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New charm resonances

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1 Introduction

In the last five years we have witnessed a renaissance of charm spectroscopy. Several new charmed states have been observed, using data samples collected by so-called B-factories i.e. e^+e^- storage rings dedicated to the studies of CP violation in the sector of the beauty quark. These machines are running essentially at the center-of-mass (CMS) energy corresponding to the maximum of the $\Upsilon(4S)$ resonance (10.58 GeV/c^2). There are three such accelerators and detectors, which are currently taking data. The oldest one, which contributed a lot of to the heavy flavour physics in the past twenty years, is the CLEO apparatus [1,2] at the CESR [3] storage-ring (Cornell, USA). After collecting the data sample of 16 fb^{-1}, the CLEO collaboration has moved since 2003 to the lower energy working point corresponding to the maximum of the $\psi(3770)$. The other two detectors working at B-factories: the BaBar [4] at PEP-II [5] (Stanford, USA) and Belle [6] at KEKB [7] (Tsukuba, Japan) have collected in the last few years enormous data samples corresponding to 370 fb^{-1}(630 fb^{-1}), respectively. The KEKB is, in fact, the record holder as far as the luminosity is concerned with its peak value of 1.65×10^{34} cm^{-2}s^{-1}. It is worthwile to stress here that the cross-section for the continuum process $e^+e^- \to c\overline{c}$ (1.3 nb) is comparable to the one for the reaction $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ (1.1 nb). As a result, B-factories can be safely considered as c-factories too. Moreover, charmed hadrons can he reconstructed here relatively easy, due the 'clean' environment provided by e^+e^- collisions.

This paper is divided into several chapters, each one of them discussing the observation of an individual new state and entitled with its name. The following new meson-like charmed hadrons are talked over: $X(3872)$, $Y(3940)$, $X(3940)$, $\chi'_{c2}(3930)$, $Y(4260)$, h_c and the $c\overline{s}$ states D_{sJ}. Then the following new observations of charmed barions will be described: $\Sigma_c(2800)$, $\Lambda_c(2940)$, $\Xi_{cx}(2980)$, $\Xi_{cx}(3077)$ and Ω^*_c.

2 X(3872)

The first new charmed resonance, marked as X(3872), was discovered by the Belle collaboration in 2003 [8] by analyzing exclusive decays[1] $B^+ \to \pi^+\pi^- J/\psi K^+$, $J/\psi \to l^+l^-$. The B mesons were reconstructed using two kinematical variables: the energy offset $\Delta E = \sum_i E_i - E_{beam}$ and the beam-constrained mass $M_{bc} = \sqrt{E_{beam}^2 - \sum_i (\vec{p_i})^2}$, where E_i and $\vec{p_i}$ are the center-of-mass (CMS) energies and momenta of the selected B meson decay products and E_{beam} is the CMS beam energy. A very narrow peak in the invariant mass spectrum of the system $\pi^+\pi^- J/\psi$ was observed (Fig. 2) with a statistical significance above 10 σ. The mass of the resonance was determined to be $(3872.0 \pm 0.6 \pm 0.5)$ MeV/c^2 and a width below 2.3 MeV (90% C.L.), which is consistent with the detector resolution.

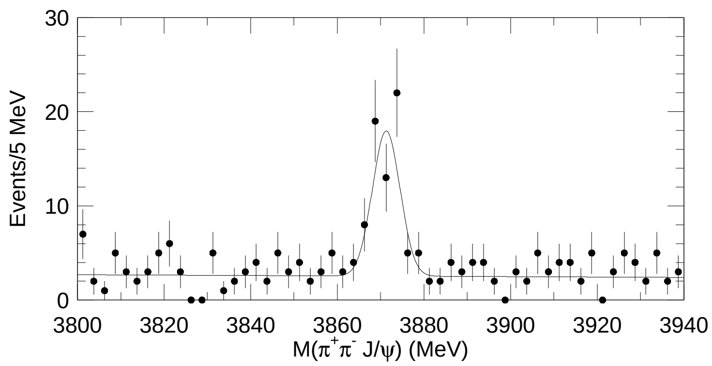

Figure 1: The mass distribution of $J/\psi\pi^+\pi^-$ for the X(3872) resonance, as measured by Belle collaboration.

The observation of $X(3872)$ was very quickly confirmed by the CDF [9], D0 [10] and BaBar [11] experiments. At first glance the $X(3872)$ would appear as an ideal candidate for one of the, unobserved yet, charmonium states. Among $(c\overline{c})$ states, the ones expected to be closest in mass to X are those belonging to the multiplets $1D$ and $2P$ multiplets [12]– [15]. However, it soon turned out that the, discussed below, properties of none of these states are in agreement with measured properties of $X(3872)$. This fact stimulated the development of several theoretical models assuming the exotic nature of this new resonance. In particular, the coincidence of the X mass with the $D^0\overline{D^{*0}}$ threshold i.e. (3871.3 ± 1.0) MeV/c^2 has prompted many theoretical speculations that X(3872) may be a so-called deuson [16]– [19] i.e. a loosely bound molecular state of these two mesons or a tetraquark i.e. a tightly bound open charm diquark-antidiquark state [20, 21]. Other models attributed the $X(3872)$ as a $(c\overline{c})$-

[1] charge conjugate modes are included everywhere, unless otherwise specified.

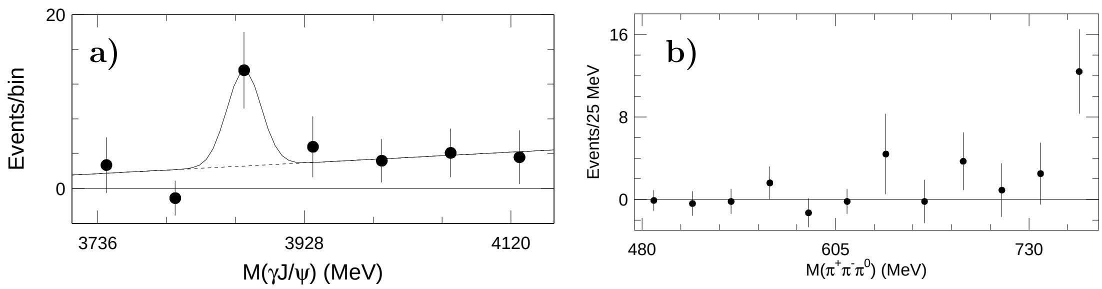

Figure 2: The yield of B mesons from the decay **a)** $B^0 \to \gamma J/\psi K$, in bins of the $\gamma J/\psi$ invariant mass and **b)** $B^0 \to \pi^+\pi^-\pi^0 J/\psi K$, in bins of the $\pi^+\pi^-\pi^0$ invariant mass, determined by the Belle collaboration from fits to the ΔE and M_{bc} distributions.

gluon hybrid meson [22], a glueball with a $(c\overline{c})$ admixture [23] or the so called threshold cusp effect [24].

The Belle collaboration, has also provided the first evidence for two new decay modes of the $X(3872)$: $X \to \gamma J/\psi$ and $X \to \pi^+\pi^-\pi^0 J/\psi$ [25], observed in exclusive B meson decays to the final states $\gamma J/\psi K$ and $\pi^+\pi^-\pi^0 J/\psi K$, respectively. The yield of the decay $B \to \gamma J/\psi K$ plotted in bins of the $\gamma J/\psi$ invariant mass (Fig. 2**a)**) exhibits an excess of 13.6 ± 4.4 events (statistical significance of 4σ). This evidence was was recently confirmed by the BaBar collaboration [26] with the signal yield of 19.2 ± 5.7 events (3.4σ). The observation of this decay establishes unambiguously that the charge-conjugation parity of the X(3872) is positive and indicates the presence of the $c\overline{c}$ component in its wave function. The partial width ratio $\Gamma(X \to \gamma J/\psi)/\Gamma(X \to \pi^+\pi^- J/\psi)$ amounts to 0.14 ± 0.05. This result is, in particular, in contradiction with the χ'_{c1} (1^{++} charmonium) assignment for X as in this case a value around 40 would be expected. The second decay mode $X \to \pi^+\pi^-\pi^0 J/\psi$ was found to be dominated by the sub-threshold decay $X \to \omega^* J/\psi$. This is motivated by the fact that the yield of B mesons plotted in bins of the $\pi^+\pi^-\pi^0$ invariant mass (Fig 2**b)**) inside of the signal region from the decay $X \to \pi^+\pi^-\pi^0 J/\psi$ is consistent with zero except for the $M(\pi^+\pi^-\pi^0) > 750$ MeV/c^2. There, the excess of 12.4 ± 4.1 events (4.3σ) is observed. The ratio of branching fractions $\mathrm{B}(X \to \pi^+\pi^-\pi^0 J/\psi)/\mathrm{B}(X \to \pi^+\pi^- J/\psi)$. was measured to be $1.0 \pm 0.4 \pm 0.3$, which implies a large violation of isospin symmetry. This in turn points at the presence of both $u\overline{u}$ and $d\overline{d}$ pairs in the X wave function. The overall properties of the above two decays are in reasonable agreement with the $D^0\overline{D}^{0*}$ molecule hypothesis.

