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Charmonium and Charm Spectroscopy

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In this talk, we review the recent experimental developments on charmonium and charm spectroscopy based on the data samples taken by the BESIII, Belle, LHCb and CMS experiments. We concentrate on the resonant parameter measurement of χ_{cJ} , η_c , $\eta_c(2S)$, observation of $\psi(1^3D_3)$ candidate and alternative $\chi_{c0}(2P)$ candidate, observation of excited B_c states, $\Xi(2930)$ states, excited Ω_c states and doubly charm baryon, and the study of Λ_c^* states.

I. INTRODUCTION

Since the observation of J/ψ meson in 1974 [1, 2], many charmonium states have been observed [3, 4]. Charmonia are charmed-quark and anticharmedquark states $(C\bar{C})$ bound by the strong interaction, and they can be described well by potential models. States below the $D\bar{D}$ threshold have all been observed, and match with prediction well. Above the $D\bar{D}$ threshold, only few states have been measured and identified. Further more, after the discovery of the X(3872) meson [5], a lot of unexpected states (called charmoniumlike states or XYZ particles) have been observed [6–8]. They could be candidates for charmonium states, however, they have strange properties which make them more like exotic states rather than conventional mesons.

Charmed baryons consist of one heavy charm quark and two light (u, d, s) quarks. Large mass difference provides a natural way to classify these states using Heavy Quark Effective Theory (HQET). Diquark correlation is enhanced by weak Color Magnetic Interaction with a heavy quark. So diquark can be considered as new degree of freedom. Charmed baryon spectroscopy provides an ideal place for studying the dynamics of the light quarks in the environment of a heavy quark. Recent years there are great progresses in our understandings of the charmed baryons. But the spin-parity assignments of many of the observed states are still to be discovered.

The B_c meson is unique system of two heavy quarks in a bound state. The ground state was discovered in 1998 by the CDF Collaboration [9]. The spectrum of this heavy quarkonium family is predicted to be very populated by QCD potential models and Lattice QCD [10–13], but spectroscopic observations and measurements of production properties remain scarce due to the small production rate.

In this article, we briefly introduce the most recent results on the Charmonium and Charm Spectroscopy.

II. CHARMONIUM SPECTROSCOPY

A. Precise $\chi_{c1,2}$ parameters measurement using $\chi_{c1,2} \rightarrow J/\psi \mu^+ \mu^-$

Recently, LHCb observed the decays $\chi_{c1,2} \rightarrow$ $J/\psi\mu^+\mu^-$ base on its full run I and part of run II data [14]. Then those decays were used to measured the χ_{c1} and χ_{c2} masses together with the χ_{c2} natural width. With an extended unbinned maximum likelihood fit performing to the $J/\psi\mu^+\mu^-$ invariant mass distribution as shown in Fig. 1, the masses of χ_{c1} and χ_{c2} are measured as 3510.71 \pm 0.04 \pm 0.09 MeV/ c^2 and $3556.10 \pm 0.06 \pm 0.11 \text{ MeV}/c^2$, respectively, and the natural width of χ_{c2} is measured as $2.10 \pm 0.20 \pm$ 0.02 MeV. The measurements are in good agreement with and have comparable precision to the world average [15]. This observations open up a new avenue for hadron spectroscopy at the LHC. It will be possible to extend measurements down to very low $p_T(\chi_{c1,c2})$ probing further QCD predictions.

Soon after, BESIII also studied the decays $\chi_{c1,2} \rightarrow J/\psi \mu^+ \mu^-$ via the radiative process $\psi(3686) \rightarrow \gamma \chi_{cJ}$ [16]. With the world-average branching fractions of $\psi(3686) \rightarrow \gamma \chi_{cJ}$ and $J/\psi \rightarrow l^+ l^-$ [15], the

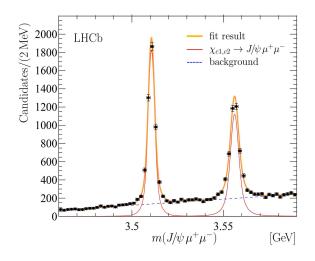


FIG. 1: Mass distribution for selected $J/\psi\mu^+\mu^-$ candidates.

