Excited Charmed Mesons: Observations, Analyses and Puzzles

P. Colangelo, F. De Fazio and R. Ferrandes

*Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Italy*

Abstract

We review the status of recently observed positive parity charmed resonances, both in the non-strange and in the strange sector. We describe the experimental findings, the main theoretical analyses and the open problems deserving further investigations.
1 Introduction

This is an exciting period for hadron spectroscopy, due to the discovery of several new particles with unexpected and intriguing features. It is fair to mention first the increasing evidence of pentaquark states [1], the observation of which requires a deeper understanding of QCD interactions at low energy. Furthermore, both the $\bar{b}b$ and $\bar{c}c$ spectra were enriched by the observation of a meson belonging to the $d$-wave multiplet of the $\Upsilon$ system, and of $X(3870)$ and the first radial excitation of $\eta_c$ in the charmonium [2]. A new doubly charmed $\Xi_{cc}^+$ baryon was detected [3]. Last, but not least, excited charmed mesons have been observed both in the strange and non-strange sector, providing new information about the spectroscopy of the open charm system. In this paper we describe the experimental results concerning such new charmed resonances, as well as a number of theoretical analyses aimed at understanding their phenomenology.

As we shall see, there are various and different interpretations of these charmed resonances, and in the following we discuss them in detail. However, it is important at the beginning to settle the scene, and we consider the heavy quark theory as the most suitable theoretical framework to start our study [4].

The analysis of hadrons containing a single heavy quark $Q = c, b$ is greatly simplified if one considers the limit of infinitely heavy quark. This is due to the fact that such a quark acts as a static colour source, and its spin $s_Q$ is decoupled from the total angular momentum $s_\ell$ of all other hadronic (light) degrees of freedom.

There are several consequences of that. One is that it is possible to classify heavy hadrons using $s_\ell$ as a good quantum number. Therefore, heavy mesons can be collected in doublets, each one corresponding to a particular value of $s_\ell$ and parity, with the members of each doublet degenerate in mass. The degeneracy condition is broken if $1/m_Q$ corrections are taken into account. In this case, the mass formula for a heavy meson:

\[ M_H = m_Q + \bar{\Lambda} + \frac{\mu_x^2 - \mu_G^2}{2m_Q} \]

involves the binding energy parameter $\bar{\Lambda}$ and two parameters $\mu_x^2$ and $\mu_G^2$ representing the matrix elements of the kinetic energy and the chromomagnetic operators over the considered meson. Such operators appear at order $1/m_Q$ in the effective Lagrangian of the heavy quark effective theory [4]. $\mu_G^2$ depends on the spin $J$ of the hadron and is therefore responsible of the mass splitting between the two members of a doublet, which is a $1/m_Q$ effect. It can be written as: $\mu_G^2 = -2 \left[ J(J + 1) - \frac{3}{2} \right] \lambda_2$. $\bar{\Lambda}$, together with $\lambda_2$ (or $\mu_G^2$) and
\[ \mu_u^2, \] are independent of the heavy quark mass and, in \( SU(3)_F \) limit, of the flavour of the light quark. All the three parameters, however, are different for different doublets.

The lowest lying \( Q\bar{q} \) mesons correspond to \( \ell = 0 \) (the s-wave states of the quark model) with \( s_\ell^P = \frac{1}{2}^- \). This doublet comprises two states with spin-parity \( J^P = (0^-, 1^-) \). For \( \ell = 1 \) (p-wave states of the quark model), it could be either \( s_\ell^P = \frac{1}{2}^+ \) or \( s_\ell^P = \frac{3}{2}^+ \). The two corresponding doublets have \( J^P = (0^+, 1^+) \) and \( J^P = (1^+, 2^+) \). To fix the notations, we denote the members of the \( J^P = (0^+, 1^+) \) charm doublet with \( s_\ell^P = \frac{1}{2}^+ \) as \((D_0^*, D_1')\) and \((D_{s0}^*, D_{s1}')\) for non-strange and strange states, respectively, and those of the \( J^P = (1^+, 2^+) \) doublet with \( s_\ell^P = \frac{3}{2}^+ \) as \((D_1, D_2^*)\) and \((D_{s1}, D_{s2}^*)\). Finite heavy quark mass effects can induce a mixing between the two axial vectors, giving rise to two \( 1^+ \) mass eigenstates; however, in the following we neglect the mixing since, as we argue below, it can be at most of few degrees in the case of charm.

