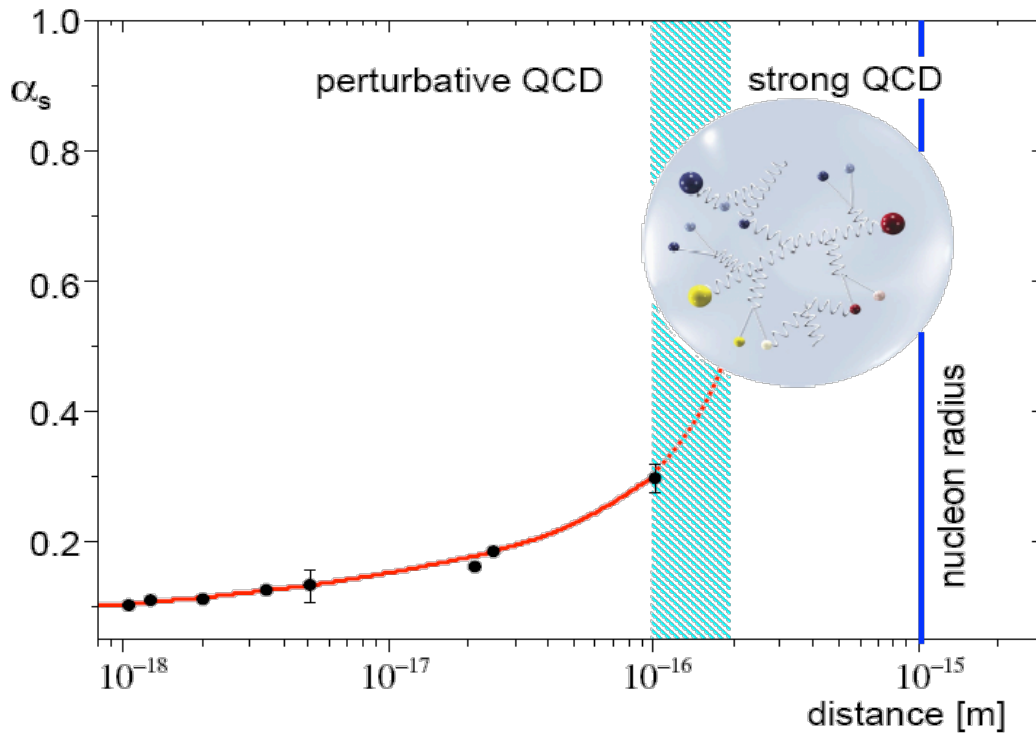


Figure 1: The strong coupling constant, α_s , as a function of the distance scale. Towards larger distances, QCD becomes non-perturbative, and gives rise to spectacular phenomena such as the generation of hadron masses and quark confinement.

1. Introduction

1.1 The strong force and QCD

The fundamental building blocks of Quantum Chromodynamics (QCD) are the quarks which interact with each other by exchanging gluons. QCD is well understood at short-distance scales, much shorter than the size of a nucleon ($< 10^{-15}$ m). In this regime, the basic quark-gluon interaction is sufficiently weak. In fact, many processes at high energies can quantitatively be described by perturbative QCD. Perturbation theory fails when the distance among quarks becomes comparable to the size of the nucleon. Under these conditions, in the regime of non-perturbative strong QCD, the force among the quarks becomes so strong that they cannot be further separated (see illustration in Fig. 1). As a consequence of the strong coupling, we observe the relatively heavy mass of hadrons, such as protons and neutrons, which is two orders of magnitude larger than the sum of the masses of the individual quarks. This quantitatively yet-unexplained behavior is related to the self-interaction of gluons leading to the formation of gluonic flux tubes connecting the quarks. As a consequence, quarks have never been observed as free particles and are confined within hadrons, i.e. the baryons containing three valence quarks or mesons containing a quark-antiquark pair.

Besides the presence of conventional hadrons consisting of three quarks, baryons, or two quarks, mesons, the intriguing color nature of QCD allows for the existence of gluon-rich mat-

ter, such as hybrids and glueballs, states composed of more than three quarks, or weakly bound states composed of mesons, the so-called molecular states. Although, experimental hints for their existence are available, there is yet no unambiguous discovery of such states. A systematic approach exploiting a clean environment and high statistics data has a good discovery potential in the search for the new form of hadronic matter.

1.2 Charmonium: the positronium of QCD

The BESIII collaboration exploits the bound state of a charm quark (c) and a charm antiquark (\bar{c}), known as charmonium, to study as part of an extensive physics program the dynamics of the strong force in an energy regime that corresponds to the transition between perturbative and non-perturbative QCD. Charmonium is one of the most simplest two-body systems in the field of hadronic physics. The charm quark is relatively heavy in mass, allowing theoretical analyses that are based on a non-relativistic framework with relativistic corrections such as spin-orbit and spin-spin forces. Moreover, the charmonium states below the open-charm threshold are narrow as a consequence of the OZI suppression rule and, hence, can easily be identified as sharp needles on top of a continuous background, thereby forming ideal beacons of QCD. The level scheme of lower-lying bound charmonium states is very similar to that of positronium or the hydrogen atom. Figure 2) gives an overview of the established mass spectrum of charmonium-like particles in the regime that is accessible by BESIII. The charmonium states below the open-charm threshold can be described fairly well in terms of heavy-quark potential models and rigorous lattice QCD calculations. Precision measurements of the mass and width of the charmonium spectrum give, therefore, access to the confinement potential in QCD. In addition, the various charmonium states with well-defined spin and parity serve as ideal systems to study via their decay modes the validity of perturbative QCD and to probe the light-quark sector as well. For more details concerning the underlying motivation of exploiting charmonium, I refer to Ref. [1].

2. The BESIII experiment

BEPCII is a two-ring e^+e^- collider designed for a peak luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ at a center-of-mass energy of 3770 MeV. The cylindrical core of the BESIII detector consists of a helium-gas-based drift chamber, a plastic scintillator time-of-flight system, and a CsI(Tl) electromagnetic calorimeter, all enclosed in a superconducting solenoidal magnet providing a 1 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel. The charged particle and photon acceptance is 93% of 4π , and the charged particle momentum and photon energy resolutions at 1 GeV are 0.5% and 2.5%, respectively. More details on the features and capabilities of BESIII are provided in Ref. [2]. Both the BEPCII facility and the BESIII detector are major upgrades of the BESII detector and the BEPC accelerator. The first collisions with the complete setup took place in July of 2008. The first physics production runs started in the first half of 2009. Already during writing of this paper, the amount of data samples collected for the J/ψ , $\psi(3686)$, and $\psi(3770)$ is significantly larger than that obtained by the CLEO collaboration, thereby reaching a new world record in statistics.