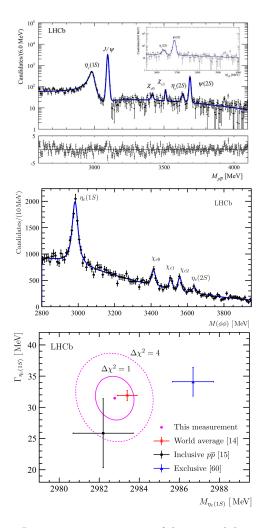


FIG. 2: Invariant mass spectrum of the $p\bar{p}$ candidates (top) and $\phi\phi$ combinations (middle). Contour plot of $\Gamma_{\eta_c(1S)}$ and $M_{\eta_c(1S)}$ using $\eta_c \to \phi\phi$ decays (bottom). The red cross, black square and blue triangle with error bars indicate the world average [15], the result from Ref. [17], and the result from Ref. [19], respectively.

absolute branching fractions of $\chi_{c1,2} \rightarrow J/\psi \mu^+ \mu^-$ are measured as $(2.51 \pm 0.18 \pm 0.20) \times 10^{-4}$ and $(2.33 \pm 0.18 \pm 0.29) \times 10^{-4}$, respectively. Which can be used to study the production of $\chi_{c1,2}$ with this mode on LHC experiments.

B. Charmonia from *B* meson decay

The $\eta_c(1S)$ state is the lowest S-wave spin-singlet charmonium state and has been observed in various processes. The measurements of the $\eta_c(1S)$ mass and width in radiative charmonium transitions show a tension with those determined in different processes such as two-photon production and B decays [15]. Recently, LHCb performed a study of $B^+ \rightarrow p\bar{p}K^+$ with the exclusive reconstruction method [17]. The $\eta_c(2S)$ is first observed in $p\bar{p}$ final states as shown in Fig. 2. The relative branching fraction is measured as: $\mathcal{R}_{\eta_c(2S)} \equiv \frac{\mathcal{B}(B^+ \to \eta_c(2S)K^+) \times \mathcal{B}(\eta_c(2S) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})}$ = (1.58 ± 0.33 ± 0.09) ×10⁻². But there are no signals for decays $B^+ \to \psi(3770)(\to p\bar{p})K^+$ and $B^+ \to X(3872)(\to p\bar{p})K^+$ observed. The upper limits of the relative branching fractions at 90 % confidence level are estimated as: $\mathcal{R}_{\psi(3770)} < 9 \times 10^{-2}$ and $\mathcal{R}_{X(3872)} < 0.20 \times 10^{-2}$, respectively. The differences between $M(J/\psi)$ and $M(\eta_c(1S))$, between $M(\psi(2S))$ and $M(\eta_c(2S))$ are measured to be 110.2 ± 0.5 ± 0.9 MeV/c² and 52.5 ± 1.7 ± 0.6 MeV/c², respectively. The natural width of the $\eta_c(1S)$ is measured as $\Gamma_{\eta_c(1S)}$ = 34.0 ± 1.9 ± 1.3 MeV. In contrast to the determinations using radiative decays, these mass and width determinations do not depend on the knowledge of the line shapes of the magnetic dipole transition.

Soon after, LHCb performed a study of the inclusive production of charmonium states in b-hadron decays using decays to ϕ -mesons [18]. The first evidence for the decay $\eta_c(2S) \rightarrow \phi \phi$ is observed as shown in Fig. 2. The masses of $\chi_{c0}, \chi_{c1}, \chi_{c2}, \eta_c(1S)$ and $\eta_c(2S)$ are measured as $3413.0 \pm 1.9 \pm 0.6 \text{ MeV}/c^2$, $3508.4 \pm$ $1.9 \pm 0.7 \text{ MeV}/c^2$, $3557.3 \pm 1.7 \pm 0.7 \text{ MeV}/c^2$, $2982.8 \pm 1.0 \pm 0.5 \text{ MeV}/c^2$ and $3636.4 \pm 4.1 \pm 0.7 \text{ MeV}/c^2$, respectively. The natural width of the $\eta_c(1S)$ is measured as $31.4 \pm 3.5 \pm 2.0$ MeV. The measurements of the $\eta_c(1S)$ mass and natural width using $\eta_c(1S)$ meson decays to $\phi\phi$ are consistent with the studies using decays to $p\bar{p}$ and the world average. The measured $\eta_c(1S)$ mass is below the result in exclusive method [19] as shown in Fig. 2.