The Belle collaboration also attempted to determine the J^{PC} quantum numbers of the X(3872) [27] by studying the angular distributions of the decay $X \to \pi^+\pi^- J/\psi$, as suggested by J.L. Rosner [28] Among the twelve possible J^{PC} assignments, half (0^{--}, 0^{+-}, 1^{--}, 1^{+-}, 2^{--} and 2^{+-}) may be discarded due to their negative charge conjugation-parity. The assignments 0^{-+} and 0^{++} are strongly disfavoured by the

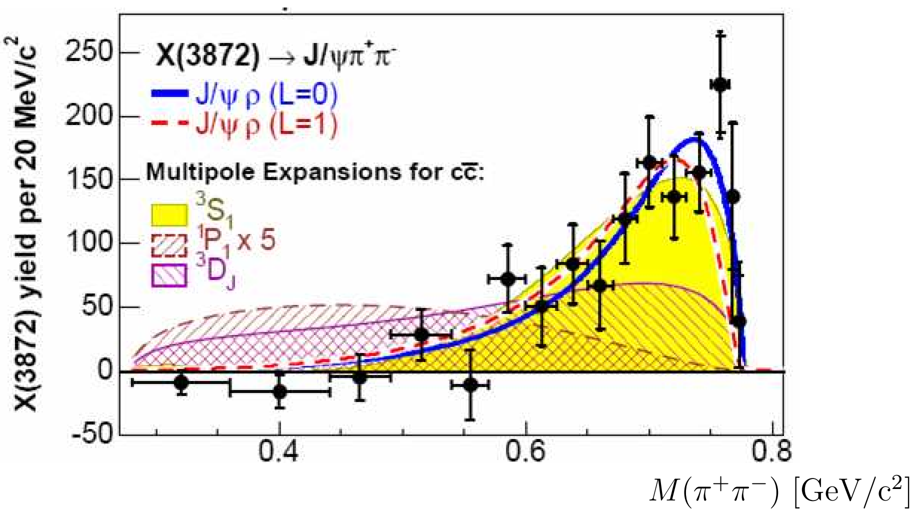

Figure 3: The dipion mass spectrum for the $X(3872)$ (data points), as measured by the CDF collaboration, together with fits to different J^{PC} hypotheses.

analysis of angular distributions. The additional two odd-parity possibilities: 1^{-+} and 2^{-+} are discarded as for them the dipion invariant mass spectrum is expected to be much softer to compare with the data. The above considerations leave only two assignments: 1^{++} and 2^{++} as the possible J^{PC} of X. The decay angular distributions and $\pi^+\pi^-$ angular distribution agree well with the $1^{+}+$ hypothesis.

The assignment 2^{++} was disfavoured by the recent observation by Belle [29] of a near-threshold enhancement in the $D^0\overline{D^0}\pi^0$ invariant mass in $B \to KD^0\overline{D^0}\pi^0$ decays. It corresponds to 23.4 ± 5.6 signal events (6.4σ) at mass $(3875.4 \pm 0.7 \pm 1.1)$ MeV/c^2 which is around two standard deviations higher than the world average for $X(3872)$ [30]. Taking for granted that the observed near-threshold enhancement is due to the $X(3872)$, the decay of a spin 2 state to three pseudoscalars ($D^0\overline{D^0}\pi^0$) would require at least one pair of them to be in a relative D wave. In such a configuration the near threshold production would be strongly suppressed by a centrifugal barrier.

The CDF collaboration [31] has recently studied the spin-parity of $X(3872)$ using a high-statistics sample of ≈ 3000 events of $X(3872) \to \pi^+\pi^- J/\psi$. The shape of the $\pi^+\pi^-$ invariant mass distribution was compared with the predictions corresponding to all relevant J^{PC} values. (Fig. 2). It was found that both 1^{++} and 2^{-+} assignments fit reasobably the data.

Collecting the above information it seems the most plausible that X(3872) is a deuson. This conjecture is supported in particular by the pattern of its decay modes and the favoured spin-parity assignment 1^{++}.

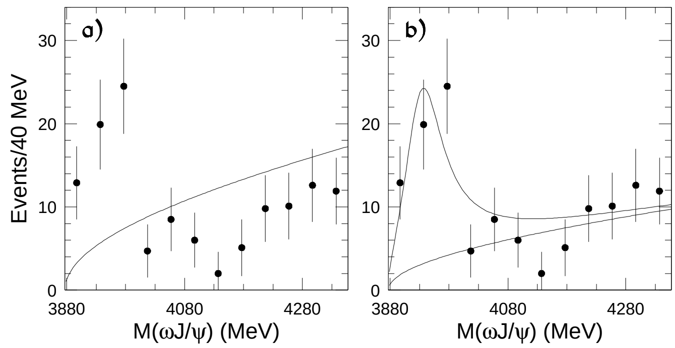

Figure 4: $B^+ \to K^+\omega J/\psi$ signal yields vs $M(\omega J/\psi)$ as determined by the Belle collaboration. The curve in (a) shows the result of a fit that includes only a phase-space-like threshold function. The curve in (b) corresponds to the result of a fit that includes an S-wave Breit-Wigner resonance term.

3 Y(3940)

In 2004 The Belle collaboration observed another new state, denoted as Y(3940) and produced in $B^+ \to K\omega J/\psi$ decays [32]. In this study events with $M(K\omega) < 1.6$ GeV/c^2 were rejected in order to remove the contribution from $K^* \to Kw$ decays. A fit to the $\omega J/\psi$ invariant-mass distribution (Fig.4) yielded a signal of 58 ± 11 events (8.1σ) corresponding to a mass of ($3943\pm11\pm13$) MeV/c^2 and the width ($87\pm22\pm26$) MeV.

Both mass and width of Y are in agreement with expectations for a radially excited charmonium state χ'_{cJ}. This interpretation is also strengthened by the observation of the corresponding $(b\bar{b})$ decay $\chi'_{b1} \to \omega\Upsilon(1S)$ [33]. Such a $(c\bar{c})$ state would, however, decay predominantly to $D\overline{D}^{(*)}$ pairs, which is not observed. Moreover, for the χ'_{cJ} hypothesis one would expect that $\mathcal{B}(B \to K\chi'_{cJ}) < \mathcal{B}(B \to K\chi_{cJ}) = 4\times10^{-4}$. Taking into account the value of the product $\mathcal{B}(B \to KY)\mathcal{B}(Y \to \omega J/\psi) = (7.1\pm1.3\pm3.1)\times 10^{-5}$, determined by Belle, this implies that $\mathcal{B}(Y \to \omega J/\psi) > 12$ %. Such a value would seem exceptionally high for any charmonium state with a mass above $D\overline{D}^{(*)}$ threshold.

