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Experimental overview of charmonium spectroscopy

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In this talk, I review the recent experimental results on charmonium spectroscopy from BESIII, Belle, BaBar and CLEOc. Below the open-charm threshold, the masses and widths of spin-singlet states η_c , $\eta_c(2S)$, h_c are measured with high precision. Above the threshold, $\chi_{c2}(2P)$ is identified in the process $\gamma\gamma \rightarrow \chi_{c2}(2P) \rightarrow \gamma D\bar{D}$; Evidence of $X(3823)$ is found in the $M(\chi_{c1}\gamma)$ invariant-mass distribution for $B \rightarrow \gamma\chi_{c1}K$ decays, the measured properties are consistent with the missing $\psi_2(1^2D_2)$ state.

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1 Introduction

Charmonium spectroscopy is an ideal place for studying the dynamics of quantum chromodynamics(QCD) in the interplay of perturbative and non-perturbative QCD regime. The non-relativistic model including color Coulomb, linear scalar potential, spin-spin, and spin-orbit interaction, has made great successes in the description of the charmonium spectrum [1]. A relativised version was developed by Godfrey and Isgur [2] by taking into account relativistic correction and other effects. States with $J^{PC} = 1^{--}$ can be produced directly through electron positron annihilation, and present themselves as enhancements in the total hadronic cross section. Apart from the widely studied J/ψ and $\psi(2S)$ states, the vectors $\psi(4040)$, $\psi(4415)$, and $\psi(3770)$ have also been found [3, 4, 5, 6, 7], assigned as $\psi(3^3S_1)$, $\psi(4^3S_1)$, $\psi(1^3D_1)$ and $\psi(2^3D_1)$, respectively. All predicted charmonium states below the DD threshold have been observed in experiment. Among them, the spin-singlet states η_c , $\eta_c(2S)$, h_c are poorly measured. While above the threshold, experimental information on the charmonium states is rather limited.

2 The $\eta_c(1S)$

The mass and width of the lowest lying charmonium state, the η_c (1^1S_0), continue to have large uncertainties when compared to those of other charmonium states [8]. Early measurements of the properties of the η_c using J/ψ radiative transitions [9, 10] found a mass and width of 2978 MeV/ c^2 and 10 MeV, respectively. However, recent experiments, including photon-photon fusion and B decays, have reported a significantly higher mass and a much wider width [11, 12, 13, 14]. The most recent study by the CLEOc experiment, using both $\psi' \rightarrow \gamma\eta_c$ and $J/\psi \rightarrow \gamma\eta_c$, pointed out a distortion of the η_c line shape in ψ' decays [15]. CLEOc attributed the η_c line-shape distortion to the energy dependence of the “hindered” $M1$ transition matrix element.

At BESIII, the η_c 's are produced through $\psi' \rightarrow \gamma\eta_c$, and the η_c mass and width are determined [16] by fits to the invariant-mass spectra of exclusive η_c decay modes. Six modes are used to reconstruct the η_c : $K_S K^+ \pi^-$, $K^+ K^- \pi^0$, $\eta \pi^+ \pi^-$, $K_S K^+ \pi^+ \pi^- \pi^-$, $K^+ K^- \pi^+ \pi^- \pi^0$, and $3(\pi^+ \pi^-)$, where the K_S is reconstructed in $\pi^+ \pi^-$, and the η and π^0 in $\gamma\gamma$ decays. Figure 1 shows the η_c invariant-mass distributions for selected η_c candidates, together with the estimated $\pi^0 X_i$ backgrounds (X_i represents the η_c final states under study), the continuum backgrounds normalized by luminosity, and other ψ' decay backgrounds estimated from the inclusive MC sample. A clear η_c signal is evident in every decay mode. The η_c signal has an obviously asymmetric shape that suggests possible interference with a non-resonant γX_i amplitude. The fitted relative phases between the signal and the non-resonant component from each mode are consistent within 3σ , which may suggest a common phase in all the modes