C. Charmonium in near-threshold $D\bar{D}$ spectroscopy

Recently, with the full Run I and Run II data, LHCb observed a new narrow charmonium state, the X(3842) resonance in $D^0 \overline{D}{}^0$ and $D^+ D^-$ final states as shown in Fig. 3 [20]. The mass and the natural width of this state are measured to be 3842.71 $\pm 0.16 \pm 0.12 \text{ MeV}/c^2$ and $2.79 \pm 0.51 \pm 0.35 \text{ MeV}$, respectively. The observed mass and narrow natural width suggest the interpretation of the new state as the unobserved spin-3 $\psi_3(1^3D_3)$ charmonium state. In addition, prompt hadroproduction of the $\psi(3770)$ and $\chi_{c2}(3930)$ states is observed for the first time. The mass of $\psi(3770)$ is measured as 3778.1 \pm 0.7 \pm $0.6 \text{ MeV}/c^2$, which agrees well with and has a better precision than the current world average [15]. The mass and width of $\chi_{c2}(3930)$ are measured as $3921.9 \pm$ $0.6 \pm 0.2 \text{ MeV}/c^2$ and $36.6 \pm 1.9 \pm 0.9 \text{ MeV}$, which are more precise than previous measurements made at e^+e^- machines. But the mass is 2σ lower than the current world average whilst the natural width is 2σ higher. It is interesting to note that the mea-

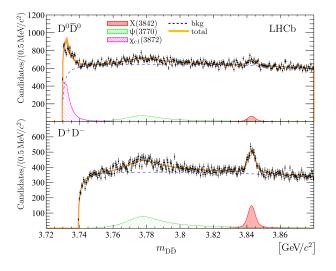


FIG. 3: Mass spectra of (top) $D^0 \bar{D}^0$ and (bottom) $D^+ D^-$ candidates in the near-threshold $m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$ region.

sured value of the mass is roughly midway between the masses quoted in Ref. [21] for this state and and for the X(3915) meson, which is only known to decay to the $J/\psi\omega$ final state [22]. Further studies are needed to understand if there are two distinct charmonium states in this region or only one.

D. Alternative $\chi_{c0}(2P)$ candidate in $e^+e^- \rightarrow J/\psi D\bar{D}$

X(3915) was observed by Belle [23], then confirmed by BaBar [22] in $B \to (J/\psi\omega)K$. Soon after, it was observed by both Belle and BaBar in $\gamma\gamma \to J/\psi\omega$ [24, 25]. BaBar determined its J^{PC} as 0^{++} , then identified it as the candidate of $\chi_{c0}(2P)$. But this will face several difficulties: X(3915) is too narrower with a measured width 20 MeV than the expected $\chi_{c0}(2P)$ width 100 MeV [26]; $\chi_{c0}(2P)$ is expected to decay strongly to $D\bar{D}$ in an S-wave [27], but has not yes been observed experimentally for X(3915); in this case, the $2^{3}P_{2} - 2^{3}P_{0}$ splitting is unnaturally smaller than the mass difference for the bottomonium states $\chi_{bJ}(2P)$, which is inconsistent with expectations based on the heavier bottom quark mass.

Recently, Belle attempted to search for alternative $\chi_{c0}(2P)$ via double-charmonium production in association with the J/ψ [28]. With full amplitude analysis of $e^+e^- \rightarrow J/\psi D\bar{D}$, they observed an obvious signal for a new charmoniumlike state $X^*(3860)$ in the $D\bar{D}$ final states as shown in Fig. 4. Its mass and width are measured as 3862^{+26+40}_{-32-13} MeV/ c^2 and $201^{+154+88}_{-67-82}$ MeV, respectively. Which is consistent with potential model expectations for $\chi_{c0}(2P)$ [29]. And the $J^{PC} = 0^{++}$ hypothesis is favored over 2^{++} with 2.5σ . The properties of the new state $X^*(3860)$ are well

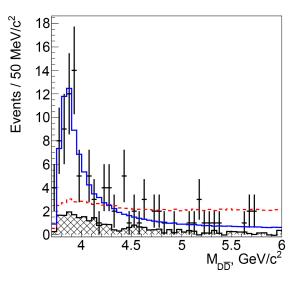


FIG. 4: Projections of the signal fit results in the default model onto $M_{D\bar{D}}$. The points with error bars are the data, the hatched histograms are the background, the blue solid line is the fit with a new X^* resonance $(J^{PC} = 0^{++})$ and the red dashed line is the fit with nonresonant amplitude only.

matched to expectations for the $\chi_{c0}(2P)$ resonance. So it seems to be a better candidate for the $\chi_{c0}(2P)$ charmonium state than the X(3915).