The above drawbacks of the conventional charmonium interpretation of Y, in particular the lack of its decay to $D\overline{D}^{(*)}$ and a large $\mathcal{B}(Y \to \omega J/\psi)$, are in fact advantages while taking for granted the hypothesis of a $c\bar{c}$-gluon hybrid [34]. This is also supported by the lattice QCD calculations [35] which indicate that a partial width for the decay to $K\omega J/\psi$ are comparable to the value measured by Belle. However, the masses of $c\bar{c}$-gluon mesons predicted by these calculations [35]– [37] are between

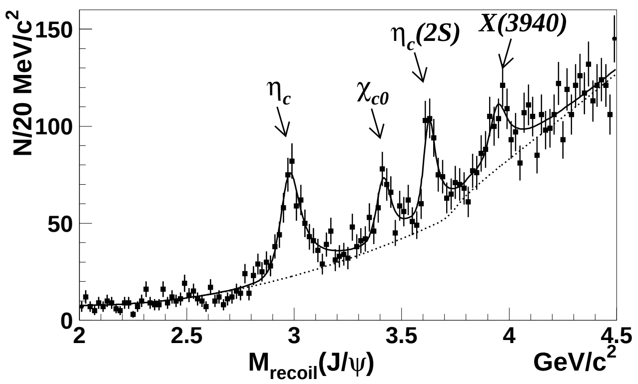

Figure 5: The distribution of masses recoiling against the reconstructed J/ψ measured by the Belle collaboration in inclusive $e^+e^- \rightarrow J/\psi X$ events. The four enhancements, from left to right, correspond to the η_c, χ_{c0}, $\eta_c(2S)$ and a new state $X(3940)$.

4300 and 4500 MeV/c^2 i.e. substantially higher than the measured value.

4 X(3940)

Yet another particle, marked as $X(3940)$ with the mass of 3940 MeV/c^2 was observed by the Belle collaboration in the process $e^+e^- \rightarrow J/\psi X$ [38]. Its signal was seen in the spectrum of the J/ψ recoil mass (Fig. 5) defined as $M_{recoil}(J/\psi) = \sqrt{(E_{CMS} - E^*_{J/\psi})^2 - (cp^*_{J/\psi})^2/c^2}$, where E_{CMS} is the center-of-mass energy of the event and $E^*_{J/\psi}$ ($p^*_{J/\psi}$) denote the CMS energy (momentum) of the J/ψ, respectively. The previous studies of this process reveiled the presence of three states: η_c, χ_{c0} and $\eta_c(2S)$. The new analysis, using significantly higher statistics, provided the observation of the fourth particle in the J/ψ recoil mass spectrum. Its mass was estimated to be $(3943 \pm 6 \pm 6)$ MeV/c^2 and and the width smaller than 52 MeV (90 % C.L.). The search for $X(3940)$ decay modes yielded the evidence for $X \rightarrow D^*\overline{D}$ ($\mathcal{B} = 96^{+45}_{-32} \pm 22$ %). No signal was observed for $X \rightarrow D\overline{D}$ ($\mathcal{B} < 41$ % (90 % C.L.)) and $X \rightarrow \omega J/\psi$ ($\mathcal{B} < 26$ % (90 % C.L.)) The properties of X(3940) match the expectations [15] of the 3^1S_0 charmonium state, denoted also as $\eta_c^{''}$.

It is appropriate to stress here that, in spite the same mass measured, it is extremely unlikely that the states $X(3940)$ and $Y(3940)$ coincide. The X(3940) decays to $D\overline{D}^*$ and does not decay to $\omega J/\psi$. for the Y(3940) the situation is reversed, as far as the above-mentioned decays are concerned.

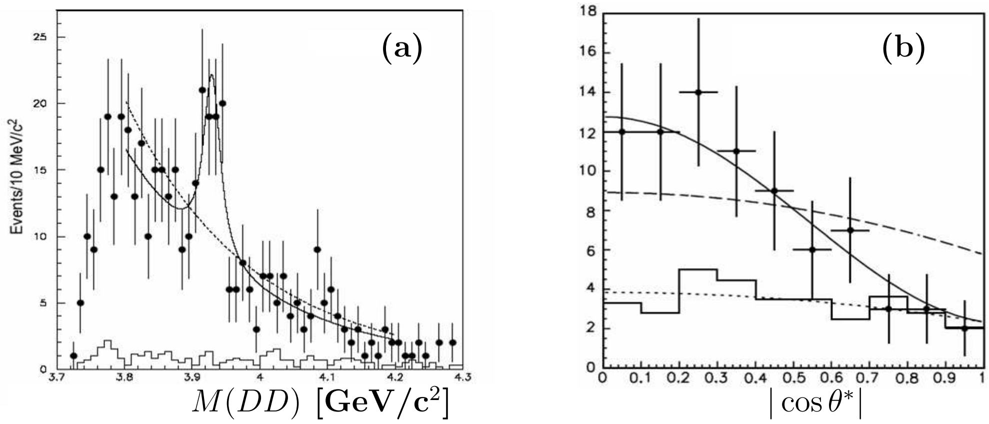

Figure 6: **(a)** Invariant mass distribution of $D\overline{D}$ pairs produced in two photon processes as measured by Belle. The solid (dashed) curve shows the fits with (without) a resonance component. The histogram corresponds to the distribution of the events from the D-mass sidebands. **(b)** The distribution of the angle θ^* of a D meson relative to the beam axis in the $\gamma\gamma$ CMS frame. The data points correspond to the $3.91 < M(D\overline{D}) < 3.95$ MeV/c^2 region. The solid histogram shows the yield of background scaled from $M(D\overline{D})$ sidebands. The solid and dashed curves represent expectations for spin-2 and spin-0 hypotheses, respectively. The dotted curve interpolates the non-peak background.

5 $\chi'_{c2}(3930)$

The Belle collaboration has also performed the search for the production of new resonances in the process $\gamma\gamma \to D\overline{D}$ [39]. Here the two-photon processes are studied in the "zero-tag" mode, where the final state electron and positron are not detected and the transverse momentum of the $D\overline{D}$ system is very small. The analysis yielded an observation of a new state, marked as $Z(3930)$, at the mass and width of $(3929 \pm 5 \pm 2)$ MeV/c^2 and $(29 \pm 10 \pm 2)$ MeV, respectively (Fig. 6 a)). The statistical significance of the signal amounted to 5.3σ. The product of the two-photon radiative width and branching fraction for the decay to $D\overline{D}$ was found to be $\Gamma_{\gamma\gamma} \times \mathcal{B}(Z(3930) \to D\overline{D}) =$ $(0.18 \pm 0.05 \pm 0.03)$ keV. The properties of this new state match the expectations [15,40] for the radially excited $(c\overline{c})$ states χ'_{c0} and χ'_{c2}. A study of angular distribution of the D mesons in the $\gamma\gamma$ CMS frame showed that that spin-2 assignment is strongly favoured over the spin-0 hypothesis. Thus the state $Z(3930)$ can be safely interpreted as the χ'_{c2} 2^3P_2 charmonium.

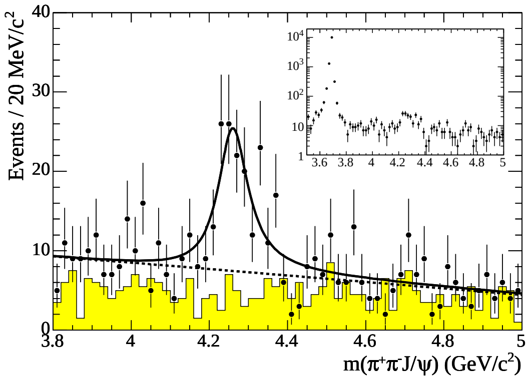

Figure 7: The $\pi^+\pi^- J/\psi$ invariant mass spectrum measured by BaBar in the range 3.8–5.0 GeV/c^2 and (inset) over a wider range that includes the $\psi(2S)$. The points represent the data and the shaded histogram corresponds to the scaled data from the J/ψ mass sidebands. The solid line shows the result of the single-resonance fit. The dashed curve represents the background component.