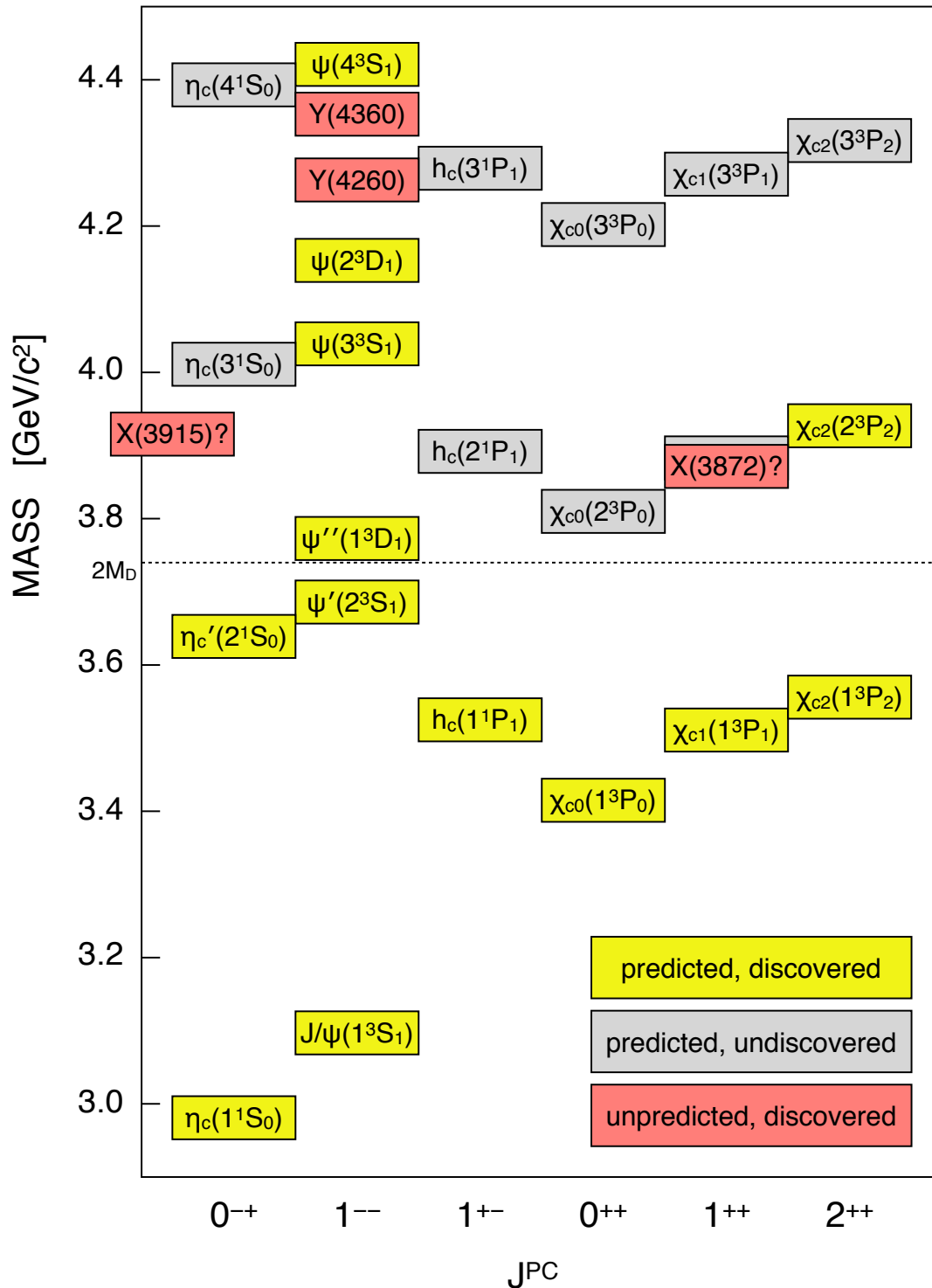


Figure 2: The mass spectrum of charmonium(-like) states in the energy interval available in BESIII and as a function of their spin-parity, J^{PC} . The yellow boxes represent charmonium states predicted by theory and confirmed by experiment. The grey boxes are those charmonium states that are predicted but not yet discovered. The red boxes are discovered charmonium-like states which nature is still mysterious. The dashed line indicates the open-charm ($D\bar{D}$) threshold. The figure is taken from a presentation by R. Mitchell.

3. Highlights in charmonium spectroscopy and decays

In this paper, I discuss a few of the highlights that were obtained within the charmonium spectroscopy and decays program of BESIII. This program of BESIII resulted so far in a variety of papers that can be found in Refs. [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29]. The bulk of the activities below the open-charm threshold focuses on precision measurements of the properties of charmonium states, such as their masses, total widths, line shapes, and partial decay rates. This data provide an excellent basis to reveal the details of the confinement potential, to perform perturbative QCD tests, and to study systematically non-perturbative, long-distance, contributions within a controlled environment. In addition, new states were discovered or confirmed with a large discovery potential above the open-charm threshold.

3.1 The ground state and its first radial excitation of charmonium, $\eta_c(1S, 2S)$

Our present knowledge on the basic properties, such as mass and width, of the vector meson states ($J^{PC} = 1^{--}$) of charmonium is excellent due to the huge amount of data available. In contrary, the properties of the pseudo-scalar ($J^{PC} = 0^{-+}$) charmonium states, including the ground state of charmonium and its radial excitation ($\eta_c(1S, 2S)$), are poorly understood. For a large part this is due to the fact that these states cannot be populated directly via e^+e^- annihilations. One can, however, study these states indirectly in e^+e^- experiments via two-photon fusion, B decays, or, as pursued with BESIII, via the magnetic-dipole (M1) transition $\psi(1S, 2S) \rightarrow \gamma\eta_c$.

Previously published measurements of the mass and width of the ground state, $\eta_c(1S)$, show large discrepancies among the various channels that were employed in the corresponding experiments [30]. The large statistics of BESIII allow to make a detailed study of the line shape of the $\eta_c(1S)$ via the channel $\psi(3686) \rightarrow \gamma\eta_c(1S)$ with the η_c decaying in six exclusive channels. Figure 3 shows the result of the analysis. In all the decays, a clear signal from the η_c can be observed with a small amount of background. Note that the η_c signal has an obviously asymmetric shape: there is a long tail on the low-mass side while on the high-mass side the η_c signal drops rapidly and the data dips below the expected level of the smooth background, suggesting a possible interference with a non-resonant contribution. A fit was performed for which the signal is described by a Breit-Wigner (BW) convolved with a resolution function and including the possibility of an interference with a non-resonant background. The statistical significance of the interference was found to be 15σ . Although, the nature of this interfering non-resonant contribution is not well understood yet, the high-statistics BESIII results show that a naive fit including a BW signal together with a smooth background assumption could result a misleading value for the mass and width of the extracted η_c resonance parameters. With the fitting procedure of BESIII a mass of $M=2984.3\pm 0.6(\text{stat.})\pm 0.6(\text{syst.}) \text{ MeV}/c^2$ and a width of $\Gamma=32.0\pm 1.2(\text{stat.})\pm 1.0(\text{syst.}) \text{ MeV}$ were extracted. The BESIII results are consistent with that from photon-photon fusion and B decays. Using this measurement together with the world-average $J\psi$ mass [30], one obtains for the S -wave hyperfine mass splitting a value of $\Delta M_{hf}(1S)=M(J/\psi) - M(\eta_c)=112.6\pm 0.8 \text{ MeV}/c^2$, which agrees well with recent lattice computations [31, 32, 33] and sheds light on the spin-dependent interactions in quarkonium states. More details can be found in Ref. [14].

The experimental database on the first radially excited state of the ground state, $\eta_c(2S)$, is scarce. The $\eta_c(2S)$ was first observed by the Belle collaboration in the process $B^\pm \rightarrow K^\pm\eta_c(2S)$

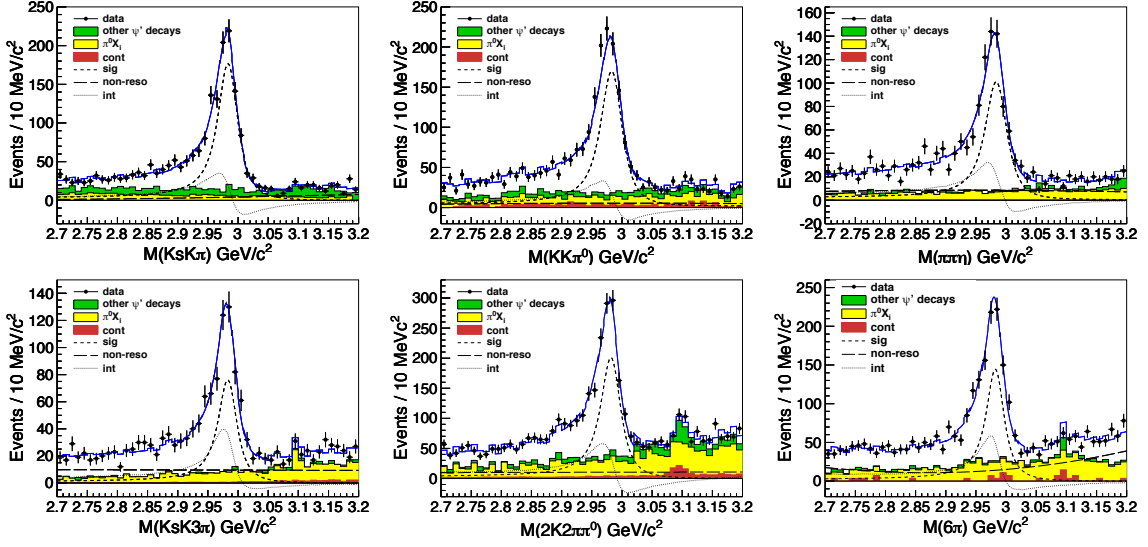


Figure 3: The $M(X_i)$ invariant mass distributions for various decays, X_i , with the fit results superimposed. Points are data and the various curves are the total fit results. Signals are shown as short-dashed lines; the non-resonant components as long-dashed lines; and the interference between them as dotted lines. Shaded histograms are various backgrounds studied independently. The figure is taken from Ref. [14].