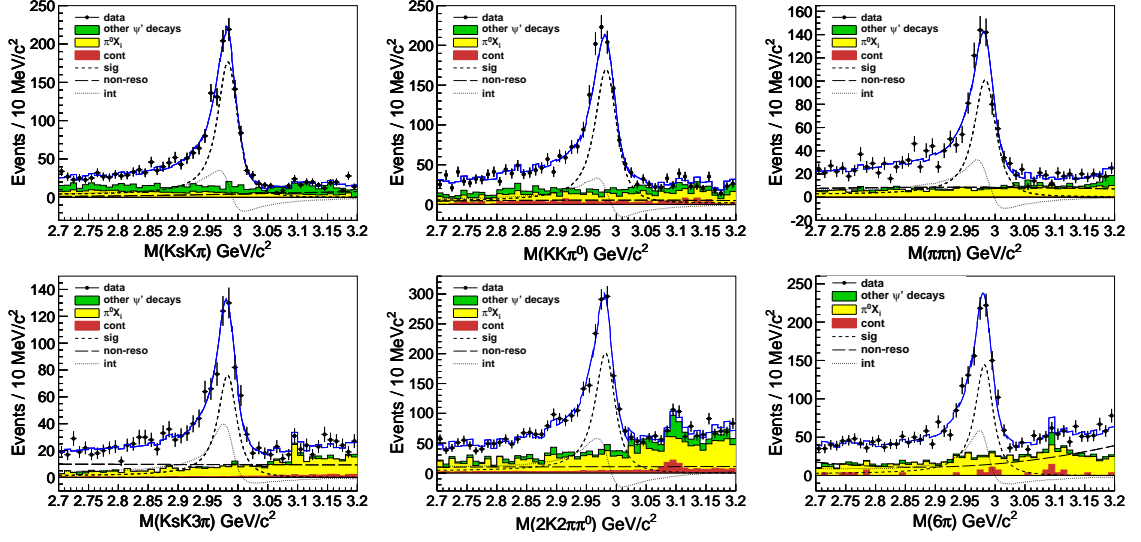


Figure 1: The $M(X_i)$ invariant-mass distributions for the η_c decays to $K_S K^+ \pi^-$, $K^+ K^- \pi^0$, $\eta \pi^+ \pi^-$, $K_S K^+ \pi^+ \pi^- \pi^-$, $K^+ K^- \pi^+ \pi^- \pi^0$ and $3(\pi^+ \pi^-)$, respectively, with the fit results superimposed. Points are data and the solid lines are the total fit results. The continuum backgrounds for $K_S K^+ \pi^-$ and $\eta \pi^+ \pi^-$ decays are negligible.

under study. A fit with a common phase (i.e. the phases are constrained to be the same) describes the data well. The results on the η_c mass and width are $M = 2984.3 \pm 0.6(\text{stat.}) \pm 0.6(\text{syst.}) \text{ MeV}/c^2$ and $\Gamma = 32.0 \pm 1.2(\text{stat.}) \pm 1.0(\text{syst.}) \text{ MeV}$, respectively.

The measurements of η_c mass and width are consistent with those from two photon-photon fusion, ψ' transition, and B decays. Hyperfine splitting is $\Delta M(1S) = 112.5 \pm 0.8 \text{ MeV}/c^2$ which agrees well with recent lattice computations [17].

3 The h_c (1^1P_1)

Information about the spin-dependent interaction of heavy quarks can be obtained from precise measurement of the $1P$ hyperfine mass splitting $\Delta M_{hf} \equiv \langle M(1^3P_J) \rangle - M(1^1P_1)$, where $\langle M(1^3P_J) \rangle = (M(\chi_{c0}) + 3M(\chi_{c1}) + 5M(\chi_{c2}))/9 = 3525.30 \pm 0.04 \text{ MeV}/c^2$ [8] is the spin-weighted centroid of the 3P_J mass and $M(1^1P_1)$ is the mass of the singlet state h_c . A non-zero hyperfine splitting may give an indication of non-vanishing spin-spin interactions in charmonium potential models [18]. CLEOc and BESIII measured [19, 20] the h_c in the π^0 recoil mass distribution for $\psi' \rightarrow \pi^0 h_c$ with and without the subsequent radiative decay $h_c \rightarrow \gamma \eta_c$ previously.