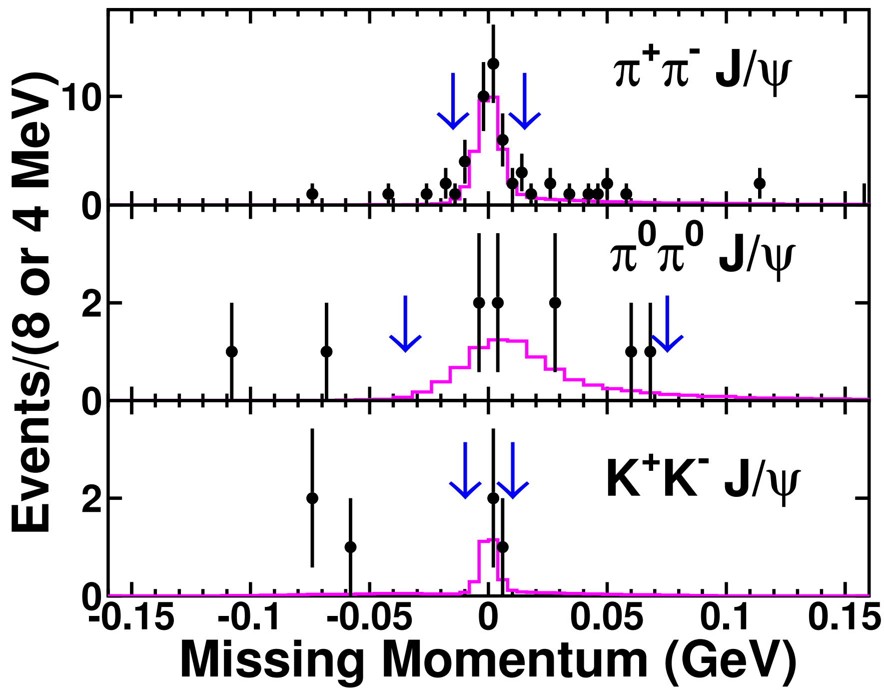

Figure 8: The missing momentum distribution measured by Cleo collaboration for $\pi^+\pi^- J/\psi$ (top), $\pi^0\pi^0 J/\psi$ (middle) and $K^+K^- J/\psi$ (bottom) in the data at $\sqrt{s} = 4.26$ GeV (data points) and the signal shape as predicted by MC simulation (histogram) scaled to the net signal size.

6 $Y(4260)$

The BaBar collaboration has studied initial-radiation (ISR) processes [41] $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ and observed a broad resonance in the invariant mass spectrum of $\pi^+\pi^- J/\psi$ near 4.26 GeV/c^2(Fig. 7). The photon radiated from an initial e^+e^- collision is not detected directly. Since the new state, marked as $Y(4260)$, is produced in ISR events, its spin-parity is well defined as 1^{--}. The existence of $Y(4260)$ was soon confirmed by CLEO [42] and Belle [43] collaborations. The relevant parameters of this new state are collected in Table 1. It is worthwile to note that the values measured so far by three collaborations are only marginally consistent.

The CLEO collaboration has also provided the first observation of $Y(4260) \to \pi^0\pi^0 J/\psi)$ (5.1σ) and found the first evidence for $Y(4260) \to K^+K^- J/\psi)$ (3.7σ) [42] (Fig. 8). Simultaneously, the e^+e^- cross-sections at $\sqrt{s} = 4.26$ GeV were determined for $\pi^+\pi^- J/\psi$ and $\pi^0\pi^0 J/\psi$ final states to be $(58^{+12}_{-10} \pm 4)$ pb and $(23^{+12}_{-8} \pm 1)$ pb, respectively.

The observation of the $\pi^0\pi^0 J/\psi$ contradicts the hypothesis that Y is a $\chi_{cJ}\rho$ molecule [44]. The interpretation of Y as a baryonium state [45] is strongly disfavoured by the fact that the $\pi^0\pi^0 J/\psi$ rate is about half that of $\pi^+\pi^- J/\psi$. The $Y(4260)$ is located at the dip in $R(e^+e^- \to \textit{hadrons})$. Similar drop of the cross-section was also found by Belle in the exclusive reaction $e^+e^- \to D^{*+}D^{*-}$, measured as a function of the CMS energy using ISR events [46]. This dip could be accomodated as a result of $\psi(3S) - \psi(4S)$ interference, provided that $Y(4260)$ can be interpreted as the conventional charmonium state $\psi(4S)$ [47]. Then, however, the $\psi(3S)$ should exhibit a substantial coupling to $\pi^+\pi^- J/\psi$, which is not observed. Two other viable models describe the $Y(4260)$ as a tetraquark [48] or a $c\bar{c}$-gluon hybrid meson [49]–[51]. The unambiguos interpretation of $Y(4260)$ can be possibly obtained as a result of careful studies of its open-charm decays, in particular those with D meson (both S and P wave) pairs.

The BaBar collaboration has studied the exclusive production of the $D\overline{D}$ system ($D = D^0$ or D^+) through initial state radiation [52]. As seen in Fig 9, the $D\overline{D}$ mass spectrum shows a clear $\psi(3770)$ signal and two further structures, centered around 3.9 and 4.1 GeV/c^2. No evidence was found for $Y(4260) \to D\overline{D}$, leading to an upper

	BaBar	CLEO	Belle (preliminary)
Yield (significance)	125 ± 23 ($> 8\sigma$)	$14.1^{+5.2}_{-4.2}$ (4.9σ)	165^{+24+7}_{-22-23} ($> 7\sigma$)
Mass (MeV/c^2)	$4259 \pm 8^{+2}_{-6}$	$4283^{+17}_{-16} \pm 4$	$4295 \pm 10^{+11}_{-5}$
Width (MeV)	$88 \pm 23^{+6}_{-4}$	$70^{+40}_{-25} \pm 5$	133^{+26+13}_{-22-6}

Table 1: The parameters of the $Y(4260)$ resonance, as measured by BaBar, CLEO and Belle.

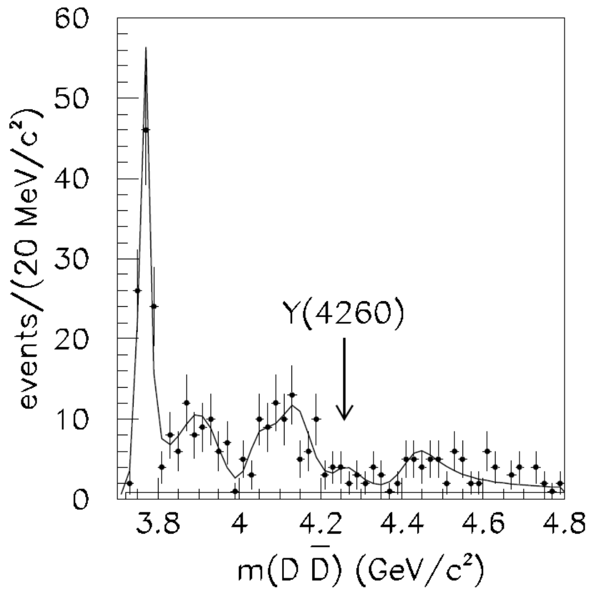

Figure 9: The $D\overline{D}$ mass spectrum for the ISR sample, as measured by BaBar. The arrow indicates the expected position of the $Y(4260)$.

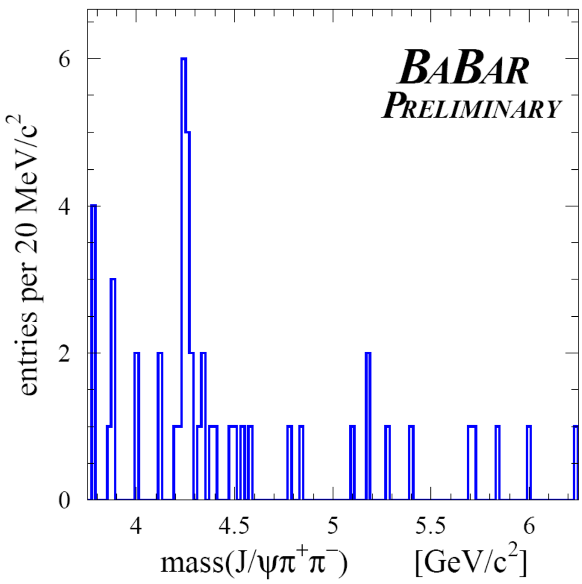

Figure 10: The $\pi^+\pi^- J/\psi$ mass spectrum for the ISR sample, as measured by BaBar in the analysis with the detection of the hard photon radiated from an initial e^+e^- collision.