A distinctive feature between the two \( \ell = 1 \) doublets is their expected width. In fact, the strong decays of the members of the \( s_\ell^P = \frac{3}{2}^+ \) doublet can proceed by emitting light pseudoscalar mesons in \( d \)-wave, while the emission is in \( s \)-wave for the doublet \( s_\ell^P = \frac{1}{2}^+ \). Thus, \( s_\ell^P = \frac{3}{2}^+ \) mesons are expected to be narrower than \( s_\ell^P = \frac{1}{2}^+ \) ones, simply due to the different dependence of the two-body decay rates on the three-momentum of the emitted meson. The six \( s_\ell^P = \frac{3}{2}^+ \) \( c\bar{u}, c\bar{d} \) and \( c\bar{s} \) states have been observed with precision at the level of few MeV for the mass and the width, thanks, in particular, to their narrowness and to their abundant production in various experimental setup, at fixed target, in \( e^+ e^- \) continuum production, in \( B \) and \( Z^0 \) decays [5].

The case is different for the members of the doublet \( s_\ell^P = \frac{1}{2}^+ \), which are the subject of this review paper. There have been recent experimental observations of particles that can be recognized as members of this doublet in the case of charm. However, for non-strange particles not all the charge configurations have been observed, so far, and there is some disagreement in the mass measurements made by different experiments. As for \( c\bar{s} \) mesons, evidence has been recently collected of very narrow states, in contradiction with the expectation of particles having broad width, a feature which has prompted an intense activity to clarify the issue.

Moreover, in case of the assignment of the newly observed states to the low-lying positive parity doublet, the comparison of the features of corresponding non-strange and strange mesons arises some questions, for example concerning the mass difference between strange and non-strange mesons and the spin splitting within each doublet.

In the following we review (in Section 2) the experimental observations for both non-strange and strange charmed mesons, in particular the measurement of masses and decay
branching fractions. Then we discuss various theoretical studies aimed at shedding light on the structure of these mesons. In particular, in Section 3 we consider the analyses of the spectroscopy of the newly observed states, with different approaches and interpretations. In Section 4 we analyse the decays of the new charmed resonances, as they can be useful for understanding their structure. After a discussion concerning the beauty sector, we present our conclusions in the last Section.

2 Observations

2.1 Evidence of broad $c\bar{u}$, $c\bar{d}$ states: $D_0^{*0}$, $D_0^{*+}$ and $D_1^0$

The first evidence of $c\bar{q}$ broad states was provided by Cleo Collaboration [6], which observed a state of mass 2460 MeV and width 290 MeV with the features of an axial vector meson. More recently, Belle and Focus Collaborations, looking at $D\pi$ and $D\pi\pi$ invariant mass distributions, provided further elements in support of the existence of one scalar and one axial charmed meson that could be interpreted as the states belonging to the $1^+$ $c\bar{u}$, $c\bar{d}$ doublets.

The Belle observation is based on the study of charmed mesons produced in $B$ decays through the transition $B \to D^{**}\pi$, with a $D^{**}$ a generic $l = 1$ meson [7]. A Dalitz plot analysis is carried out for the final states $D^+\pi^-\pi^-$ and $D^{*+}\pi^-\pi^-$. In the former case, the Dalitz analysis includes the amplitude of the $D_2^{*+}\pi^-\pi^-$ mode, the contributions of processes involving virtual production of $D^{*0}\pi^-$ and $B^{*0}\pi^-$, and the amplitude of a $D\pi$ structure with free mass, free width and assigned $J^P = 0^+$ quantum numbers. As reported by Belle [7], a fit of the projection of the Dalitz plot to the $D\pi$ axis, where the pion is the one having the smallest momentum, favours the presence of the scalar contribution. The $D\pi$ mass distribution is depicted in fig. 1; the mass and width of the broad state obtained by the fit are collected in Table 1.