In order to reduce background and improve the precision, BESIII uses 16 exclu-

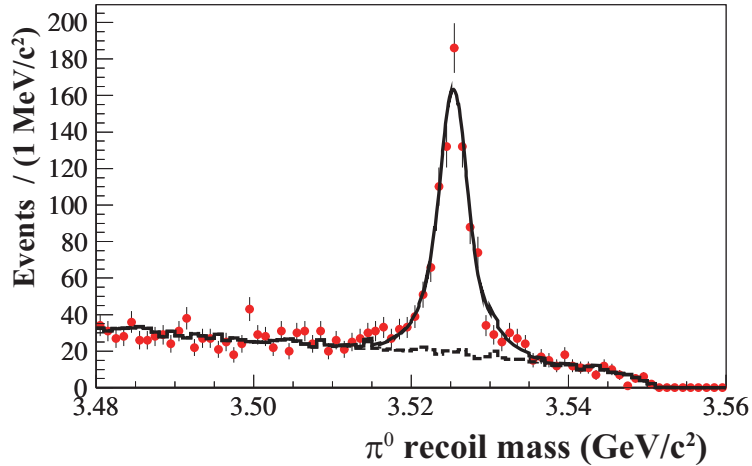


Figure 2: The π^0 recoil mass spectrum in $\psi(3686) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c, \eta_c \rightarrow X_i$ summed over the 16 final states X_i . The dots with error bars represent the π^0 recoil mass spectrum in data. The solid line shows the total fit function and the dashed line is the background component of the fit.

sive hadronic η_c decay modes to reconstruct $h_c \rightarrow \gamma \eta_c$ [21], where the 16 hadronic final states include $p\bar{p}$, $2(\pi^+\pi^-)$, $2(K^+K^-)$, $K^+K^-\pi^+\pi^-$, $p\bar{p}\pi^+\pi^-$, $3(\pi^+\pi^-)$, $K^+K^-2(\pi^+\pi^-)$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $K_S K^\pm \pi^\mp$, $K_S K^\pm \pi^\mp \pi^\pm \pi^\mp$, $\pi^+\pi^-\eta$, $K^+K^-\eta$, $2(\pi^+\pi^-\eta)$, $\pi^+\pi^-\pi^0\pi^0$, and $2(\pi^+\pi^-\pi^0\pi^0)$. By doing so, the ratio of signal to background can be improved significantly. A simultaneous fit to the π^0 recoil mass distributions of the 16 decay modes is performed to extract signal, the sum of all the decay modes is shown in Fig. 2. From 106 M ψ' , 835 ± 35 signal events are obtained. The measured h_c mass and width are $M = 3525.31 \pm 0.11 \pm 0.14$ MeV/ c^2 , $\Gamma = 0.70 \pm 0.28 \pm 0.22$ MeV, and mass splitting $\Delta M(1^1P_1) = -0.01 \pm 0.11 \pm 0.15$ MeV/ c^2 which is consistent with the lowest-order expectation that the $1P$ hyperfine splitting is zero. Where the first errors are statistical and second are systematic. The results are in agreement with the inclusive analysis results [19, 20].