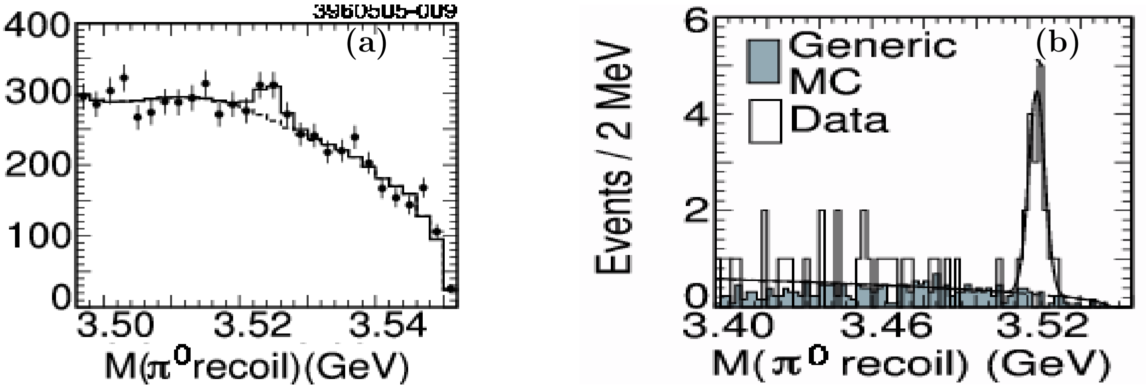

Figure 11: The recoil mass against π^0 for **(a)** inclusive (i.e. no reconstruction of the η_c) and **(b)** exclusive η_c reconstruction in the reaction $\psi(2S) \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$, as measured by CLEO collaboration.

limit $\frac{\mathcal{B}(Y(4260)\to D\overline{D})}{\mathcal{B}(Y(4260)\to\pi^+\pi^- J/\psi)} < 7.6$ (90 % C.L.). This number is over an order of magnitude smaller to compare with the value for the $\psi(3770)$ which makes the interpretation of $Y(4260)$ as a conventional $c\overline{c}$, rather doubtful.

The BaBar collaboration has also searched for the processes $e^+e^- \to (J/\psi\gamma\gamma)\gamma_{ISR}$ and $e^+e^- \to (J/\psi\pi^+\pi^-)\gamma_{ISR}$ [53], where the hard photon radiated from an initial electron-positron collision is directly detected. In the latter final state the signal of $Y(4260)$ was observed (Fig. 10). Its mass and width are consistent with the the values originally reported by BaBar in [41]. In the $(J/\psi\gamma\gamma)\gamma_{ISR}$ final state, no events were found in the $Y(4260)$ mass region in the $J/\psi\eta$, $J/\psi\pi^0$ and $\chi_{c2}\gamma$ distributions.

7 h_c

The CLEO collaboration has observed the h_c ($^1P1$) state of charmonium in the reaction $\psi(2S) \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$ [54]. The signal in the π^0 recoil mass was observed both for the inclusive reaction (Fig. 11 a)), where the decay products of the η_c are not identified, and for exclusive processes (Fig. 11 b)), in which η_c decays are reconstructed in seven hadronic decay channels ($\sim$ 10 % of all η_c decays). The results of the inclusive and exclusive analyses were combined and yielded $M(h_c) = (3524.4 \pm 0.6 \pm 0.4)$ MeV/c^2 (in agreement with [55]) and $\mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$. Together with the well known mass value of the ^3P_J centroid ($< M(^3P_J) >= (3525.36\pm0.06)$ MeV/c^2 [30]), it has allowed to determine for the first time the hyperfine splitting for the P states of charmonium: $\Delta M_{hf}(< M(^3P_J) > -M(^1P_1) = (+1.0\pm0.6\pm0.4)$ MeV/c^2. This agrees well with the simplest calculations assuming the potential composed of a vector Coulombic ($\sim r$) and a scalar confining ($\sim 1/r$) terms. They are both spin independent and as a result the hyperfine splitting should be zero. Larger values of the ΔM_{hf} could be accomodated only after the inclusion of the higher-order corrections [56, 57], which is not confirmed by the CLEO measurement.

8 D_{sJ} mesons

The symbol D_{sJ} is often used to mark orbital excitations of the $c\overline{s}$ bound states. Four such P-wave mesons are expected in the framework of potential models, inspired by the heavy quark symmetry (HQS) [58, 59]. They can be naturally splitted in two doublets differing in the orbital momentum of light degrees of freedom (j_q). The states with $j_q = 3/2$ are predicted to be narrow and were identified as the $D_{s1}(2536)$ (Argus) and $D_{s2}(2573)$ (Cleo) in 1989 (1994), respectively. The mesons belonging to the $j_q = 1/2$ are expected to be much wider i.e. more difficult to observe.

Two candidates for such states were found in 2003. First the BaBar collaboration provided the evidence for the state $D_{sJ}(2317)^+$ (Fig. 12), decaying to $D_s^+\pi^0$ [60]. The observation by Cleo of the second state $D_{sJ}(2460)$ (Fig. 13), in the decay to $D_s^{*+}\pi^0$ [61], followed almost immediately. Both signals were found in the continuum processes $e^+e^- \to c\overline{c}$. There were soon confirmed by the Belle collaboration, together with an additional evidence of their presence in B meson exclusive decays [62]. Two other decay modes to the final states $D_s\gamma$ and $D_s\pi^+\pi^-$ (implies a spin of at least one) were observed for the $D_{sJ}(2460)^+$.

The discussed below, unexpected properties of both new mesons questioned the interpretation of both new mesons as ($c\overline{s}$, $j_q = 1/2$) bound states. First of all the widths of both the $D_{sJ}(2317)$ and $D_{sJ}(2460)$ turned out to be very small, consistent with the experimental resolution (< 4.6 MeV and < 5.5 MeV, respectively). Also their masses, measured to be below the DK (D*K) thresholds, respectively, appeared to be significantly lower to compare with HQS expectations, On the other side the study of angular distributions of the $D_{sJ}(2317)$ and $D_{sJ}(2460)$ decay products, performed by BaBar [63] and Belle [64], favoured strongly their spin-parity assignments 0^+ and 1^+, in agreement with HQS predictions. This motivated a vigorous answer from the side of theorists, proposing several exotic explanations for the two new mesons. In particular, the $D_{sJ}(2317)$ and $D_{sJ}(2460)$ were interpreted as $D^{(*)}K$ molecules [65, 66] or the chiral doublers of the D_s and D_s^* [67, 68]. Assuming that current mass predictions of HQS are wrong (they can in fact be shifted to lower values, in the presence of a strong S wave coupling to $DK^{(*)}$), both new D_{sJ} mesons could be comfortably interpreted as coventional ($c\overline{s}$) states. Provided that their predicted masses may be lowered below the respective $D^{(*)}K$ thresholds, the narrow widths of the $D_{sJ}(2317)$ and $D_{sJ}(2460)$ are naturally explained. These low masses would clearly allow the observed electromagnetic and isospin-violating decays of the the two states to be pronounced. Thus, the two new D_{sJ} mesons can be interpreted as conventional states

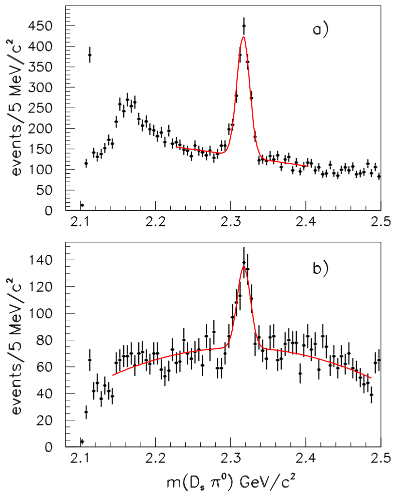

Figure 12: The $D_s^+\pi^0$ mass distributions for **(a)** the decay $D_s^+ \to K^+K^-\pi^+$ and **(b)** $D_s^+ \to K^+K^-\pi^+\pi^0$, as measured by BaBar. The solid curves represent the fits, described in [60].

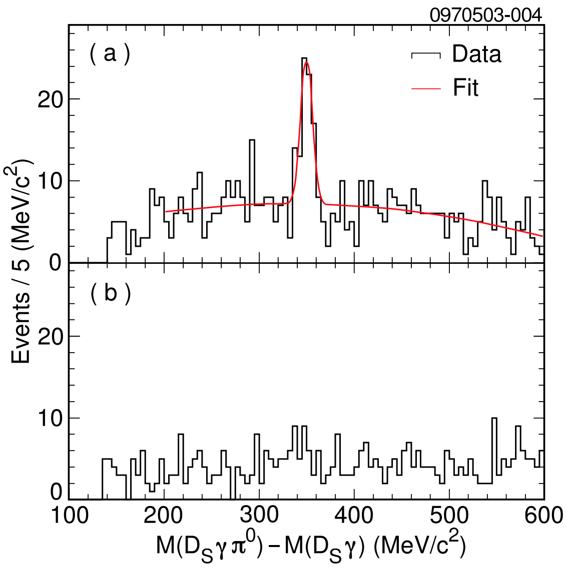

Figure 13: The mass difference $\Delta M(D_s^*\pi^0) = M(D_s\gamma\pi^0) - M(D_s\gamma)$, measured by the Cleo collaboration for **(a)** combinations where the $D_s\gamma$ system is consistent with D_s^* decay and **(b)** $D_s\gamma$ combinations selected from the D_s^* mass sideband regions.