with $\eta_c(2S) \rightarrow K_S^0 K^\pm \pi^\mp$ [34] and later on confirmed in the two-photon production of $K_S^0 K^\pm \pi^m p$ [35, 36] and in the double-charmonium production process $e^+e^- \rightarrow J/\psi c\bar{c}$ [37, 38]. A controversial observation of the $\eta_c(2S)$ was made in the past with the crystal ball setup. This experiment performed an inclusive measurement of the energy spectrum of photons in $\psi(3686)$ decays and found a peak that corresponds to a missing mass of 3592 ± 5 MeV/ c^2 which they attributed to an observation of the $\eta_c(2S)$ [39]. Surprisingly, this measurement of the $\eta_c(2S)$ mass turns out to be significantly smaller than all the ones measured by Belle, BaBar, and CLEO. With the statistics collected with BESIII and the capability of the setup to study exclusive channels, a first observation of the M1 transition was made possible in the reaction $\psi(3686) \rightarrow \gamma \eta_c(2S)$ with $\eta_c(2S) \rightarrow K \bar{K} \pi$. The results are depicted in Fig. 4. Besides the strong and well-understood background signals from the $\chi_{c1,2}$ resonances and from initial and final-state radiative background processes, a clear peak can be observed in the expected mass region of the $\eta_c(2S)$. A simultaneous likelihood fit results in a measurement of the $\eta_c(2S)$ mass of $M = 3637.6 \pm 2.9(\text{stat.}) \pm 1.6(\text{syst.})$ MeV/ c^2 and a width of $\Gamma = 16.9 \pm 6.4(\text{stat.}) \pm 4.8(\text{syst.})$ MeV. In addition, a first measurement of the branching fraction of the M1 transition $\psi(3686) \rightarrow \gamma \eta_c(2S)$ resulted in $B = (6.8 \pm 1.1(\text{stat.}) \pm 4.5(\text{syst.})) \times 10^{-4}$ where the relatively large systematic error stems from the uncertainty of the branching fraction of $\eta_c(2S) \rightarrow K \bar{K} \pi$ which was taken from a BaBar measurement [40]. More details of the BESIII observation and corresponding measurements can be found in Ref. [18]. More recently, the BESIII collaboration made an observation of the $\eta_c(2S)$ via the exclusive process $\psi(3686) \rightarrow \gamma K_S^0 K^+ \pi^- \pi^+ \pi^-$ [29]. The extracted mass and width of this measurement were found to be within two and one standard deviations, respectively, from the measurements of the first $\eta_c(2S)$ observation of BESIII.

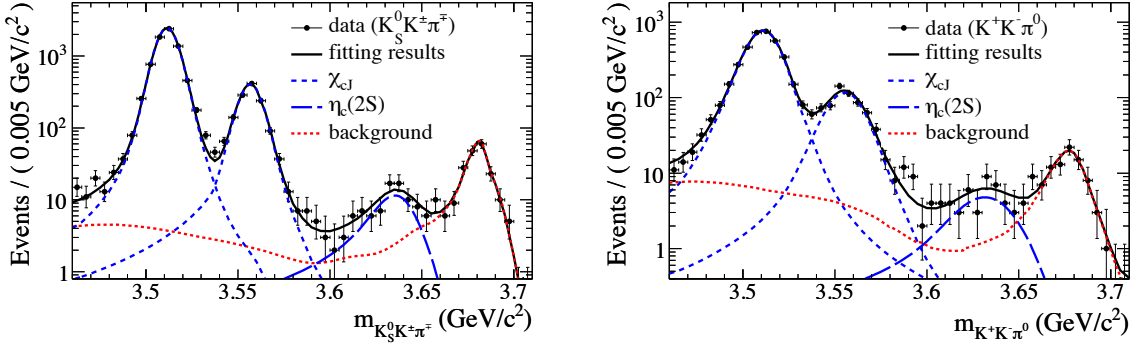


Figure 4: The invariant mass spectrum for $K_S^0 K^\pm \pi^\mp$ (left panel), $K^+ K^- \pi^0$ (right panel), and the simultaneous likelihood fit to the three resonances and combined background sources. The figure is taken from Ref. [18].

3.2 The singlet P-wave state of charmonium, h_c

One of the important aspects related to quark confinement is the spin structure of the $q\bar{q}$ potential. The role of the spin-dependence in the hyperfine splitting of the P -waves is of particular interest. For this purpose, a precise measurement of the mass and decay channels of the singlet- P resonance, h_c , is of extreme importance. This state has been studied by the BESIII collaboration via the isospin-forbidden transition, $\psi(3686) \rightarrow \pi^0 h_c$. The results of this analysis are shown in Fig. 5. Clear signals have been observed for this decay with and without the subsequent radiative decay, $h_c \rightarrow \gamma \eta_c$. This has led to a measurement of the mass and the total width of the h_c of $M=3525.40 \pm 0.13(\text{stat.}) \pm 0.18(\text{syst.}) \text{ MeV}/c^2$ and $\Gamma=0.73 \pm 0.45(\text{stat.}) \pm 0.28(\text{syst.}) \text{ MeV}$ ($< 1.44 \text{ MeV}$ at 90% C.L.), respectively. Furthermore, for the first time the branching fractions of the decays $\psi(3686) \rightarrow \pi^0 h_c$ and $h_c \rightarrow \gamma \eta_c$ were determined and found to be $\mathcal{B}(\psi(3686) \rightarrow \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$ and $\mathcal{B}(h_c \rightarrow \gamma \eta_c) = (54.3 \pm 6.7 \pm 5.2)\%$, respectively. For a more detailed discussion, I refer to Ref. [3].

More recently, the process $\psi(3686) \rightarrow \pi^0 h_c$ followed by $h_c \rightarrow \gamma \eta_c$ was re-analyzed by BESIII with an exclusive-reconstruction technique. For this, the signal-to-background ratio was improved drastically by selecting 16 exclusive hadronic decays of the η_c . The results of this work are shown in Fig. 6. A clear signal from the h_c can be observed with an improved significance with respect to the data shown in Fig. 5. This analysis resulted in the world's best determination of the h_c mass of $M=3525.31 \pm 0.11(\text{stat.}) \pm 0.14(\text{syst.}) \text{ MeV}/c^2$ and a width of $\Gamma=0.70 \pm 0.28(\text{stat.}) \pm 0.22(\text{syst.}) \text{ MeV}$. With this mass measurement together with the very-well determined masses of the triplet P -waves in charmonium, $\chi_{c0,1,2}$, one finds for the $1P$ -wave hyperfine mass splitting a value of $\Delta M_{hf} \equiv M(1^3P) - M(1^1P_1) = -0.01 \pm 0.11(\text{stat.}) \pm 0.15(\text{syst.}) \text{ MeV}/c^2$, which is consistent with the absence of a strong spin-spin interaction. Details of the analysis and results can be found in Ref. [23].

3.3 Two- and three-photon decays of charmonium

Decays of positronium to more than one photon are regarded as ideal test-beds for quantum electrodynamics (QED). Similarly, the multi-photon decays of charmonium states can serve as promising processes to test the strong-force equivalent of QED, namely QCD [1]. In general, multi-