Figure 3 shows the hadronic mass spectrum. We notice the η_c line shape in the $E1$ transition $h_c \rightarrow \gamma \eta_c$ is not as distorted as in the $\psi' \rightarrow \gamma \eta_c$ decays (as seen in Fig. 1). The branching ratio of $h_c \rightarrow \gamma \eta_c$ is about 50% (branching ratio of $M1$ transition $\psi' \rightarrow \gamma \eta_c$ is about 0.3%), non-resonant interfering backgrounds to the dominant transition is small. With the larger ψ' data sample and the advantage of negligible interference effects, we expect that $h_c \rightarrow \gamma \eta_c$ will provide the most reliable determinations of the η_c resonance parameters in the future.

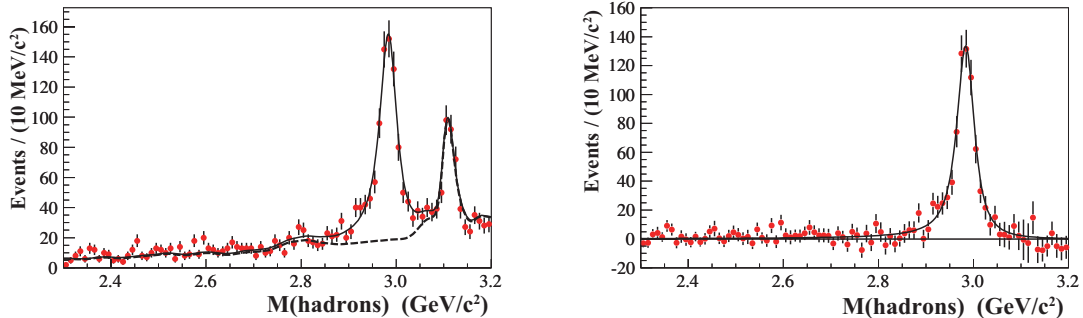


Figure 3: Left: the hadronic mass spectrum in $\psi' \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c, \eta_c \rightarrow X_i$ summed over the 16 final states X_i . Right: the background-subtracted hadronic mass spectrum with the signal shape overlaid. The dots with error bars represent the hadronic mass spectrum in data. The solid line shows the total fit function and the dashed line is the background component of the fit.

4 The $\eta_c(2S)$

The radially excited $n = 2$ spin-singlet S -wave state, the $\eta_c(2S)$ meson, was not well established until the Belle collaboration found the $\eta_c(2S)$ signal at $3654 \pm 6(\text{stat.}) \pm 8(\text{syst.}) \text{ MeV}/c^2$ in the $K_S K^+ \pi^-$ invariant-mass distribution in a sample of exclusive $\eta_c(2S) \rightarrow K_S K^+ \pi^-$ decays [22]. Since then measurements of $\eta_c(2S)$ in photon-photon fusion to $K \bar{K} \pi$ final state have been reported [11, 12, 23], as well as in double charmonium production [24, 25]. CLEO searched for $\eta_c(2S)$ in the radiative decay $\psi' \rightarrow \gamma \eta_c(2S)$, found no clear signals in its sample of 25M ψ' [26]. The challenge of this measurement is the detection of 50 MeV photons.

With 519 fb^{-1} , BaBar observed [27] $\eta_c(2S) \rightarrow K_S K^+ \pi^-$ and $\eta_c(2S) \rightarrow K^+ K^- \pi^+ \pi^- \pi^0$ produced in photon-photon fusion for the first time. They measured the mass and width of η_c and $\eta_c(2S)$ in $K_S K^+ \pi^-$ decays, $M(\eta_c) = 2982.5 \pm 0.4 \pm 1.4 \text{ MeV}/c^2$, $\Gamma(\eta_c) = 32.1 \pm 1.1 \pm 1.3 \text{ MeV}$, $M(\eta_c(2S)) = 3638.5 \pm 1.5 \pm 0.8 \text{ MeV}/c^2$, $\Gamma(\eta_c(2S)) = 13.4 \pm 4.6 \pm 3.2 \text{ MeV}$.