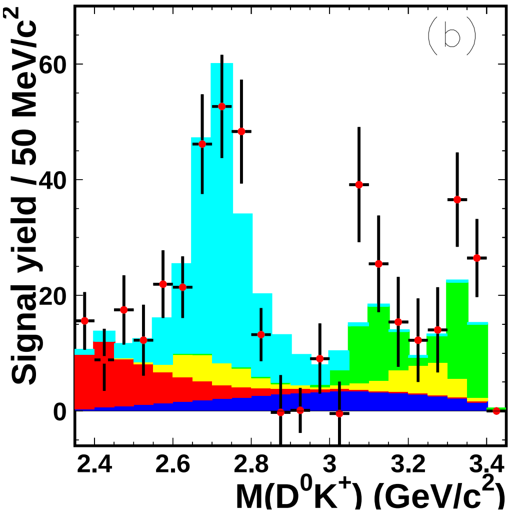

Figure 14: $B^+ \to \overline{D^0} D^0 K^+$ signal yield vs $M(D^0K^+)$ (data points) as measured by Belle. Additively superimposed histograms denote the contributions from $D_{sJ}(2700)$ (blue), $\psi(3770)$ (green), $\psi(4160)$ (yellow), threshold (red) and phase-space (navy blue) components.

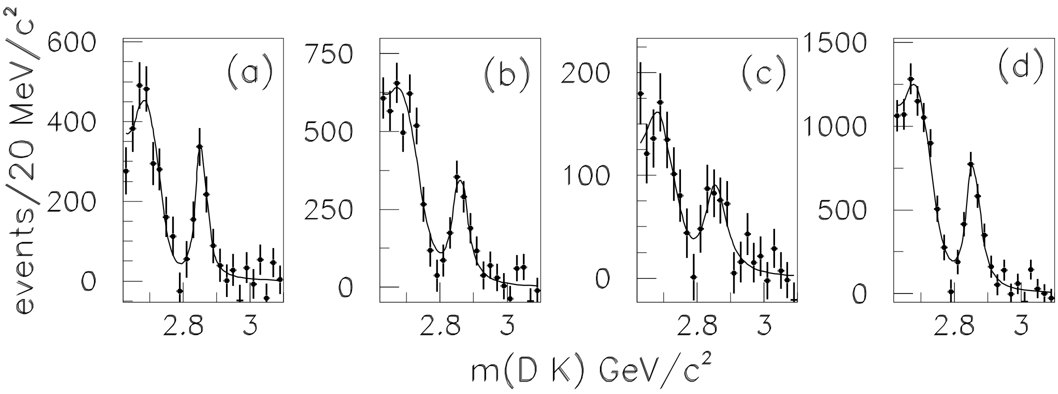

Figure 15: Background subtracted DK invariant mass distributions measured by BaBar collaboration for **(a)** $D^0(\to K^-\pi^+)K^+$, **(b)** $D^0(\to K^-\pi^+\pi^0)K^+$, **(c)** $D^+(\to K^-\pi^+\pi^+)K^0_s$ and **(d)** the sum of all modes in the 2.86 GeV/c^2 mass range. The curves are the fitted functions described in [73].

D^*_{s0} and D_{s1} ([69]– [71]).

Yet another charm-strange meson, marked as $D_{sJ}(2700)$ and produced in $B^+ \to \overline{D^0} D_{sJ}$, $D_{sJ} \to D^0 K^+$ was observed by Belle [72] (Fig. 14). This state has a mass of $M = (2715 \pm 11^{+11}_{-14})$ MeV/c^2 and a width $\Gamma = (115 \pm 20^{+36}_{-32})$ MeV and its signal corresponds to 182 ± 30 events. The study of $D_{sJ}(2700)$ helicity angle distributions strongly favours the spin parity assignment of 1^-.

Recent observations concerning the D_{sJ} family are completed by the study of three inclusive processes $e^+e^- \to D^0K^+X, D^0 \to K^-\pi^+$, $e^+e^- \to D^0K^+X, D^0 \to K^-\pi^+\pi^0$ and $e^+e^- \to D^+K^0_sX, D^+ \to K^-\pi^+\pi^+$ performed by BaBar [73]. The distributions of DK invariant mass (Fig. 15) show a clear signal of a new charm-strange meson, marked as $D_{sJ}(2860)$, with a mass of $M = (2856.6 \pm 1.5 \pm 5.0)$ MeV/c^2 and a width $\Gamma = (47 \pm 7 \pm 10)$ MeV. The decay to two pseudoscalars implies a natural spin-parity for this state $(0^+, 1^-, ...)$ and the value $J^P = 3^-$ is predicted in [74]. According to [75], the $D_{sJ}(2860)$ could be a radial excitation of $D^*_{sJ}(2317)$. However, other assignments cannot be ruled out. Moreover, a second broad enhancement is observed around 2.69 GeV/c^2 (Fig. 15). This state was temporarily marked as $X(2690)^+$ and clearly further inputs are necessary in order to understand its origin. Its mass was determined to be $M = (2688 \pm 4 \pm 3)$ MeV/c^2 and a width $\Gamma = (112 \pm 7 \pm 36)$ MeV. It would be very interesting to check if there is any association between the $D_{sJ}(2700)$ and $X(2690)$.

9 $\Sigma_c(2800)$

The Belle collaboration has provided the first evidence [76] for an isotriplet of excited charmed baryons $\Sigma_c(2800)$ decaying into the $\Lambda_c^+\pi^-$, $\Lambda_c^+\pi^0$ and $\Lambda_c^+\pi^+$ final states. As shown in Fig. 16, clear enhancements around 0.51 GeV/c^2 are seen in the distributions of the mass difference $\Delta M(\Lambda_c^+\pi) = M(\Lambda_c^+\pi) - M(\Lambda_c^+)$ for the $\Lambda_c^+\pi^-$, $\Lambda_c^+\pi^0$, and $\Lambda_c^+\pi^+$ combinations. The mass differences ΔM together with the widths of the states $\Sigma_c(2800)$ are collected in Table 2. These states are identified as the members of the predicted Σ_{c2}, $J^P = 3/2^-$ isospin triplet [77]. The enhancement near $\Delta M = 0.43$ GeV/c^2 (cf Fig. 16), in the spectra corresponding to $\Lambda_c^+\pi^-$ and $\Lambda_c^+\pi^+$ combinations, is attributed to feed-down from the decay $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$, as verified by reconstructing $\Lambda_c(2880)$ in the data.

10 $\Lambda_c(2940)^+$ and $\Lambda_c(2880)^+$

The charmed baryon $\Lambda_c(2940)^+$ was first observed by the BaBar collaboration in the pD^0 final state [78] (Fig. 17). The signal at 2.88 GeV/c^2 is due to the decay $\Lambda_c(2880)^+ \to pD^0$. This comprises the first observation of the above decay channel (the baryon $\Lambda_c(2880)^+$ was first seen by CLEO in the final state $\Lambda_c^+\pi^+\pi^-$ [79]). The

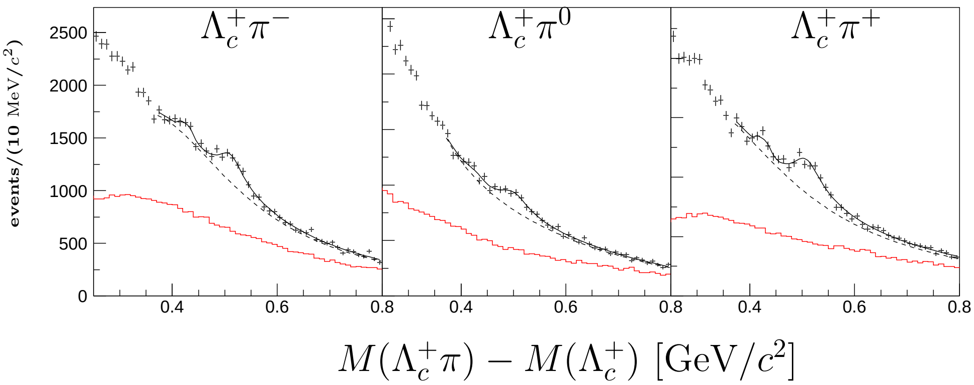

Figure 16: $M(\Lambda_c^+\pi) - M(\Lambda_c)$ distributions of the selected $\Lambda_c^+\pi^-$ (left), $\Lambda_c^+\pi^0$ (middle), and $\Lambda_c^+\pi^+$ (right) combinations. Data from the Λ_c^+ signal window (points with error bars) and normalized sidebands (histograms) are shown, together with the fits (solid curves) and their combinatorial background components (dashed).