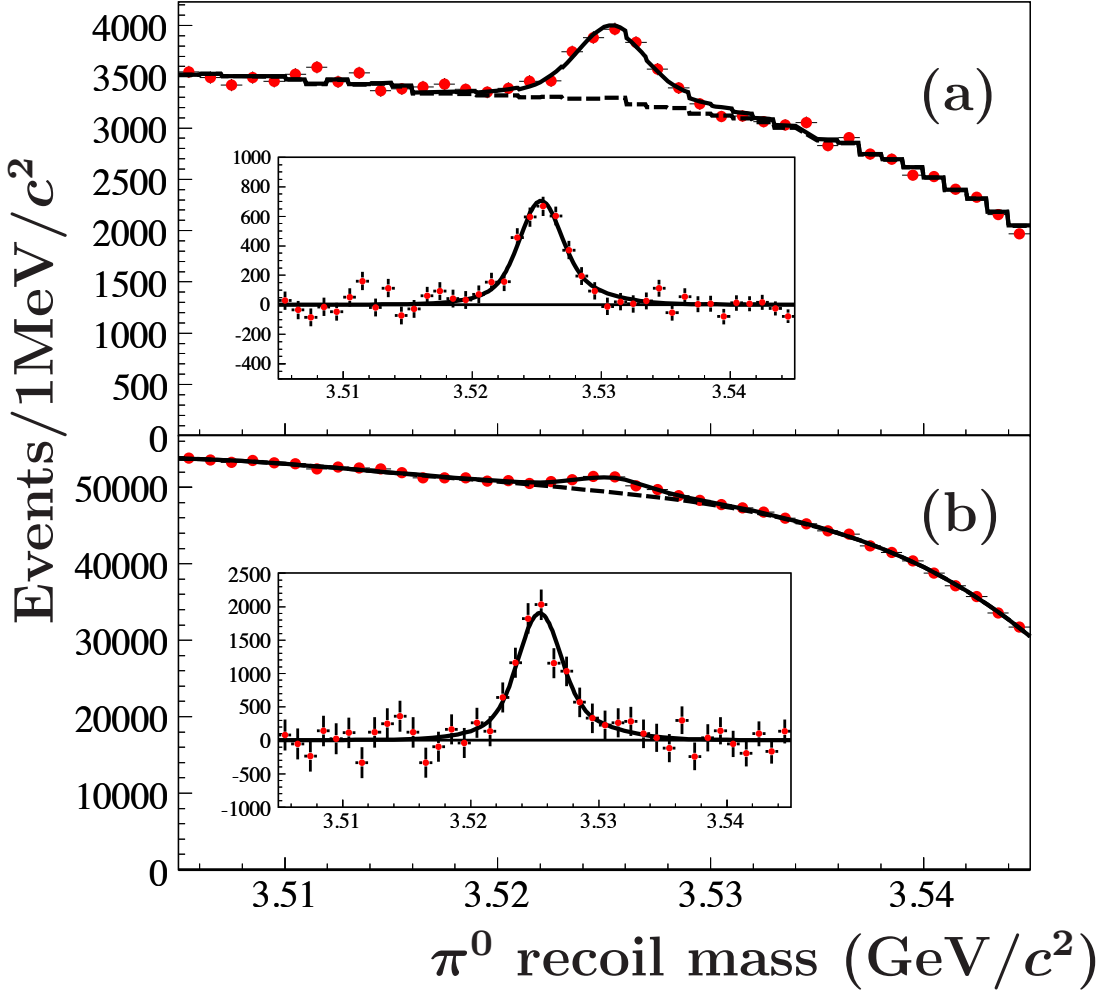


Figure 5: (a) The π^0 recoil mass spectrum and fit for the E1-tagged analysis of $\psi(3686) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c$; (b) the π^0 recoil mass spectrum and fit for the inclusive analysis of $\psi(3686) \rightarrow \pi^0 h_c$. Fits are shown as solid lines, background as dashed lines. The insets show the background-subtracted spectra. Figures are taken from Ref. [3] and described there in more detail.

photon decays provide a clean tool to study the nature of interquark forces via the annihilation of the c and \bar{c} quarks. For this reason, the BESIII collaboration has studied various multi-photon decays of charmonium states below the open-charm threshold.

A precision measurement of the two-photon widths of the triplet P -waves in charmonium via the processes $\chi_{c0,2} \rightarrow \gamma\gamma$ have been performed in analog to the corresponding triplet states of positronium. In lowest order, for both positronium and charmonium, the ratio of the two-photon decays $R_{th}^{(0)} = \frac{\Gamma(\chi_{c2} \rightarrow \gamma\gamma)}{\Gamma(\chi_{c0} \rightarrow \gamma\gamma)} = 4/15 \approx 0.27$ [1]. Any discrepancy from this simple lowest order prediction can arise due to QCD radiative corrections and relativistic corrections. Hence, a measurement on R and a comparison with theory, allows to systematically test such corrections and will, thereby, guide the development of QCD theory.

With BESIII, one can access the χ_c states via the electric-dipole (E1) transition $\psi(3686) \rightarrow$

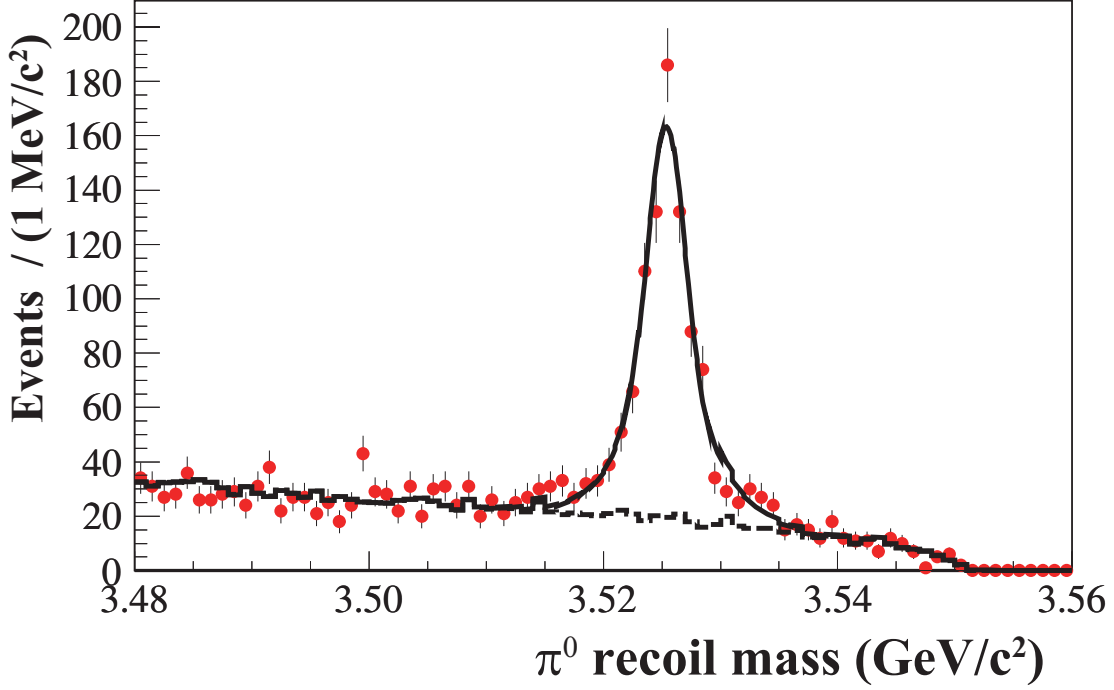


Figure 6: The π^0 recoil mass spectrum in $\psi(3686) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$, $\eta_c \rightarrow X_i$ summed over 16 various final states X_i . The dots with error bars represent data, the solid line shows the total fit function, and the dashed line is the background component of the fit. The figure is taken from Ref. [23].

$\gamma \chi_c$, and look for its subsequent decay into photons, e.g. $\chi_c \rightarrow \gamma \gamma$. Figure 7 shows the results obtained with BESIII. The figure depicts the energy distribution of the candidate E1-transition photon, γ_1 , whereby additionally two photons have been registered. Clearly, one observes strong signals from the processes $\chi_{c0,2} \rightarrow \gamma \gamma$. The decay $\chi_{c1} \rightarrow \gamma \gamma$ cannot be observed, which can be explained by the Landau-Yang theorem. BESIII finds branching fractions of $\mathcal{B}(\chi_{c0} \rightarrow \gamma \gamma) = (2.24 \pm 0.19(\text{stat.}) \pm 0.15(\text{syst.})) \times 10^{-4}$ and $\mathcal{B}(\chi_{c2} \rightarrow \gamma \gamma) = (3.21 \pm 0.18(\text{stat.}) \pm 0.22(\text{syst.})) \times 10^{-4}$, which both agrees with the less-precise results from the CLEO experiment [41]. With these branching fractions, one obtains a value of $R = 0.27 \pm 0.04$, where various systematic errors cancel out. Although, the experimental measurement of R agrees with the lowest-order prediction of $R_{th}^{(0)}$, it deviates significantly with the first-order predictions including radiative corrections, $R_{th}^{(1)} = 0.116 \pm 0.010$ [1]. In addition, the BESIII data allow for the first time a helicity amplitude analysis for the decay $\psi(3686) \rightarrow \gamma \chi_{c2}$ with $\chi_{c2} \rightarrow \gamma \gamma$. The ratio of the two-photon partial widths for the helicity-zero and helicity-two components in the decay $\chi_{c2} \rightarrow \gamma \gamma$ is determined to be $f_{0/2} = 0.00 \pm 0.02(\text{stat.}) \pm 0.02(\text{syst.})$. Note that the helicity-zero component is highly suppressed, which observation is consistent with relativistic potential calculations. For a detailed description, I refer to [17].