A similar analysis, carried out for $D^{*+}\pi^-\pi^-$, provides evidence of a broad resonance with quantum numbers compatible with the assignment $J^P = 1^+$. The Belle $D^*\pi$ mass distribution is also depicted in fig. 1. The contributions of the two other charmed states $D_1$ and $D_2^*$ are not sufficient to fit the mass distribution; a further contribution, representing a broad state, is needed, the mass and width of which are reported in Table 1. Through this analysis, a new determination of mass and width of the two other positive parity charmed states $D_2^*$ and $D_1$ has also been obtained, together with a measurement of the mixing angle between the two $1^+$ states: $\omega = -0.10 \pm 0.03 \pm 0.02 \pm 0.02 \text{ rad (} \theta \simeq -6^0\)
Figure 1: Background-subtracted $D\pi$ (left) and $D^*\pi$ (right) mass distributions obtained by Belle Collaboration [7]. Hatched histograms show the contributions of the various amplitudes, open histograms show the coherent sum of all contributions.

suggesting that such a mixing can safely be neglected.

An analogous study has been carried out by Focus Collaboration [8], which considered both the $D^0\pi^+$ and $D^+\pi^-$ charge configurations. Also in this case, a broad scalar contribution is required to fit the $D\pi$ mass distribution. The values of mass and width quoted by Focus are collected in Table 1. The values for the mass of $D^*_0^{0}$, measured by Belle and Focus, are marginally compatible; nevertheless, we include in Table 1 their average, as well as the average of Belle and Cleo data for the axial vector state.

Table 1: Mass and width of broad resonances observed in $D\pi$ and $D^*\pi$ systems.

|                  | Belle Collab. [7] | Focus Collab. [8] | Average       |
|------------------|-------------------|-------------------|---------------|
| $D^0_0$          | M (MeV)           | 2308 ± 17 ± 15 ± 28| 2407 ± 21 ± 35| 2351 ± 27     |
|                  | $\Gamma$ (MeV)    | 276 ± 21 ± 18 ± 60| 240 ± 55 ± 59 | 262 ± 51      |
| $D^*_0^+$        | M (MeV)           |                   | 2403 ± 14 ± 35|               |
|                  | $\Gamma$ (MeV)    |                   | 283 ± 24 ± 34 |               |

|                  | Belle Collab. [7] | Cleo Collab. [6] | Average       |
|------------------|-------------------|------------------|---------------|
| $D^0_1$          | M (MeV)           | 2427 ± 26 ± 20 ± 15| 2461$^{+107}_{-76}$ ± 10 ± 32| 2438 ± 30     |
|                  | $\Gamma$ (MeV)    | 384$^{+107}_{-75}$ ± 24 ± 70| 290$^{+101}_{-79}$ ± 26 ± 36| 329 ± 84     |
The peak was also found by reconstructing $D_s^0$ through $D_s^0 \to K^+K^-\pi^+\pi^-\pi^0$. Fig. 2 shows the BaBar signal for $D_{sJ}^*(2317)$. No evidence for $D_{sJ}^*(2317)\to D_s\pi^0\gamma, D_s^*\gamma$ and $D_s\gamma\gamma$ was found.

The resonance was also observed by Belle [10] and Cleo Collaborations [11] (fig. 2), with mass reported in Table 2. Even in these cases, the measured width was compatible with the experimental resolution, thus suggesting a smaller intrinsic width of the resonance. An observation was reported more recently by Focus Collaboration [12], with a preliminary measurement of the mass $M_{D_{sJ}^*(2317)} = 2323 \pm 2$ MeV, slightly above the values obtained by the other three experiments.