Table 2: Parameters of the baryons $\Sigma_c(2800)^0$, $\Sigma_c(2800)^+$ and $\Sigma_c(2800)^{++}$ as measured by Belle.

State	ΔM [MeV/c^2]	Width [MeV]	Yield/10^3	Significance (σ)
$\Sigma_c(2800)^0$	$515.4^{+3.2+2.1}_{-3.1-6.0}$	61^{+18+22}_{-13-13}	$2.24^{+0.79+1.03}_{-0.55-0.50}$	8.6
$\Sigma_c(2800)^+$	$505.4^{+5.8+12.4}_{-4.6-2.0}$	62^{+37+52}_{-23-38}	$1.54^{+1.05+1.40}_{-0.57-0.88}$	6.2
$\Sigma_c(2800)^{++}$	$514.5^{+3.4+2.8}_{-3.1-4.9}$	75^{+18+22}_{-13-11}	$2.81^{+0.82+0.71}_{-0.60-0.49}$	10.0

Table 3: Parameters of the baryons $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$, as determined by BaBar and Belle.

State	Expt.	Mass [MeV/c^2]	Width [MeV]	Yield (events)
$\Lambda_c(2880)^+$	BaBar	$2881.9 \pm 0.1 \pm 0.5$	$5.8 \pm 1.5 \pm 1.1$	2800 ± 190
$\Lambda_c(2880)^+$	Belle	$2881.2 \pm 0.2^{+0.4}_{-0.3}$	$5.5^{+0.7}_{-0.3} \pm 0.4$	$880 \pm 50 \pm 40$
$\Lambda_c(2940)^+$	BaBar	$2939.8 \pm 1.3 \pm 1.0$	$17.5 \pm 5.2 \pm 5.9$	2280 ± 310
$\Lambda_c(2940)^+$	Belle	$2937.9 \pm 1.0^{+1.8}_{-0.4}$	$10 \pm 4 \pm 5$	$210^{+70+100}_{-40-60}$

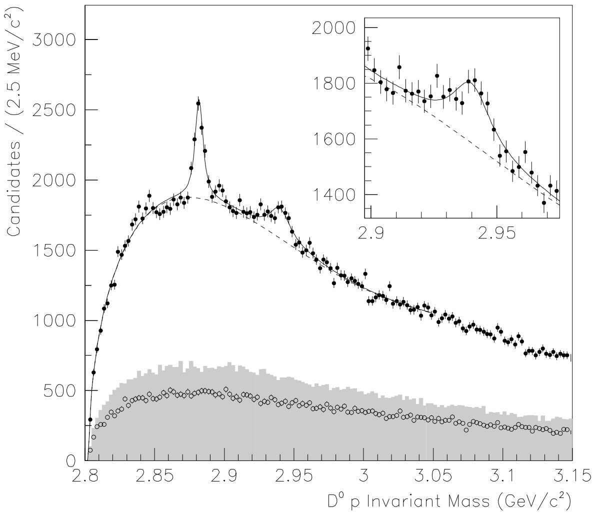

Figure 17: Invariant mass distribution of pD^0 pairs, as measured by BaBar collaboration (data points). The shaded histogram and open circles correspond to the D^0 mass sidebands and wrong-sign $p\overline{D^0}$ candidates, respectively. The inset shows the pD^0 mass spectrum in the range 2.9–2.975 GeV/c^2.

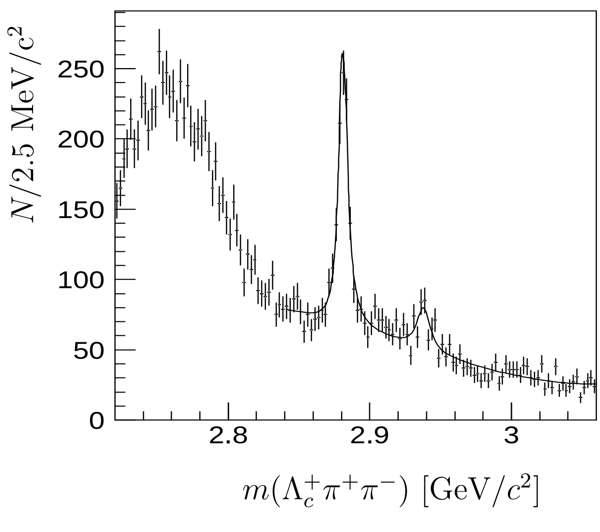

Figure 18: The invariant mass distribution of the $\Lambda_c^+\pi^+\pi^-$ combinations as measured by the Belle collaboration. The plot corresponds to the $\Sigma_c(2455)$ mass peak of the $\Lambda_c\pi^\pm$ combinations. The signals of $\Lambda_c(2765)^+$, $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ can be clearly distinguished.

search for a doubly-charged partner of the $\Lambda_c(2940)^+$, performed by BaBar in the final state pD^+, gave negative results [78].

The Belle collaboration has recently reported the evidence for another decay mode $\Lambda_c(2940)^+ \to \Sigma_c(2455)^{0,++}\pi^\pm$ [80] (Fig. 18). The study of angular distributions of the decay $\Lambda_c(2880)^+ \to \Sigma_c^{0,++}\pi^\pm$ strongly favours a $\Lambda_c(2880)^+$ spin assignment of $\frac{5}{2}$ over $\frac{3}{2}$ and $\frac{1}{2}$ [80].

The parameteters of both $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ measured by Belle and BaBar, are in good overall agreement (Table 3).

11 $\Xi_{cx}(2980)$ and $\Xi_{cx}(3077)$

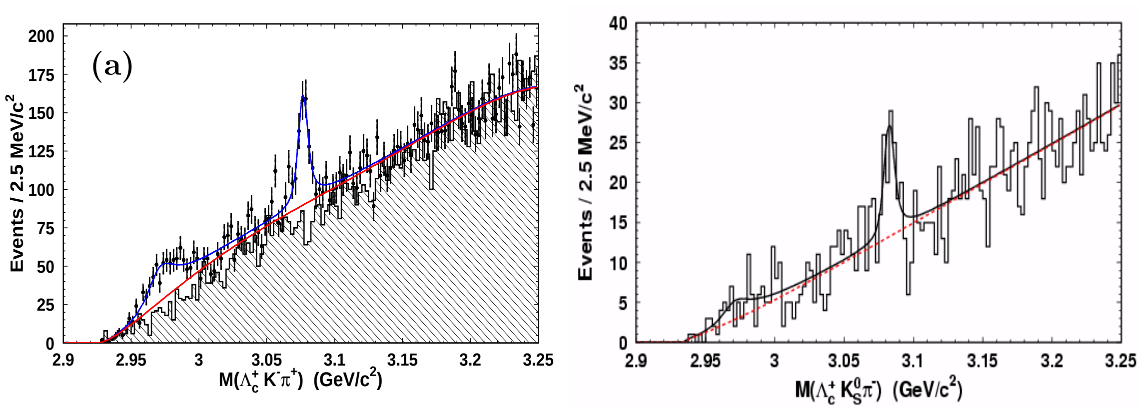

Figure 19: **(a)**: $M(\Lambda_c^+ K^- \pi^+)$ distribution (points with error bars) together with the fit (solid curve). The dashed region represents the background component corresponding to the wrong-sign combinations $\Lambda_c^+ K^+ \pi^-$. **(b)**: $M(\Lambda_c^+ K_s^0 \pi^+)$ distribution (points) together with the overlaid fitting curve. Both spectra were measured by the Belle collaboration.