The two-photon decay of the $\eta_c(1S) \rightarrow \gamma \gamma$ is experimentally very challenging and it is one of the key benchmarks for BESIII to demonstrate its capabilities. Since the $\eta_c(1S)$ cannot be created directly in e^+e^- annihilations, one has to exploit the suppressed radiative M1 transitions of the

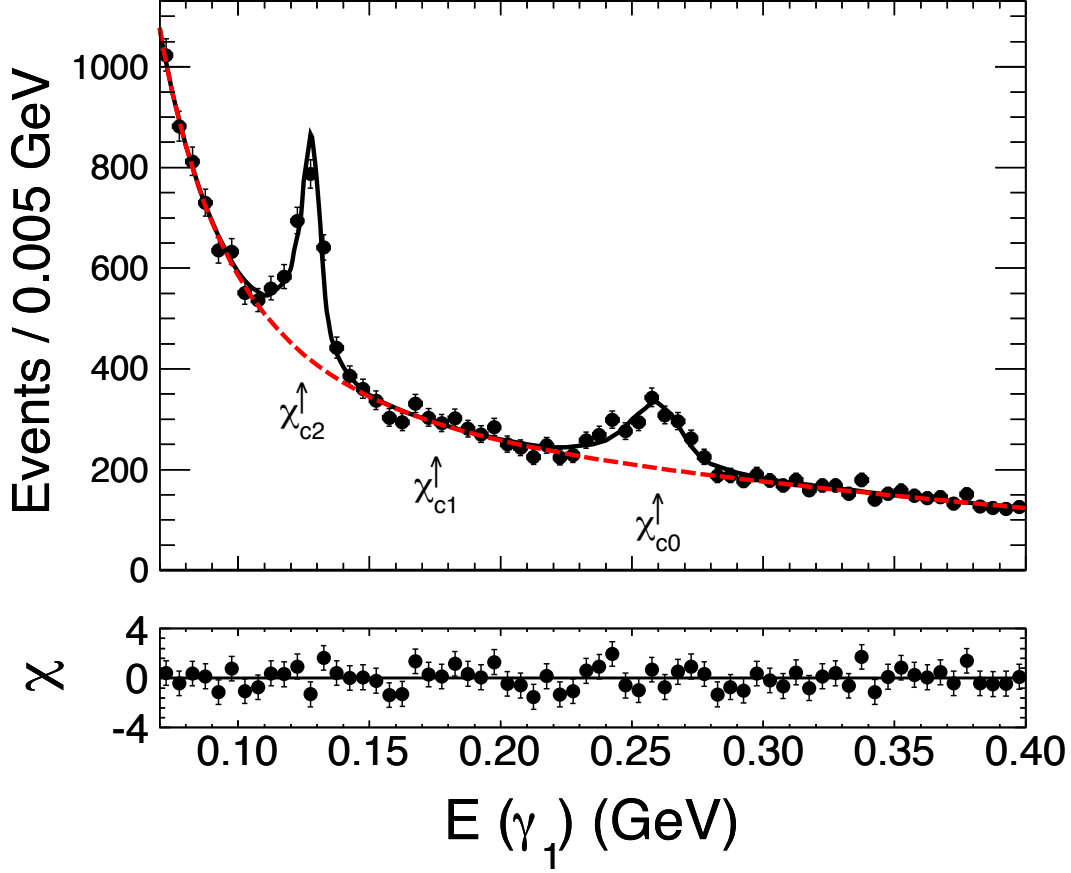


Figure 7: The upper plot shows the fitted E_{γ_1} spectrum for the $\psi(3686)$ data sample. The expected positions of E_{γ_1} from $\chi_{c0,1,2}$ are indicated by arrows. The dashed curve shows the background line shape and the solid curve the result of the full fit. The lower plot illustrates the quality of the fit by plotting the number of standard deviations, χ , of data points with respect to the fitted curve. The figure is taken from Ref. [17] and described there in more detail.

vector-meson states of charmonium. With BESIII, the $\eta_c(1S) \rightarrow \gamma\gamma$ channel has been studied via the cascade process $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$ with $J/\psi \rightarrow \gamma\eta_c(1S)$ and, eventually, $\eta_c(1S) \rightarrow \gamma\gamma$. Although, BESIII also has taken a large data sample at the J/ψ mass, the additional $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$ has the advantage of tagging exclusively on the J/ψ . Also note that the branching fraction of the $\pi^+\pi^-$ is relatively large (34%). Besides the two-photon decay of the $\eta_c(1S)$, the same study also provides access to the direct three-photon transition of the $J/\psi \rightarrow 3\gamma$. Note that the charge conjugation of the J/ψ does not allow an annihilation of the $c\bar{c}$ into two photons. The photon energy spectrum of the $J/\psi \rightarrow 3\gamma$ can as well be used to study the internal structure of the J/ψ , since the value of the photon energy is a measure for the distance between the quarks.

Figure 8 shows a key ploy of the $J/\psi \rightarrow 3\gamma$ analysis. The figure shows the projections of a two-dimensional maximum likelihood fit that was performed on the distributions with respect to the two-photon invariant mass, $M(\gamma\gamma)_{1g}$, of the two photons with the highest energy, and the chisquare of the four-constraint kinematic fit, χ_{4C}^2 . The fit was used to estimate the yields of the direct $J/\psi \rightarrow 3\gamma$ process and the cascade channel $J/\psi \rightarrow \gamma(\gamma\gamma)_{\eta_c(1S)}$. Although the data suffer

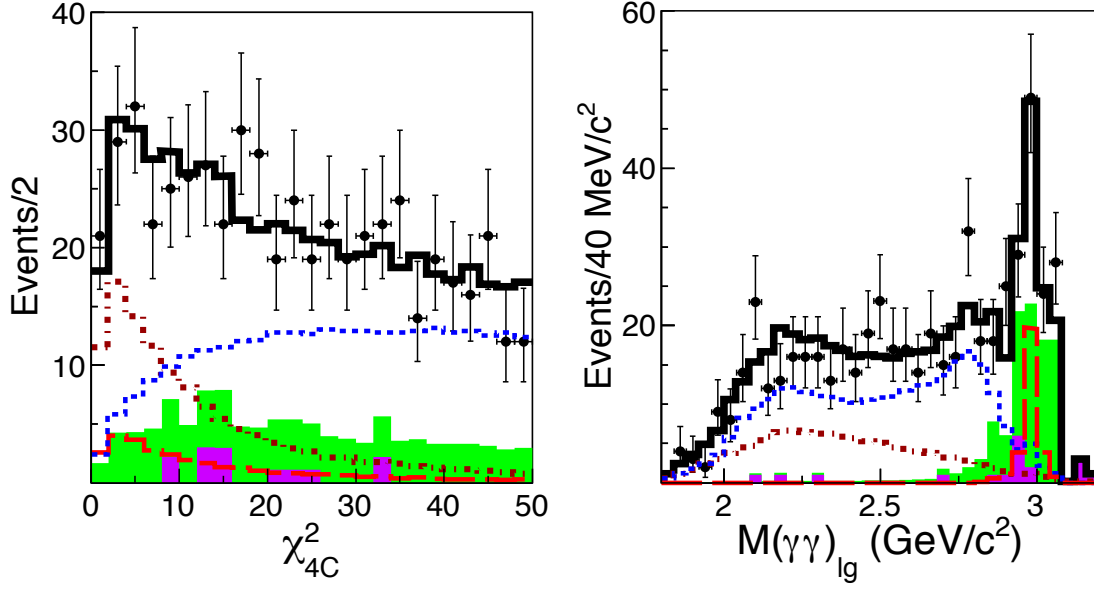


Figure 8: The left panel shows the chisquare distribution of a four-constraint fit, χ^2_{4C} and the right panel shows the two-photon invariant mass, $M(\gamma\gamma)_{lg}$, both for the process $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$ with $J/\psi \rightarrow 3\gamma$. The data are indicated as points with error bars and the results of a multi-dimensional fit are shown as thick solid lines. The (dark red) dotted-dashed, (red) dashed and (blue) dotted lines show contributions from $J/\psi \rightarrow 3\gamma$, $J/\psi \rightarrow \gamma\eta_c$, and $J/\psi \rightarrow \gamma\pi^0\pi^0$, respectively. The stacked histogram represents the backgrounds from $J/\psi \rightarrow \gamma\pi^0/\eta/\eta'$ (light shaded and green) and non- J/ψ decays (dark shaded and violet). This figure is taken from Ref. [25] and described there in more detail.

from well-understood background sources from the decays $J/\psi \rightarrow \gamma\pi^0\pi^0$ and $J/\psi \rightarrow \gamma\pi^0/\eta/\eta'$, the fit provides a clear evidence of the presence of contributions from the two- and three-photon decays of the $\eta_c(1S)$ and J/ψ , respectively. The branching fraction of the direct decay of $J/\psi \rightarrow 3\gamma$ is measured to be $\mathcal{B}(J/\psi \rightarrow 3\gamma) = (11.3 \pm 1.8 \pm 2.0) \times 10^{-6}$, which is consistent with and more accurate than the result from CLEO [42]. The measured relative branching fraction $\mathcal{B}(J/\psi \rightarrow 3\gamma)/\mathcal{B}(J/\psi \rightarrow e^+e^-)$ is incompatible with expectations including first-order QCD corrections, pointing to a need for further improvements of the QCD radiative and relativistic corrections. More details can be found at Ref. [25].

3.4 Charmed-meson loops and isospin-violating transitions

Isospin is known to be a good symmetry in the charmonium states below the $D\bar{D}$ -production threshold. The decay rates of isospin-symmetry breaking modes are in general found to be very small. For example, the branching fraction of the isospin-violating transition $\psi(3686) \rightarrow \pi^0 J/\psi$ is known to be much smaller than the branching fraction to other hadronic transitions such as the $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$ process.