The observation of the decay $D_{sJ}^*(2317)\to D_s\pi^0$ implies for $D_{sJ}^*(2317)$ natural spin-parity. The helicity angle distribution of $D_s\pi^0$ obtained by BaBar (fig. 3) is consistent with the spin 0 assignment, even though it does not rule out other possibilities; the absence of a peak in the $D_s\gamma$ final state supports the spin-parity assignment $J^P = 0^+$. The measured
mass is below the $DK$ threshold $s_{DK^0} = 2.36$ GeV.

2.3 The meson $D_{sJ}(2460)$

Together with the $D_{sJ}^*(2317)$, Cleo Collaboration reported the observation of a narrow resonance in the $D_{sJ}^*\pi^0$ system [11], with mass close to 2.46 GeV and width consistent with the experimental resolution. The peak observed by Cleo is shown in fig. 4. The observation of such a state, named $D_{sJ}(2460)$, is made difficult because of a cross-feed ambiguity, due to the numerical relation among the meson masses: $M(D_{sJ}(2460)) - M(D_{sJ}^*(2317)) \approx M(D_{sJ}^*(2317)) - M(D_s) \approx 350$ MeV, which makes possible that a $D_{sJ}^*\pi^0$ candidate is combined with a random photon such that the $D_s^{*+}\gamma$ combination accidentally falls in the $D_{sJ}^*\pi^0$ signal region. In such a case, $D_{sJ}^*(2317) \rightarrow D_{sJ}^{*+}\pi^0$ would feed up into the $D_{sJ}(2460) \rightarrow D_{sJ}^{*+}\pi^0$ signal region. A Monte Carlo simulation of $D_{sJ}^*(2317)$ production and decay to $D_{sJ}^{*+}\pi^0$ shows that this occurs for 10% of the reconstructed decays.

$D_{sJ}(2460)$ was also observed by Belle and BaBar, both in the charm continuum [10, 14], both in $B$ decays [15, 16], with mass and width reported in Table 2. In fig. 4 we depict the Belle signal of the radiative decay $D_{sJ}(2460) \rightarrow D_s\gamma$ reconstructed in $B$ transitions. The measured mass in these two experiments turns out to be smaller than in Cleo measurement, even though the results are marginally compatible: the average of all the determinations is reported in Table 2.

The experimental observations are consistent with the quantum number assignment
$D^*_{sJ}(2317) \rightarrow D_s\pi^0$, (b) $D^*_{sJ}(2460) \rightarrow D_s\pi^0$ and (c) $D_{sJ}(2460) \rightarrow D_s\gamma$.

Table 2: Mass and width of the narrow resonances $D^*_{sJ}(2317)$ and $D_{sJ}(2460)$ measured by BaBar, Belle and Cleo Collaborations. The average value for the mass is also reported.

| $D^*_{sJ}(2317)$          | $D_{sJ}(2460)$          | Collaboration    |
|---------------------------|-------------------------|------------------|
| M (GeV)                   | Γ (GeV)                 | M (GeV)          | Γ (GeV) |        |
| 2317.3 ± 0.4 ± 0.8        | < 10                    | 2458.0 ± 1.0 ± 1.0 | < 10    | BaBar [9, 14] |
| 2317.2 ± 0.5 ± 0.9        | < 4.6                   | 2456.5 ± 1.3 ± 1.3 | < 5.5   | Belle [15] |
| 2318.5 ± 1.2 ± 1.1        | < 7                     | 2463.6 ± 1.7 ± 1.2 | < 7     | Cleo [11] |
| 2317.4 ± 0.6              |                         | 2458.8 ± 1.0      |         |            |

$J^P = 1^+$: the decay $D_{sJ}(2460) \rightarrow D^*_s\pi^0$ implies that $D_{sJ}(2460)$ has unnatural spin-parity; the observation of the radiative decay in $D_{s}\gamma$ rules out $J = 0$, and, finally, helicity distributions measured by Belle and BaBar in $B$ decays are consistent with $J = 1$, as shown in fig. 5. The mass of $D_{sJ}(2460)$ is below the $D^*K$ threshold $s_{D^*+K^0} = 2.51$ GeV.