In the beginning of this year, the Belle collaboration reported the first observation of two baryons [81], denoted as $\Xi_{cx}(2980)^+$ and $\Xi_{cx}(3077)^+$ and decaying into $\Lambda_c^+ K^- \pi^+$ (Fig. 19(a)). The existence of both new particles were quickly confirmed by BaBar [82]. Assuming that these states carry charm and strangeness, the above observation would comprise the first example of a baryonic decay in which the initial c and s quarks are carried away by two different final state particles. Most naturally, these two states would be interpreted as excited charm-strange baryons Ξ_c. This interpretation is strengthened by the positive results of the search for neutral isospin related partners of the above states (Fig. 19(b)), performed by Belle in $\Lambda_c^+ K_s^0 \pi^-$ final state [81]. It yielded an evidence of the $\Xi_{cx}(3077)^0$ together with a broad enhancement near the threshold i.e. in the mass range corresponding to the $\Xi_{cx}(2980)^0$.

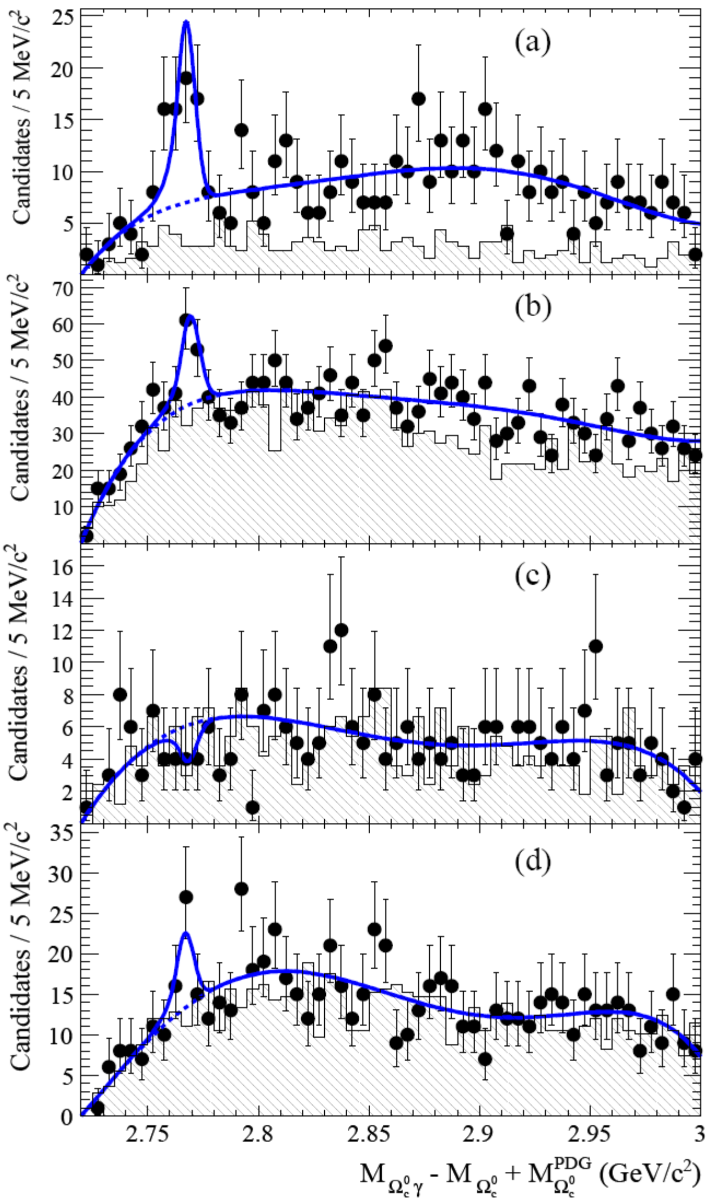

Figure 20: The invariant mass distributions of $\Omega_c^{*0} \to \Omega_c^0\gamma$ candidates with Ω_c^0 reconstructed by BaBar in the decay modes **(a)** $\Omega^-\pi^+$, **(b)** $\Omega^-\pi^+\pi^0$, **(c)** $\Omega^-\pi^+\pi^-\pi^+$ and **(d)** $\Xi^-K^-\pi^+\pi^+$. The points with error bars represent the data, the dashed line corresponds to the combinatorial background and the solid line is the sum of signal and background. The shaded histograms correspond to the mass distribution expected from the mass sideband of Ω_c^0.

The preliminary parameters of the states $\Xi_{cx}(2980)^+$ and $\Xi_{cx}(3077)^+$ are collected in Table 4.

In the $\Lambda_c^+ K^- \pi^+ (\pi^+)$ final state, the SELEX collaboration [83] reported the observation of two double charmed baryon: Ξ_{cc}^+ with a mass of 3520 MeV/c^2 and Ξ_{cc}^{++} with a mass of 3460 MeV/c^2. The studies by Belle [81] and BaBar [85] show no evidence for these states. The BaBar collaboration estimated the following 95 % C.L. upper limits on the ratio of production cross-sections: $\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)/\sigma(\Lambda_c^+) < 2.7 \times 10^{-4}$ and $\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)/\sigma(\Lambda_c^+) < 4.0 \times 10^{-4}$ (estimated for $p^*(\Lambda_c) > 2.3$ GeV/c, where p^* denotes the CMS momentum of the Λ_c). The Belle collaboration studied only the single-charged state which yielded $\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)/\sigma(\Lambda_c^+) < 1.5 \times 10^{-4}$ (90 % C.L.; $p^*(\Lambda_c) > 2.5$ GeV/c).

Table 4: Parameters of the new charm-strange baryons $\Xi_{cx}(2980)^{+,0}$ and $\Xi_{cx}(3077)^{+,0}$

State	Expt.	Mass (MeV/c^2)	Width (MeV)	Yield (events)	Signif. (σ)
$\Xi_{cx}(2980)^+$	BaBar	$2967.1 \pm 1.9 \pm 1.0$	$23.6 \pm 2.8 \pm 1.3$	$284 \pm 45 \pm 46$	7.0
$\Xi_{cx}(2980)^+$	Belle	$2978.5 \pm 2.1 \pm 2.0$	$43.5 \pm 7.5 \pm 7.0$	405.3 ± 50.7	5.7
$\Xi_{cx}(3077)^+$	BaBar	$3076.4 \pm 0.7 \pm 0.3$	$6.2 \pm 1.6 \pm 0.5$	$204 \pm 35 \pm 12$	8.6
$\Xi_{cx}(3077)^+$	Belle	$3076.7 \pm 0.9 \pm 0.5$	$6.2 \pm 1.2 \pm 0.8$	326.0 ± 39.6	9.2
$\Xi_{cx}(2980)^0$	Belle	$2977.1 \pm 8.8 \pm 3.5$	43.5 (fixed)	42.3 ± 23.8	1.5
$\Xi_{cx}(3077)^0$	Belle	$3082.8 \pm 1.8 \pm 1.5$	$5.2 \pm 3.1 \pm 1.8$	67.1 ± 19.9	4.4

12 Ω_c^{*0}

The baryon Ω_c^{*0} was observed by the BaBar collaboration in the radiative decay $\Omega_c^0 \gamma$ [86]. This state was the last singly-charm baryon having zero orbital momentum, remaining to be experimentally detected. The Ω_c^0 was reconstructed in the decays to the final states $\Omega^- \pi^+$, $\Omega^- \pi^+ \pi^0$, $\Omega^- \pi^+ \pi^- \pi^+$ and $\Xi^- K^- \pi^+ \pi^+$ (Fig. 20). The mass difference between Ω_c^{*0} and Ω_c^0 was measured to be $\Delta M = 70.8 \pm 1.0 \pm 1.1$ MeV/c^2. This agrees with the theoretical prediction in [87, 88] and is below that described in [89].

13 Summary

The charm physics has many features of the Sleeping Beauty. After the initial publicity of the times of November revolution, it remained a calm field aimed at filling the columns of Particle Data Group booklets with new or more accurate cross-sections, branching ratios, lifetimes etc. It seems that B factories acted like a prince who kissed the Sleeping Beauty and waked her up right in the beginning of this century. The discovery of plethora of new charmed states has revitalized the charm physics and triggered many new theoretical ideas. Since the B factories are still collecting enormous samples of data, it is rather likely that some new exciting and charming discoveries are just around the corner.

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