Belle updated the analysis of $B^\pm \rightarrow K^\pm \eta_c$ and $B^\pm \rightarrow K^\pm \eta_c(2S)$ followed by η_c and $\eta_c(2S)$ decay to $K_S K^+ \pi^-$ with 535 million $B \bar{B}$ -meson pairs [14]. Both decay channels contain the backgrounds from $B^\pm \rightarrow K^\pm K_S K^+ \pi^-$ decays without intermediate charmonia, which could interfere with the signal. Belle's analysis took interference into account with no assumptions on the phase or absolute value of the interference. A two dimensional $M(K_S K^+ \pi^-) - \cos \theta$ fit was performed to extract signal, where θ is the angle between K (from B directly) with respect to K_S in the rest frame of the $K_S K^+ \pi^-$. They obtained the masses and widths of

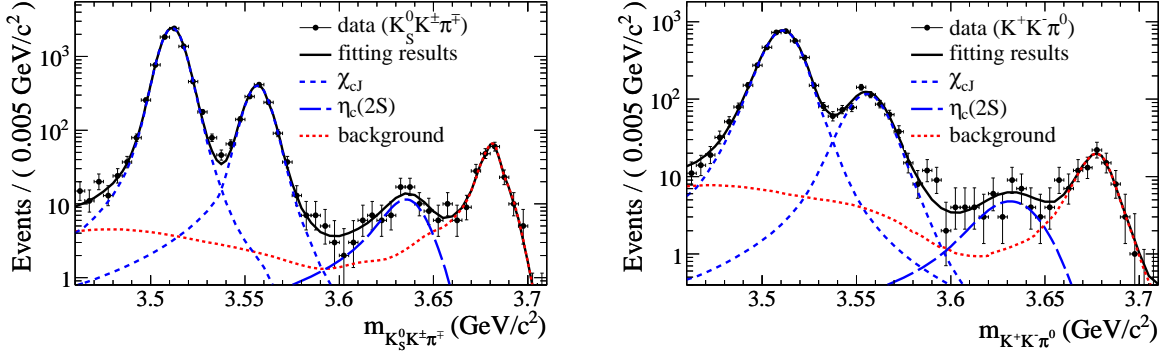


Figure 4: The $K_S K^+ \pi^-$ invariant mass for selected events for $\psi' \rightarrow \gamma K_S K^+ \pi^-$ (left) and $K K \pi^0$ (right). Points are data and the solid curve is the fit results. Blue long-dashed line is signal. Blue dashed lines are $\chi_{c1}/\chi_{c2} \rightarrow \gamma K_S K^+ \pi^-$ events. Red dotted line is for other backgrounds mainly from the decays $\psi' \rightarrow \pi^0 K_S K^+ \pi^-$, $K_S K^+ \pi^-$ and ISR/FSR production of $K_S K^+ \pi^- \gamma_{ISR}/\gamma_{FSR}$.

η_c and $\eta_c(2S)$. For the η_c meson parameters the model error is negligibly small: $M(\eta_c) = 2985.4 \pm 1.5(\text{stat.})_{-2.0}^{+0.2}(\text{syst.}) \text{ MeV}/c^2$, $\Gamma(\eta_c) = 35.1 \pm 3.1(\text{stat.})_{-1.6}^{+1.0}(\text{syst.}) \text{ MeV}/c^2$. For the $\eta_c(2S)$ meson the model and statistical uncertainties cannot be separated: $M(\eta_c(2S)) = 3636.1_{-4.1}^{+3.9}(\text{stat.} + \text{model})_{-2.0}^{+0.5}(\text{syst.}) \text{ MeV}/c^2$, $\Gamma(\eta_c(2S)) = 6.6_{-5.1}^{+8.4}(\text{stat.} + \text{model})_{-0.9}^{+2.6}(\text{syst.}) \text{ MeV}/c^2$.