The mass difference between $D_{sJ}(2460)$ and the other newly observed states and the low-lying charmed mesons is reported in Table 3. It is interesting to compare the hyperfine splitting between positive and negative parity states. Considering the PDG values [5]: $M_{D^0} - M_{D^+} = 142.12 \pm 0.07$ MeV, $M_{D^{*-}} - M_{D^+} = 140.64 \pm 0.10$ MeV and $M_{D^{*-}} - M_{D_s} = 143.9 \pm 0.4$ MeV, one realizes that the hyperfine splittings $1^+ - 0^+$ and $1^- - 0^-$ coincide in the case of strange mesons; for non-strange mesons, the mass differences are compatible.
Figure 5: Helicity distribution of $D_{sJ}(2460) \to D_s\gamma$ measured by Belle [15] (left) and BaBar [16] (right). The distributions are consistent with the assignment $J = 1$ (continuous line in the left panel, first plot in the right panel), and not with $J = 2$ (dashed line in the left panel, second plot in the right panel).

when the Belle result for the $0^+, 1^+$ masses are considered, while they disagree when the average values of the various measurements are considered.

Table 3: Hyperfine splittings between positive parity mesons, and mass differences between excited and low-lying $c\bar{q}$ and $c\bar{s}$ states. Belle data in Table 1 are used for the masses of the broad states. In parentheses we also quote the results corresponding to the averages in Table 1.

| $\Delta M$ ($c\bar{q}$) (MeV) | $\Delta M$ ($c\bar{s}$) (MeV) |
|---------------------------|---------------------------|
| $M_{D_{s0}^*} - M_{D_{s0}} = 119 \pm 26$ (87 $\pm$ 40) | $M_{D_{sJ}(2460)} - M_{D_{sJ}^*(2317)} = 141.4 \pm 1.2$ |
| $M_{D_{s0}^*} - M_{D_{s0}} = 417 \pm 36$ (428 $\pm$ 30) | $M_{D_{sJ}(2460)} - M_{D_{sJ}^*} = 246.4 \pm 1.2$ |
| $M_{D_{s0}^*} - M_{D_{s0}} = 444 \pm 36$ (487 $\pm$ 27) | $M_{D_{sJ}^*(2317)} - M_{D_{sJ}} = 348.9 \pm 0.8$ |

The measured branching fractions of two-body B decays to $D_{sJ}^*(2317)$ or $D_{sJ}(2460)$ are collected in Table 4. This is an important measurement since, as we discuss in Section 4, hints on the nature of the resonances can be provided considering ratios of radiative to hadronic decay rates, either directly measured or inferred from data in Table 4.
3 Analyses: can the masses of \((0^+, 1^+)\) \(c\bar{s}\) \((cq)\) mesons be reliably computed?

3.1 Quark models

Quark model estimates of the masses of \(p\)-wave \(c\bar{s}\) \((cq)\) states were of course available before April 2003, see Table 5 (A). Since mixing between the two \(1^+\) states has been in general accounted, the two axial-vector states are reported in Table 5 (A) as the lightest and the heaviest of the mass eigenstates.