Although the isospin-breaking is found to be very small for the light charmonium states, the mysterious $X(3872)$ resonance above the $D\bar{D}$ threshold decays predominantly via the transition $X(3872) \rightarrow \pi^+\pi^-J/\psi$ where the invariant-mass spectrum of the $\pi^+\pi^-$ pair shows a clear ρ signature [43] and, hence, is compatible with an isospin-violating decay. A possible scenario is that the $X(3872)$ is a molecular state composed of a bound $D^{*0}\bar{D}^0$ meson pair. Such an explanation

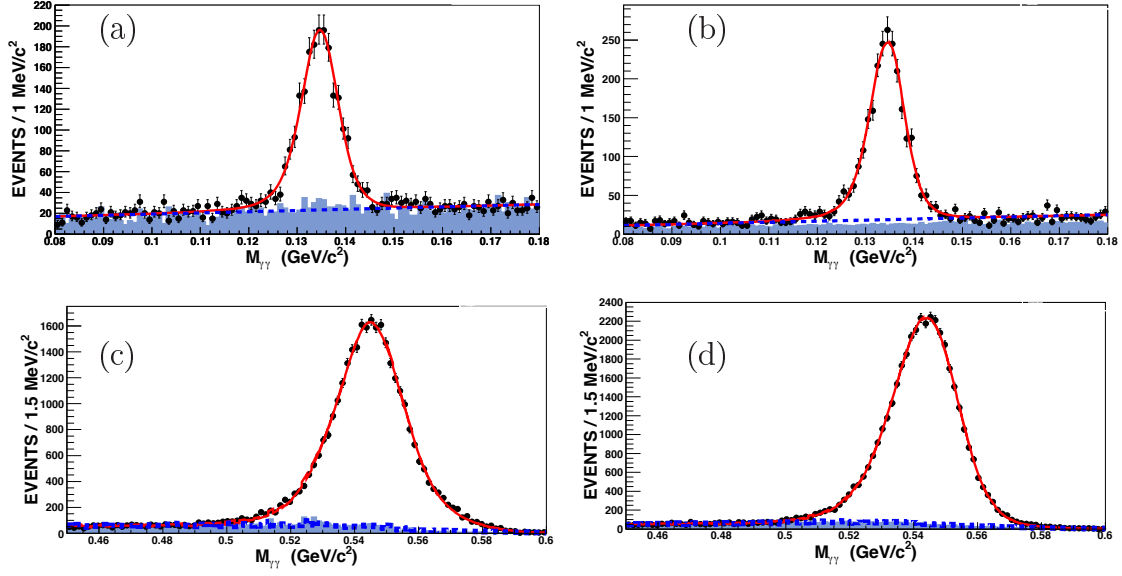


Figure 9: Two-photon invariant-mass ($M_{\gamma\gamma}$) distributions and fit results. (a) $\psi(3686) \rightarrow \pi^0 J/\psi$ with $J/\psi \rightarrow e^+e^-$, (b) $\psi(3686) \rightarrow \pi^0 J/\psi$ with $J/\psi \rightarrow \mu^+\mu^-$, (c) $\psi(3686) \rightarrow \eta J/\psi$ with $J/\psi \rightarrow e^+e^-$, (d) $\psi(3686) \rightarrow \eta J/\psi$ with $J/\psi \rightarrow \mu^+\mu^-$, where the points with error bars are data, and the solid (red) curves are the results of the total fit, and the dashed curves are the fitted background shapes. The hatched histograms represent background events obtained from Monte Carlo simulations and from analyses of sidebands in the J/ψ -mass spectrum. This figure is taken from Ref. [24] and described there in more detail.

is particularly popular since the mass of the $X(3872)$ is only slightly less than the sum of the D^0 and D^{*0} masses, pointing to a state that is weakly bound by the exchange of a color-neutral meson, similar to the deuteron. Moreover, in such a scenario, the strong isospin-breaking decay rate of the $X(3872)$ could be explained by the large mass gap between the $D^{0*} - \bar{D}^0$ and the $D^{*+} - D^-$ ($D^+ - D^{*-}$) thresholds. A better understanding of the isospin-breaking mechanism in a controlled system, such as charmonium, could be crucial to shed light on the true nature of the $X(3872)$.

A non-relativistic effective-field theoretical (NREFT) study by the Jülich and IHEP groups showed that intermediate (virtual) charmed-meson loops can be a dominant source for the isospin breaking. Detailed studies of different isospin-violating transitions in charmonium below the open-charm threshold and the effect of virtual charmed-meson loops on the widths of the transitions are described in [44, 45]. These NREFT calculations are based on a first estimate exploiting diagrams involving the lowest-lying pseudoscalar and vector charmed mesons following heavy-quark symmetry and chiral symmetry. With a complete effective field theory including Goldstone bosons, charmonia, and charmed mesons as the degrees of freedom, it would be possible in the future to make a rigorous interpretation of the nature of the XYZ states, such as the $X(3872)$, and, moreover, to extract the light-quark masses from quarkonia decays. Currently, for such a theory, quantitative predictions on individual branching fractions of isospin-forbidden decays of charmonium are difficult to make, because the information on the coupling constants $f_{\psi DD}$ between different charmonium states and DD -mesons is limited. The theory requires constraints from experimental data, in particular from measurements of decay rates of various isospin-violating transitions in charmonium.

The BESIII collaboration has started a campaign to provide the best measurements of the isospin-forbidden transition rates below the open-charm threshold. Besides the decay $\psi(3686) \rightarrow \pi^0 h_c$, presented earlier in this paper, the most precise measurement of the branching fraction of the isospin-forbidden decay $\psi(3686) \rightarrow \pi^0 J/\psi$ with $J/\psi \rightarrow l^+ l^-$ was recently published by the BESIII collaboration [24]. In addition, the branching fraction of the isospin-allowed decay $\psi(3686) \rightarrow \eta J/\psi$ was extracted. Figure 9 depicts the two-photon invariant mass spectra that were analyzed to extract the corresponding branching fractions. In all channels, a clear signal can be observed on top of a smooth background. Using this data, BESIII obtained the branching fractions $\mathcal{B}(\psi(3686) \rightarrow \pi^0 J/\psi) = (1.26 \pm 0.02(\text{stat.}) \pm 0.03(\text{syst.})) \times 10^{-3}$ and $\mathcal{B}(\psi(3686) \rightarrow \eta J/\psi) = (33.75 \pm 0.17(\text{stat.}) \pm 0.86(\text{syst.})) \times 10^{-3}$. The branching fraction ratio $R = \mathcal{B}(\psi(3686) \rightarrow \pi^0 J/\psi) / \mathcal{B}(\psi(3686) \rightarrow \eta J/\psi)$ was determined to be $(3.74 \pm 0.06(\text{stat.}) \pm 0.04(\text{syst.})) \times 10^{-2}$. These results indicate that contributions from charmed-meson loops are a possible mechanism for the dominant source of isospin violation [44].

3.5 Terra incognita

The activities below the open-charm threshold are mainly focussed towards precision charmonium studies and light-hadron spectroscopy. The physics case above the open-charm threshold is for a large part devoted to new discoveries. One of the current interests of BESIII is to study the nature of the so-called $Y(4260)$. This state was discovered via the initial-state-radiation (ISR) process $e^+ e^- \rightarrow \gamma_{\text{ISR}} \pi^+ \pi^- J/\psi$ by the BaBar collaboration [46, 47] and confirmed by CLEO [48, 49], and Belle [50]. Unlike other charmonium states with the same quantum numbers in the same mass region, such as the $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$, the $Y(4260)$ state does not have a natural place within the quark model of charmonium. Furthermore, while being well above the $D\bar{D}$ threshold, the $Y(4260)$ shows strong coupling to the $\pi^+ \pi^- J/\psi$ final state, but relatively small coupling to open charm decay modes. These aspects could point to an unconventional state, for instance, a charmonium hybrid.

Starting from the end of 2012, data were taken at a center-of-mass energy of $\sqrt{s} = 4260$ MeV. The first 525 pb^{-1} of luminosity at this energy gave already unexpected results. To the surprise of the BESIII collaboration, a new state was discovered in the invariant-mass spectrum of the $\pi^\pm J/\psi$ pair [51] (see Fig. 10). The structure has a mass of $(3899 \pm 3.6(\text{stat.}) \pm 4.9(\text{syst.})) \text{ MeV}/c^2$ and a width of $(46 \pm 10(\text{stat.}) \pm 20(\text{syst.})) \text{ MeV}$. The intriguing aspect of the state is that it couples to charmonium and that it has an electric charge, which is suggestive of a state containing more quarks than just a charm and an anti-charm quark. Also the Belle collaboration and the CLEO experiment reported short after the announcement by BESIII on a new observation of a charged charmonium-like state at a similar mass [52, 53]. Likely, many new discoveries and insights are to be expected in the upcoming years.