III. CHARM SPECTROSCOPY

A. B_c spectroscopy

Since the bc mesons cannot annihilate into gluons, the excited states below BD threshold can only undergo radiative or pionictransitions to the ground state B_c^+ . In 2014, ATLAS reported a new resonance in the $B_c^+(J/\psi\pi^+)\pi^+\pi^-$ mass spectrum with mass $6842 \pm 4 \pm 5 \text{ MeV}/c^2$ [30]. But due to large mass resolution and low signal yield, no determination could be made as to whether the observed peak is either the $B_c(2S)^+$, the $B_c^*(2S)^+$ state, or a combination of the two states.

Recently, the CMS collaboration reported the observation of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states in the $B_c^+(J/\psi\pi^+)\pi^+\pi^-$ mass spectrum with the event sample corresponding to an integrated luminosity of 143 fb⁻ recorded at $\sqrt{s} = 13$ TeV [31]. $B_c(2S)^+$ and $B_c^*(2S)^+$ states are resolved for the first time, sparated in mass by 29.1 \pm 1.5 \pm 0.7 MeV/ c^2 as shown in Fig. 5. The $B_c(2S)^+$ mass is measured to be 6871 \pm 1.2(stat) \pm 0.8(syst) \pm 0.8(B_c^+) MeV/ c^2 , where the last term is due to the uncertainty in the world-average B_c^+ mass. Because of the low-energy photon emitted in the intermediate radiative decay $B_c^{*+} \rightarrow B_c^+ \gamma$ is not reconstructed, the ob-

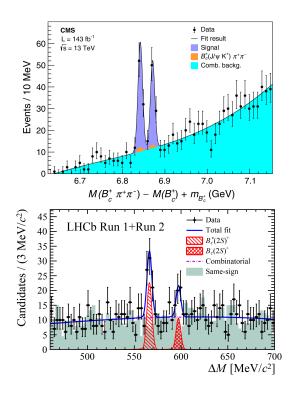


FIG. 5: The $M(B_c^+\pi^+\pi^-) - M(B_c^+) + m_{B_c^+}$ distribution with the fit results overlaid from CMS result (top). The Distribution of $\Delta M \equiv M(B_c^+\pi^+\pi^-) - M(B_c^+)$ with the fit results overlaid from LHCb result (bottom).

served $B_c^*(2S)^+$ peak has a mass lower than the true value, which remains unknown. The mass difference $M(B_c^*(2S)^+) - M(B_c^{*+})$ is measured as 567.0 ± 1.0 (total) MeV.

With the data sample corresponding to an integrated luminosity of 8.5 fb⁻¹ recorded at $\sqrt{s} = 7$, 8 and 13 TeV, LHCb also investigated the excited B_c^+ state in the $B_c^+\pi^+\pi^-$ invariant-mass spectrum [32]. A peaking structure consistent with the $B_c^*(2S)^+$ state is observed in the $B_c^+\pi^+\pi^-$ mass spectrum as shown in Fig. 5. The associated mass $M(B_c^*(2S)^+)_{rec} =$ $M(B_c^*(2S)^+) - (M(B_c^{++}) - M(B_c^{++}))$ is measured as $6841.2 \pm 0.6(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^{++}) \text{ MeV}/c^2$. A hint for a second structure consistent with the $B_c(2S)^+$ state is also observed. Its mass is measured to be $6872.1 \pm 1.3(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^{++})$ MeV/c^2 . The mass difference of the two $B_c^{(*)}(2S)^+$ peaks is determined to be $31.0 \pm 1.4 \pm 0.0 \text{ MeV}/c^2$.

B. Charmed baryons

Recently, LHCb performed an amplitude analysis of the decay $\Lambda_b^0 \to D^0 p \pi^-$ with the data sample corresponding to an integrated luminosity of 3.0 fb⁻¹ recorded at $\sqrt{s} = 7$ and 8 TeV [33]. The spectroscopy of excited Λ^+ states in the $D^0 p$ amplitude

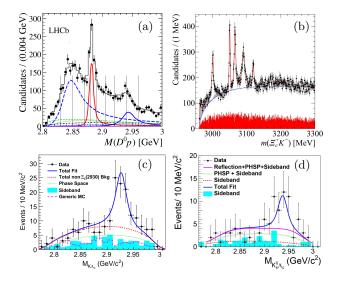


FIG. 6: Results of the fit of the $\Lambda_b^0 \to D^0 p \pi^-$ data in the $D^0 p$ mass region including the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ resonances (a). Distribution of the reconstructed invariant mass $m(\Xi_c^+ K^-)$ for all candidates passing the likelihood ratio selection (b). The invariant mass distribution of $K^-\Lambda_c^+$ (c) and $K_S^0\Lambda_c^+$ (d).