Considering Table 5 (A) one realizes that the mass of the scalar \(c\bar{s}\) was always predicted above the \(DK\) threshold of 2.36 GeV; therefore such state was expected to be massive enough to decay through isospin conserving modes, with a broad width. For the axial vector state, a few determinations also predicted mass values close to the \(D^*K\) threshold \(s_{D^*K^0} = 2.51\) GeV, with the possibility of having a narrower state [23]. Moreover, the

| Mode                                      | BaBar Collab. [16] | Belle Collab. [15] | Average |
|-------------------------------------------|-------------------|-------------------|---------|
| \(B^0 \to D_{s0}^+ D^-\) \((D_{s0}^+ \to D_s^+ \pi^0)\) | 2.09 ± 0.40 ± 0.34 | 0.86 ± 0.26 ± 0.33 | 1.09 ± 0.38 |
| \(B^0 \to D_{s0}^+ D^-\) \((D_{s0}^+ \to D_s^+ \pi^0)\) | 1.12 ± 0.38 ± 0.22 | —                  | —       |
| \(B^+ \to D_{s0}^+ D^0\) \((D_{s0}^+ \to D_s^+ \pi^0)\) | 1.28 ± 0.37 ± 0.22 | 0.81 ± 0.24 ± 0.30 | 0.94 ± 0.32 |
| \(B^+ \to D_{s0}^+ D^0\) \((D_{s0}^+ \to D_s^+ \pi^0)\) | 1.91 ± 0.84 ± 0.50 | —                  | —       |
| \(B^0 \to D_{s0}^+ D^-\) \((D_{s0}^+ \to D_s^+ \pi^0)\) | 1.71 ± 0.72 ± 0.27 | 2.27 ± 0.68 ± 0.13 | 1.98 ± 0.69 |
| \(B^0 \to D_{s1}^+ D^-\) \((D_{s1}^+ \to D_s^+ \pi^0)\) | 5.89 ± 1.24 ± 1.16 | —                  | —       |
| \(B^+ \to D_{s1}^+ D^0\) \((D_{s1}^+ \to D_s^+ \pi^0)\) | 2.07 ± 0.71 ± 0.45 | 1.19 ± 0.36 ± 0.49 | 1.45 ± 0.59 |
| \(B^+ \to D_{s1}^+ D^0\) \((D_{s1}^+ \to D_s^+ \pi^0)\) | 7.30 ± 1.68 ± 1.68 | —                  | —       |
| \(B^0 \to D_{s1}^+ D^-\) \((D_{s1}^+ \to D_s^+ \pi^0)\) | 0.92 ± 0.24 ± 0.11 | 0.82 ± 0.25 ± 0.22 | 0.86 ± 0.25 |
| \(B^0 \to D_{s1}^+ D^-\) \((D_{s1}^+ \to D_s^+ \pi^0)\) | 2.60 ± 0.39 ± 0.34 | —                  | —       |
| \(B^+ \to D_{s1}^+ D^0\) \((D_{s1}^+ \to D_s^+ \pi^0)\) | 0.80 ± 0.21 ± 0.12 | 0.56 ± 0.17 ± 0.16 | 0.63 ± 0.19 |
| \(B^+ \to D_{s1}^+ D^0\) \((D_{s1}^+ \to D_s^+ \pi^0)\) | 2.26 ± 0.47 ± 0.43 | —                  | —       |
| \(B^0 \to D_{s1}^+ D^-\) \((D_{s1}^+ \to D_s^+ \pi^0)\) | —                  | 0.13 ± 0.20 ± 0.14 | —       |
| \(B^+ \to D_{s1}^+ D^0\) \((D_{s1}^+ \to D_s^+ \pi^0)\) | —                  | 0.31 ± 0.27 ± 0.23 | —       |
Table 5: Several pre-2003 (A) and post-2003 (B) quark model determinations of the masses of $p$-wave $c\bar{s}$ ($c\bar{q}$) mesons.