4. Summary

Since the discovery of charmonium in November 1974, the field of hadron and particle physics exploiting systems made from charm quarks has made a tremendous progress. Meanwhile, all the expected charmonium states below the open-charm threshold have been discovered, and for most of them, the basic resonance parameters are well studied with high statistics data from experiments

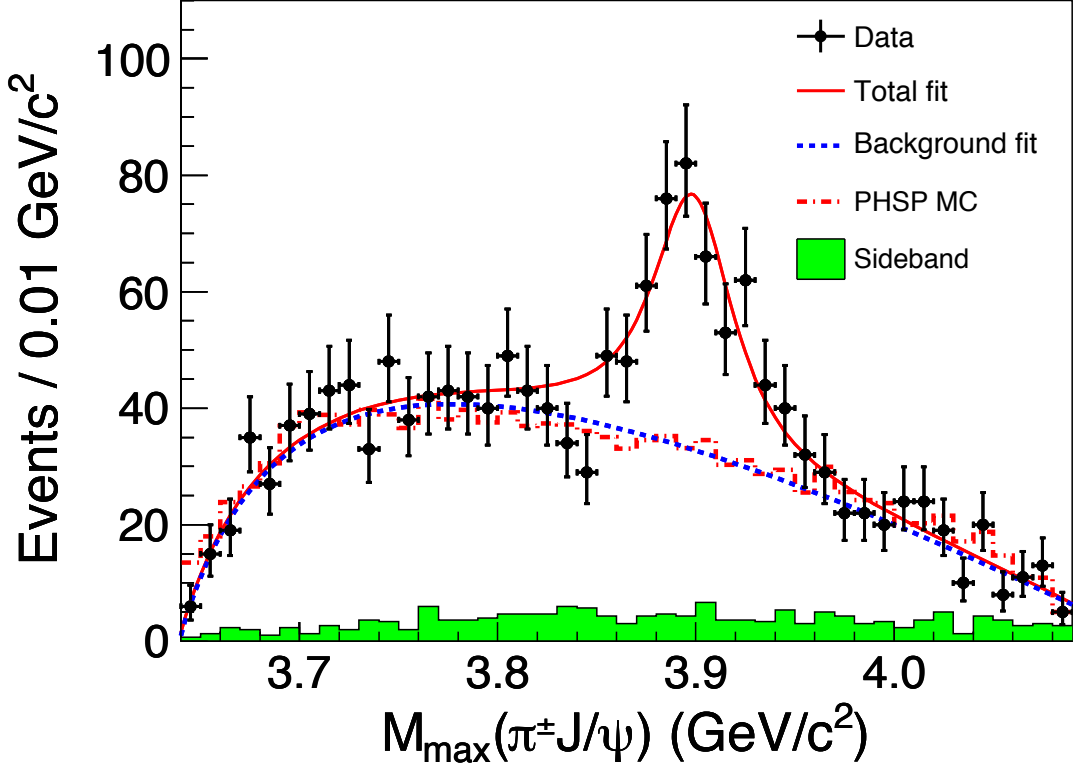


Figure 10: The invariant-mass distribution of the $\pi^\pm J/\psi$ pair in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at a center-of-mass energy of 4.26 GeV. For each event, only the maximum mass is taken out of the two combination from the two charged pions. Dots with error bars are data; the red solid curve shows the total fit; the red dot-dashed histogram shows the result of a phase space Monte Carlo simulation; and the green shaded histogram shows the normalized J/ψ sideband events. This figure is taken from Ref. [51] and described there in more detail.

such as Belle, BaBar, CLEO, and BESIII. Also, from the theoretical side, progress has been made. Precise calculations based on first principles are fastly becoming available, such as lattice QCD and effective-field theoretical approaches. The future challenges in charmonium spectroscopy are in finding and understanding the states above the open-charm threshold, in particular the recently discovered XYZ states and the many so-far unobserved higher lying charmonium states.

This paper reviews a few of the highlights obtained with BESIII. In particular, the paper summarizes the measurements that were performed on the pseudo-scalar charmonium states, the singlet P -wave, two- and three photon decays, isospin-violating transitions, and the recent BESIII activities at a center-of-mass energy of $\sqrt{s}=4.26$ GeV. BESIII is presently one of the leading experiments in the field of charmonium spectroscopy and decays and has collected a world-record on data at various energies, resulting in precision studies and new discoveries.

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References

- [1] M. B. Voloshin, *Charmonium*, Prog. Part. Nucl. Phys. **61**, 455 (2008) [hep-ph/0711.4556].
- [2] M. Ablikim *et al.* (BESIII Collaboration), *Design and construction of the BESIII detector*, Nucl. Instrum. Meth. A **614**, 345 (2010) [ins-det/0911.4960].
- [3] M. Ablikim *et al.* (BESIII Collaboration), *Measurements of $h_c(^1P_1)$ in ψ' Decays*, Phys. Rev. Lett. **104**, 132002 (2010) [hep-ex/1002.0501].
- [4] M. Ablikim *et al.* (BESIII Collaboration), *Evidence for ψ' decays into $\gamma\pi^0$ and $\gamma\eta$* , Phys. Rev. Lett. **105**, 261801 (2010) [hep-ex/1011.0885].
- [5] M. Ablikim *et al.* (BESIII Collaboration), *Branching fraction measurements of χ_{c0} and χ_{c2} to $\pi^0\pi^0$ and $\eta\eta$* , Phys. Rev. D **81**, 052005 (2010) [hep-ex/1001.5360].
- [6] M. Ablikim *et al.* (BESIII Collaboration), *Measurement of the matrix element for the decay $\eta' \rightarrow \eta\pi^+\pi^-$* , Phys. Rev. D **83**, 012003 (2011) [hep-ex/1012.1117].
- [7] M. Ablikim *et al.* (BESIII Collaboration), *First observation of the decays $\chi_{cJ} \rightarrow \pi^0\pi^0\pi^0\pi^0$* , Phys. Rev. D **83**, 012006 (2011) [hep-ex/1011.6556].
- [8] M. Ablikim *et al.* (BESIII Collaboration), *Study of χ_{cJ} radiative decays into a vector meson*, Phys. Rev. D **83**, 112005 (2011) [hep-ex/1103.5564].
- [9] M. Ablikim *et al.* (BESIII Collaboration), *Observation of χ_{cJ} decaying into the $p\bar{p}K^+K^-$ final state*, Phys. Rev. D **83**, 112009 (2011) [hep-ex/1103.2661].
- [10] M. Ablikim *et al.* (BESIII Collaboration), *Observation of χ_{c1} decays into vector meson pairs $\phi\phi$, $\omega\omega$ and $\omega\phi$* , Phys. Rev. Lett. **107**, 092001 (2011) [hep-ex/1104.5068].
- [11] M. Ablikim *et al.* (BESIII Collaboration), *Search for CP and P violating pseudoscalar decays into $\pi\pi$* , Phys. Rev. D **84**, 032006 (2011) [hep-ex/1106.5118].
- [12] M. Ablikim *et al.* (BESIII Collaboration), *Search for $\eta_c(2S)$ decays into vector meson pairs*, Phys. Rev. D **84**, 091102(R) (2011) [hep-ex/1110.0949].
- [13] M. Ablikim *et al.* (BESIII Collaboration), *Higher-order multipole amplitude measurement in ψ' decays into $\gamma\chi_{cJ}$* , Phys. Rev. D **84**, 092006 (2011) [hep-ex/1110.1742].
- [14] M. Ablikim *et al.* (BESIII Collaboration), *Measurements of the mass and width of the η_c using $\psi' \rightarrow \gamma\eta_c$* , Phys. Rev. Lett. **108**, 222002 (2012) [hep-ex/1111.0398].
- [15] M. Ablikim *et al.* (BESIII Collaboration), *Search for a light Higgs-like boson A^0 in J/ψ radiative decays*, Phys. Rev. D **85**, 092012 (2012) [hep-ex/1111.2112].
- [16] M. Ablikim *et al.* (BESIII Collaboration), *Evidence for the direct two-photon transition from ψ' to J/ψ* , Phys. Rev. Lett. **109**, 172002 (2012) [hep-ex/1204.0246].
- [17] M. Ablikim *et al.* (BESIII Collaboration), *Two-photon widths of the $\chi_{c0,2}$ states and helicity analysis for χ_{c2} to $\gamma\gamma$* , Phys. Rev. D **85**, 112008 (2012) [hep-ex/1205.4284].
- [18] M. Ablikim *et al.* (BESIII Collaboration), *First observation of the M1 transition $\psi' \rightarrow \gamma\eta'_c$* , Phys. Rev. Lett. **109**, 042003 (2012) [hep-ex/1205.5103].