Using 106 million ψ' events, BESIII searches [28] for $\eta_c(2S)$ in the decay $\psi' \rightarrow \gamma \eta_c(2S)$, with $\eta_c(2S) \rightarrow K \bar{K} \pi$. Figure 4 shows the invariant-mass distributions of $K_S K^+ \pi^-$ (left) and $K^+ K^- \pi^0$ (right), where a three-constraints kinematic fit has been applied (in which the energy of the photon is allowed to float). The solid curve in Fig. 4 shows fitting results of an unbinned maximum likelihood fit with four components: signal, χ_{c1} , χ_{c2} and other background (coming from ψ' decays to $\pi^0 K \bar{K} \pi$, $K \bar{K} \pi$ and ISR/FSR production of $K \bar{K} \pi \gamma_{ISR}/\gamma_{FSR}$). The fit yields 81 ± 14 signal events for the $K_S K^+ \pi^-$ channel and 46 ± 11 for the $K^+ K^- \pi^0$ channel, and gives the mass $M(\eta_c(2S)) = 3637.6 \pm 2.9 \pm 1.6 \text{ MeV}/c^2$ and width $\Gamma(\eta_c(2S)) = 16.9 \pm 6.4 \pm 4.8 \text{ MeV}$. The statistical significance of the signal is more than 11.1σ . Using the detection efficiency determined from MC simulation, the product branching fraction is obtained $\mathcal{B}(\psi' \rightarrow \gamma \eta_c(2S)) \times \mathcal{B}(\eta_c(2S) \rightarrow K \bar{K} \pi) = (1.30 \pm 0.20 \pm 0.30) \times 10^{-5}$. Using the result $\mathcal{B}(\eta_c(2S) \rightarrow K \bar{K} \pi) = (1.9 \pm 0.4 \pm 1.1)\%$ from BaBar [29] gives the branching fraction $\mathcal{B}(\psi' \rightarrow \gamma \eta_c(2S)) = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$. This result is consistent with CLEOc upper limit [26] and predictions of potential models [30].

With the same data sample, BESIII also studies [31] $\eta_c(2S) \rightarrow K_S K^+ \pi^+ \pi^- \pi^-$ in the decay $\psi' \rightarrow \gamma \eta_c(2S)$. Evidence of $\eta_c(2S) \rightarrow K_S K^+ \pi^+ \pi^- \pi^-$ is found with a statistical significance of 4.2σ . The product branching fraction is $\mathcal{B}(\psi' \rightarrow \gamma \eta_c(2S)) \times$

$$\mathcal{B}(\eta_c(2S) \rightarrow K_S K^+ \pi^+ \pi^- \pi^-) = (7.03 \pm 2.10(\text{stat.}) \pm 0.70(\text{syst.})) \times 10^{-6}.$$

5 The $\chi_{c2}(2P)$

With a data sample of 395 fb^{-1} , Belle observes [32] an enhancement in the $D\bar{D}$ mass distribution from $e^+e^- \rightarrow e^+e^-D\bar{D}$ events with a statistical significance of 5.3σ . The $D\bar{D}$ is exclusively reconstructed with four combination of decays, $D^0 \rightarrow K^-\pi^+$, $\bar{D}^0 \rightarrow K^+\pi^-$; $D^0 \rightarrow K^-\pi^+$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$; $D^0 \rightarrow K^-\pi^+$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^+\pi^-$; $D^+ \rightarrow K^-\pi^+\pi^+$, $D^- \rightarrow K^+\pi^-\pi^-$. To enhance exclusive two-photon $\gamma\gamma \rightarrow D\bar{D}$ production, the total transverse momentum in the e^+e^- c.m. frame with respect to the beam direction is required to be less than $50 \text{ MeV}/c^2$. The mass and width are measured to be $M = 3929 \pm 5(\text{stat.}) \pm 2(\text{syst.}) \text{ MeV}/c^2$, and $\Gamma = 29 \pm 10(\text{stat.}) \pm 2(\text{syst.}) \text{ MeV}$. The angular distributions of candidate events are consistent with the spin-2 helicity-2 hypothesis, and inconsistent with spin-0. This result has been confirmed by BaBar [33].