(A)

|                  | $D^{*}_{s0}(D^{*}_{0})$ (GeV) | $1^{+}_{L} c\bar{s}$ ($c\bar{q}$) (GeV) | $1^{-}_{L} c\bar{s}$ ($c\bar{q}$) (GeV) | $D^{*}_{s2}(D^{*}_{2})$ GeV | Ref. |
|------------------|-------------------------------|----------------------------------------|----------------------------------------|-----------------------------|------|
|                  | 2.48 (2.40)                   | 2.55 (2.46)                            | 2.55 (2.47)                            | 2.59 (2.50)                 | [17] |
|                  | 2.38 (2.27)                   | 2.51 (2.40)                            | 2.52 (2.41)                            | 2.58 (2.46)                 | [18] |
|                  | 2.388 (2.279)                 | 2.521 (2.407)                          | 2.536 (2.421)                          | 2.573 (2.465)               | [19] |
|                  | 2.508 (2.438)                 | 2.515 (2.414)                          | 2.569 (2.501)                          | 2.560 (2.459)               | [20] |
|                  | 2.455 (2.341)                 | 2.502 (2.389)                          | 2.522 (2.407)                          | 2.586 (2.477)               | [21] |
|                  | 2.487 (2.377)                 | 2.605 (2.490)                          | 2.535 (2.417)                          | 2.581 (2.460)               | [22] |

(B)

|                  | $D^{*}_{s0}(D^{*}_{0})$ (GeV) | $D^{*}_{s1}(D^{*}_{1})$ (GeV) | Ref. |
|------------------|-------------------------------|-------------------------------|------|
|                  | 2.408 (2.400)                 |                               | [24] |
|                  | 2.357 (2.20)                  | 2.453 (2.35)                  | [25] |
|                  |                               | 2.442 ± 0.033                | [26] |
|                  | 2.288 (2.2)                   | 2.465 (2.383)                 | [27] |
|                  |                               | 2.446                         | [28] |

non-strange mesons were always predicted to be lighter than the strange one, with typical mass splitting of 70 – 100 MeV in case of $0^{+}$ mesons.

The discrepancy essentially between the observed mass and width of $D^{*}_{sJ}(2317)$ and the expectation has prompted a number of analyses aimed either at refining the results to corroborate the $c\bar{s}$ interpretation, or at providing interpretations in different frameworks.

Results of new mass determinations (or elaborations of previous analyses) are presented in Table 5 (B). For example, in a quark model with short-distance Coulomb and long-distance scalar potential, with spin-spin, spin-orbit and tensor terms, using as an input the experimental values $M_{D^{*}_{2}} = 2.459$ GeV, $M_{D^{*}_{1}} = 2.422$ GeV and $M_{D^{*}_{0}} = 2.290$ GeV, a prediction for $M_{D^{*}_{1}}$ has been obtained for the non-strange axial resonance [24]. In the $c\bar{s}$ case, using $M_{D^{*}_{2}} = 2.572$ GeV, $M_{D^{*}_{1}} = 2.536$ GeV, together with $M_{D^{*}_{0}} = 2.317$ GeV, and choosing between two possible solutions the one corresponding to a narrow $D_{sJ}(2536)$, a mass close to that of $D_{sJ}(2460)$ is obtained. Other determinations are based on the Cornell potential [25], but the masses of non-strange resonances are not reproduced. Using a further version of the constituent quark model, the spin averaged mass
Table 6: Lattice results for the mass difference (in MeV) between the doublets $s^P_\ell = \frac{1}{2}^+$ and $\frac{1}{2}^-$. The uncertainty is quoted in parentheses.

| Meson $n_f = 0$ | $n_f = 2$ |
|-----------------|----------|
| static NRQCD relativ. static |
| $c\bar{s}$ | 384 (50) 465(50) 495(25) 468(43) |
| $c\bar{d}$ | 299(114) — 465(35) 472(85) |

of $(D_{s0}, D_{s1}')$ has been derived: $\frac{M_{D_{s0}} + 3M_{D_{s1}'}}{4} = 2411 \pm 25$ MeV [26], which gives the mass of $D_{s1}'$ if the $0^+$ state is identified with $D_{sJ}^*(2317)$. The old fashioned MIT bag model has been reconsidered [27]. In general, adjustments of input parameters produce a posteriori results in better agreement with observation. An exception is a model where, using Coulomb+linear potential and considering lowest order relativistic corrections, the two newly observed $c\bar{s}$ states do not fit with the theoretical results, thus suggesting a different interpretation [28].