- [19] M. Ablikim *et al.* (BESIII Collaboration), *Observation of χ_{cJ} decays to $\Lambda\bar{\Lambda}\pi^+\pi^-$* , Phys. Rev. D **86**, 052004 (2012) [hep-ex/1207.5646].
- [20] M. Ablikim *et al.* (BESIII Collaboration), *Observation of $e^+e^- \rightarrow \eta J/\psi$ at center-of-mass energy $\sqrt{s}=4.009$ GeV*, Phys. Rev. D **86**, 071101(R) (2012) [hep-ex/1208.1857].
- [21] M. Ablikim *et al.* (BESIII Collaboration), *Experimental study of ψ' decays to $K^+K^-\pi^0$ and $K^+K^-\eta$* , Phys. Rev. D **86**, 072011 (2012) [hep-ex/1208.2320].
- [22] M. Ablikim *et al.* (BESIII Collaboration), *Measurement of χ_{cJ} decaying into $pn\pi^-$ and $pn\pi^-\pi^0$* , Phys. Rev. D **86**, 052011 (2012) [hep-ex/1208.3721].
- [23] M. Ablikim *et al.* (BESIII Collaboration), *Study of $\psi(3686) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\eta_c$ via η_c exclusive decays*, Phys. Rev. D **86**, 092009 (2012) [hep-ex/1209.4963].
- [24] M. Ablikim *et al.* (BESIII Collaboration), *Precision measurements of branching fractions for $\psi(3686) \rightarrow \pi^0 J/\psi$ and $\eta J/\psi$* , Phys. Rev. D **86**, 092008 (2012) [hep-ex/1210.3746].
- [25] M. Ablikim *et al.* (BESIII Collaboration), *Evidence for $\eta_c \rightarrow \gamma\gamma$ and measurement of $J/\psi \rightarrow 3\gamma$* , Phys. Rev. D **87**, 032003 (2013) [hep-ex/1208.1461].
- [26] M. Ablikim *et al.* (BESIII Collaboration), *Search for hadronic transition $\chi_{cJ} \rightarrow \eta_c \pi^+ \pi^-$ and observation of $\chi_{cJ} \rightarrow K\bar{K}\pi\pi$* , Phys. Rev. D **87**, 012002 (2013) [hep-ex/1208.4805].
- [27] M. Ablikim *et al.* (BESIII Collaboration), *Measurements of baryon pair decays of χ_{cJ} mesons*, Phys. Rev. D **87**, 032007 (2013) [hep-ex/1211.2283].
- [28] M. Ablikim *et al.* (BESIII Collaboration), *Measurements of the branching fractions for J/ψ and $\psi(3686) \rightarrow \Lambda\bar{\Lambda}\pi^0$ and $\Lambda\bar{\Lambda}\eta$* , Phys. Rev. D **87**, 052007 (2013) [hep-ex/1211.4682].
- [29] M. Ablikim *et al.* (BESIII Collaboration), *Evidence for $\eta_c(2S)$ in $\psi(3686) \rightarrow \gamma K_S K^+ \pi^- \pi^+ \pi^-$* , Phys. Rev. D **87**, 052005 (2013) [hep-ex/1301.1476].
- [30] J. Beringer *et al.* (Particle Data Group), *Review of Particle Physics*, Phys. Rev. D **86**, 010001 (2012).
- [31] T. Burch *et al.*, *Quarkonium mass splittings in three-flavor lattice QCD*, Phys. Rev. D **81**, 034508 (2010) [hep-lat/0912.2701].
- [32] L. Levkova and C. DeTar, *Charm annihilation effects on the hyperfine splitting in charmonium*, Phys. Rev. D **83**, 074504 (2011) [hep-lat/1012.1837].
- [33] T. Kawanai and S. Sasaki, *Charmonium potential from full lattice QCD*, Phys. Rev. D **85** 091503(R) (2012) [hep-lat/1110.0888].
- [34] S.-K. Choi *et al.* (Belle Collaboration), *Observation of the $\eta_c(2S)$ in exclusive $B \rightarrow KK_S K^- \pi^+$ decays*, Phys. Rev. Lett. **89**, 102001 (2002).
- [35] B. Aubert *et al.* (BaBar Collaboration), *Measurements of the mass and width of the η_c meson and of an $\eta_c(2S)$ candidate*, Phys. Rev. Lett. **92**, 142002 (2004).
- [36] D. M. Asner *et al.* (CLEO Collaboration), *Observation of η_c' production in $\gamma\gamma$ fusion at CLEO*, Phys. Rev. Lett. **92**, 142001 (2004).
- [37] B. Aubert *et al.* (BaBar Collaboration), *Measurement of double charmonium production in e^+e^- annihilations at $\sqrt{s} = 10.6$ GeV*, Phys. Rev. D **72**, 031101 (2005).
- [38] K. Abe *et al.* (Belle Collaboration), *Observation of double $c\bar{c}$ production in e^+e^- annihilation at $\sqrt{s} = 10.6$ GeV*, Phys. Rev. Lett. **89**, 142001 (2002).

- [39] C. Edwards *et al.*, *Observation of an η'_c candidate with mass 3592 ± 5 MeV*, Phys. Rev. Lett. **48**, 70 (1982).
- [40] B. Aubert *et al.*, *Study of B-meson decays to $\eta_c K^{(*)}$, $\eta_c(2S)K^{(*)}$, and $\eta_c \gamma K^{(*)}$* , Phys. Rev. D **78**, 012006 (2008).
- [41] K. M. Ecklund *et al.* (CLEO Collaboration), *Two-photon widths of the χ_{cJ} states of charmonium*, Phys. Rev. D **78**, 091501(R) (2008).
- [42] G. S. Adams *et al.* (CLEO Collaboration), *Observation of $J/\psi \rightarrow 3\gamma$* , Phys. Rev. Lett. **101**, 101801 (2008).
- [43] S.-K. Choi *et al.* (Belle Collaboration), *Observation of a narrow charmoniumlike state in exclusive $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ Decays*, Phys. Rev. Lett. **91**, 262001 (2003).
- [44] F.-K. Guo, C. Hanhart, and U.-G. Meißner, *Extraction of the light quark mass ratio from the decays $\psi' \rightarrow J/\psi \pi^0 \eta$* , Phys. Rev. Lett. **103**, 082003 (2009) [hep-ph/0907.0521]; *ibid.* **104**, 109901(E) (2010).
- [45] F.-K. Guo *et al.*, *Novel analysis of the decays $\psi' \rightarrow h_c \pi^0$ and $\eta'_c \rightarrow \chi_{c0} \pi^0$* , Phys. Rev. D **82**, 034025 (2010) [hep-ph/1002.2712].
- [46] B. Aubert *et al.* (BaBar collaboration), *Observation of a broad structure in the $\pi^+ \pi^- J/\psi$ mass spectrum around 4.26 GeV/c²*, Phys. Rev. Lett. **95**, 142001 (2005).
- [47] J. P. Lees *et al.* (Babar Collaboration), *Study of the reaction $e^+ e^- \rightarrow J/\psi \pi^+ \pi^-$ via initial-state radiation at BABAR*, Phys. Rev. D **86**, 051102(R) (2012).
- [48] Q. He *et al.* (CLEO Collaboration), *Confirmation of the $Y(4260)$ resonance production in initial state radiation*, Phys. Rev. D **74**, 091104(R) (2006).
- [49] T. E. Coan *et al.* (CLEO Collaboration), *Charmonium decays of $Y(4260)$, $\psi(4160)$, and $\psi(4040)$* , Phys. Rev. Lett. **96**, 162003 (2006).
- [50] C. Z. Yuan *et al.* (Belle Collaboration), *Measurement of the $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ cross section via initial-state radiation at Belle*, Phys. Rev. Lett. **99**, 182004 (2007).
- [51] M. Ablikim *et al.* (BESIII Collaboration), *Observation of a charged charmoniumlike structure in $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV*, Phys. Rev. Lett. **110**, 252001 (2013) [hep-ex/1303.5949].
- [52] Z. Q. Liu *et al.* (Belle Collaboration), *Study of $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ and observation of a charged charmonium-like state at Belle*, Phys. Rev. Lett. **110**, 252002 (2013) [hep-ex/1304.0121].
- [53] T. Xiao, S. Dobbs, A. Tomaradze, and Kamal K. Seth, *Observation of the charged hadron $Z_c(3900)$ at $\sqrt{s} = 4170$ MeV*, [hep-ex/1304.3036].