6 The $\psi_2(1^3D_2 \ c\bar{c})$

Using $772 \times 10^6 \ B\bar{B}$ events, Belle observes [34] evidence of a new resonance in the $\chi_{c1}\gamma$ final state with a statistical significance of 3.8σ . The χ_{c1} is reconstructed in the decay $\chi_{c1} \rightarrow J/\psi\gamma$, where J/ψ decays to l^+l^- ($l = e$ or μ). Figure 6 shows the $\chi_{c1}\gamma$ invariant-mass distribution, the solid line is the fitting result. The mass of the state is determined to be $3823.1 \pm 1.8(\text{stat.}) \pm 0.7(\text{syst.}) \text{ MeV}/c^2$. The mass is near potential model expectations for the centroid of the 1^3D_J states. No peak is seen in the $\chi_{c2}\gamma$ decay mode, the upper limit on the ratio of the branching fraction is determined to be $R = \frac{\mathcal{B}(X(3823) \rightarrow \chi_{c2}\gamma)}{\mathcal{B}(X(3823) \rightarrow \chi_{c1}\gamma)} < 0.41$ at the 90% C.L.. This is consistent with the expectation ($R = 0.2$) for ψ_2 [35, 36, 37]. The properties of the $X(3823)$ are consistent with those expected for the $\psi_2(1^3D_2 \ c\bar{c})$ state.

7 Summary

Charmonium is the best understood hadronic system. All the lowest-lying charmonium states have been found in experiment. Their properties have been measured with high precision, which are in good agreement with theory expectation. Higher-mass charmonium mesons, such as $h_c(2P)$, χ'_{cJ} ($J = 0, 1$), are still missing from experiment. With larger data samples at different center of mass energies, searches for the missing charmonium states will be very interesting.

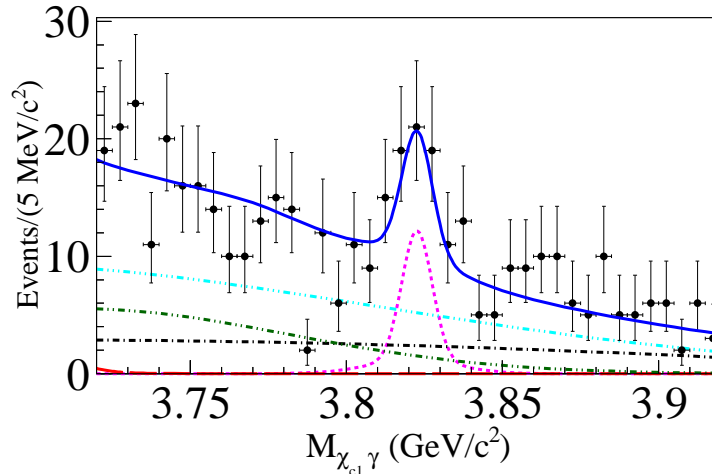


Figure 5: 2D UML fit projection of $M_{\chi_{c1}\gamma}$ distribution for the simultaneous fit of $B^\pm \rightarrow (\chi_{c1}\gamma)K^\pm$ and $B^0 \rightarrow (\chi_{c1}\gamma)K_S^0$ decays for $M_{bc} > 5.27 \text{ GeV}/c^2$. The curves show the signal [red large-dashed for ψ' , magenta dashed for $X(3823)$ and violet dotted for $X(3872)$] and the background component [black dotted-dashed for combinatorial, dark green two dotted-dashed for $B \rightarrow \psi'(\rightarrow \chi_{cJ}\gamma)K$ and cyan three dotted-dashed for peaking component] as well as the overall fit [blue solid]. $B \rightarrow \psi'(\rightarrow \chi_{cJ}\gamma)K$ is specific to the decay mode under study.

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