are studied in detail as shown in Fig. 6. The preferred spin of the $\Lambda_c(2880)^+$ state is found to be J = 5/2. The mass and width of the $\Lambda_c(2880)^+$ are measured to be 2881.75 \pm 0.29(stat) \pm 0.07(syst)^{+0.14}_{-0.20}(model) MeV/c^2 and $5.43^{+0.77}_{-0.71}(stat) \pm 0.29(syst)^{+0.75}_{-0.00}(model)$ MeV, respectively. The last uncertainty is due to the modelling of the nonresonant amplitudes. The spin and parity of the $\Lambda_c(2940)^+$ state are firstly determined as $J^P = 3/2^-$, which is consistent with its interpretations as a D^*N molecule [34] or a radial 2P excitation [35], but the other solutions with spins 1/2 to 7/2 cannot be excluded. An enhancement near the threshold of D^0p amplitude is observed with the mass and width of $2856.1^{+2.0}_{-1.7}$ (stat) $\pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model}) \text{ MeV}/c^2 \text{ and } 67.6^{+1.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model}) \text{ MeV}.$ The quantum numbers are determined as $J^P = 3/2^+$, with the parity measured relative to that of the $\Lambda_c(2880)^+$ state. The mass of the $\Lambda_c(2860)^+$ state is consistent with predictions for an orbital D-wave excited Λ_c^+ with quantum numbers $3/2^+$ based on the nonrelativistic heavy quark-light diquark model [36] and from QCD sum rules in the HQET framework [37].

The $\Xi_c(2930)$ charmed-strange baryon has only been reported by BaBar in the analysis of $B^- \to K^- \Lambda_c^+ \bar{\Lambda}^-$ [38]. A signal with a mass of $2931 \pm 3 \pm 5 \text{ MeV}/c^2$ and a width of $36 \pm 7 \pm 11 \text{ MeV}$ in $K^- \Lambda_c^+$ mass spectrum was claimed. However, neither the fit result to the spectrum nor the significance of the signal were given. Recently, Belle performed an updated measurement of $B^- \to K^- \Lambda_c^+ \bar{\Lambda}^-$ with its full $\Upsilon(4S)$ data sample corresponding to an inte-

TABLE I: Results of the fit to $m(\Xi_c^+ K^-)$ for the mass, width from LHCb data and the mass from Belle data.

Resonance	Mass~(MeV)	F (MeV)	$Mass_{Belle}$ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$3000.7\pm1.0\pm0.2$
$\Omega_c(3050)^0$	$3050.2\pm0.1\pm0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$3050.2\pm0.4\pm0.2$
$\Omega_{c}(3066)^{0}$	$3065.6\pm0.1\pm0.3^{+0.3}_{-0.5}$	$3.5\pm0.4\pm0.2$	$3064.9\pm0.6\pm0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7\pm1.0\pm0.8$	$3089.3\pm1.2\pm0.2$
$\Omega_{c}(3119)^{0}$	$3119.1\pm0.3\pm0.9^{+0.3}_{-0.5}$	$1.1\pm0.8\pm0.4$	-
$\Omega_{c}(3188)^{0}$	$3188\pm5\pm13$	$60\pm15\pm11$	$3199 \pm 9 \pm 4$

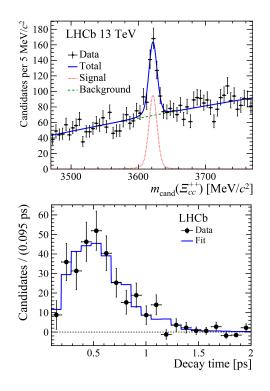


FIG. 7: Invariant mass distribution of $\Lambda_c^+ K^- \pi^+ \pi^+$ candidates with fit projections overlaid (top). Backgroundsubtracted decay-time distribution of selected $\Xi_{cc}^{++} \rightarrow \Lambda^+ K^- \pi^+ \pi^+$ candidates (bottom).

grated luminosity of 711 fb⁻¹ [39]. The $\Xi_c(2930)^0$ signal is observed with a significance of 5.1 σ as shown in Fig. 6. Its mass and width are measured as 2928.9 $\pm 3.0^{+0.9}_{-12.0}$ MeV/ c^2 and 19.5 $\pm 8.4^{+5.9}_{-7.9}$ MeV, respectively. Belle also investigate the $\Xi_c(2930)^+$ in the process $B^0 \to K_S^0 \Lambda_c^+ \bar{\Lambda}^-$ [40]. Only an evidence of the $\Xi_c(2930)^+$ with a 4.1 σ is observed in $K_S^0 \Lambda_c^+$ mass spectrum as shown in Fig. 6. Its mass and width are measured as 2942.3 $\pm 4.4 \pm 1.5$ MeV/ c^2 and 14.8 \pm 8.8 ± 2.5 MeV, respectively.

Excited Λ_c , Σ_c , Ξ_c states both have been reported, but no excited Ω_c states were observed before LHCb. Recently, LHCb searched for new Ω_c^{*0} states that decay strongly to the final state $\Xi_c^+ K^-$, base on the data sample corresponding to an integrated luminosity of 3.3 fb⁻¹ recorded at $\sqrt{s} = 7, 8$ and 13 TeV [41]. Five new, narrow excited Ω_c^0 states are observed as shown in Fig. 6: the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$. Further more, the data indicate also the presence of a broad structure around 3188 MeV. The masses and widthes of those new states are measured as shown in Table I. Soon later, Belle also measured the same process with its full data sample corresponding to an integrated luminosity of 980 fb⁻¹ [42]. All the Ω_c^{*0} except $\Omega_c(3119)^0$ are confirmed. With the width of Ω_c^{*0} states fixed to the values from LHCb result, the masses of those states are measured as list in the Table I.

The existence of doubly charmed baryons predicted by quark model [43]. Three weakly decaying qqq states with C = 2 are expected: one isospin doublet (Ξ_{cc}^{++} = ccu and $\Xi_{cc}^+ = ccd$ and one isospin singlet $(\Omega_{cc}^+ = ccs)$, each with spin-parity $J^P = 1/2^+$. The masses of the Ξ_{cc} states are predicted to lie in the range 3500 to $3700 \text{ MeV}/c^2$ [44, 45]. The observation of Ξ_{cc}^{++} has been claimed by SELEX [46, 47]. But no evidence observed by BaBar [48], FOCUS [49], Belle [50] and LHCb [51]. Recently, LHCb searched for Ξ_{cc}^{++} via the most promising channel $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$ base on the data sample corresponding to an integrated luminosity of 1.7 fb⁻¹ recorded at $\sqrt{s} = 13$ TeV [52]. Ξ_{cc}^{++} is observed for the first time as shown in Fig 7, and confirmed in an additional sample of data collected at 8 TeV. The mass of the structure is measured to be $3621 \pm 0.72 (\text{stat}) \pm 0.27 (\text{syst}) \pm 0.14 (\Lambda_c^+) \text{ MeV}/c^2.$ The last uncertainty is due to the limited knowledge of the Λ_c^+ mass. Soon later, using the same date with extra trigger requirement, the decay-time distribution of Ξ_{cc}^{++} are measured relative to $\Lambda_b^0 \to \Lambda_c^+ K^- \pi^+ \pi^-$ as shown in Fig. 7 [53]. The Ξ_{cc}^{++} lifetime is mea-sured to be $0.256_{-0.022}^{+0.024}$ (stat) ± 0.014 (syst) ps, which establishes the weakly decaying nature of the recently discovered Ξ_{cc}^{++} .

IV. SUMMARY

There is a wide range of interesting charmonium and charm spectroscopy results, but only a small selection of recent results has been presented in this talk. The Measurements of resonance parameters of χ_{c1} , χ_{c2} , η_c , $\eta_c(2S)$, and $\psi(3770)$ were improved. Candidate for $\psi(1^3D_3)$ and alternative candidate for $\chi_{c0}(2P)$ were observed. Excited B_c states, candidate for D-wave excited Λ_c states, excited Ξ_c , Ω_c states, and doubly charmed baryon Ξ_{cc}^{++} were observed. The lifetime of Ξ_{cc}^{++} was measured, which establishes the weakly decaying nature of Ξ_{cc}^{++} . BESIII will keep taking data in the region of charmonium. Belle II just started its Phase III data taking. With the upgrade, LHCb will get much more data. Many more precise spectroscopic measurements are expected in the near feature.

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