However, even in cases where updated results more favourably can be compared to data, it is unclear why previous determinations resulted to be incorrect, and what is the new physics information that must be encoded in models to reproduce the experimental measurements.

3.2 Masses of $(0^+, 1^+)$ $c\bar{s}$ ($c\bar{q}$) mesons: non perturbative methods at work

Since quark models suffer of not having a direct relation with the QCD structure of strong interactions, one could look at more fundamental approaches, namely lattice QCD and QCD sum rules.

Lattice results for the heavy meson spectrum are quoted in [29]. Particularly interesting are the determinations of the mass difference between the doublets $s^P_\ell = \frac{1}{2}^+$ and $\frac{1}{2}^-$, obtained in the static limit, either in quenched approximation [30] or for $n_f = 2$ [31]. In quenched approximation, finite charm quark mass effects were also estimated, either using NRQCD (to order $1/m^2$ [32] and $1/m^3$ [33]) or relativistic charm quarks [34], see Table 6. Relativistic effects increase the mass splitting with respect to the static case. If the effect persists in unquenched determinations, one would obtain a mass splitting between positive and negative parity doublets $\Delta M \simeq 600$ MeV, giving $M_{D_{s0}^*} = 2.57 \pm 0.11$ GeV. On this basis, it has been argued that lattice predictions are inconsistent with the
simple $q\bar{q}$ interpretation for $D_{sJ}^*(2317)$ [29]. In a different analysis, the continuum limit in quenched QCD is considered [35], and the mass splittings $1^+ - 1^-$ and $0^+ - 0^-$ turn out to be equal: $M_{D_{s0}^*} - M_{D_s} = 389 \pm 47$ MeV ($M_{D_{s0}^*} - M_{D_s} = 435 \pm 57$ MeV using different input parameters), compatible with the experimental values. Now the conclusion is that there is no discrepancy between lattice predictions and experiment, and no need to invoke other interpretations for $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$.

The absence of definite consensus about $D_{sJ}^*(2317)$ can be interpreted as a difficulty in reliably controlling the uncertainties in mass determinations by lattice QCD, at the level requested by the available spectroscopy, and an improvement in the systematics seems to be necessary to eventually reconcile the different conclusions.

As for QCD sum rules, the binding energies in eq.(1) were estimated: $\bar{\Lambda} = 0.5 \pm 0.1$ GeV [36] and $\bar{\Lambda}^+ = 1.0 \pm 0.1$ GeV [37] for negative and positive parity low-lying doublets, respectively. From $M_{0^+} - M_{0^-} \simeq \bar{\Lambda}^+ - \bar{\Lambda} + O\left(\frac{1}{m_Q}\right)$, neglecting $\frac{1}{m_Q}$ terms, one obtains: $M_{D_{s0}^*} - M_{D_s} = 500 \pm 140$ MeV (versus the experimental data in Table 3). A new QCD sum rule analysis has provided $\bar{\Lambda}^+ = 0.86 \pm 0.1$ GeV and, including $\frac{1}{m_Q}$ corrections, $M_{D_{s0}^*} = 2.42 \pm 0.13$ GeV [38]. Therefore, QCD sum results seem compatible with the identification of $D_{sJ}^*(2317)$ with the scalar $c\bar{s}$ meson, even though the accuracy of the mass determinations is not high. As discussed in Section 4, the calculation of the strong coupling governing the two-body decays of $D_{s0}^*$, $D_{s1}^*$ and of their non-strange partners is useful for the interpretation.

### 3.3 The chiral partners $(0^-, 1^-)\rightarrow(0^+, 1^+)$

It was suggested that a consistent implementation of chiral symmetry breaking requires chiral partners of pseudoscalar and vector states [39], an idea reconsidered in refs. [40, 41]. Heavy-light systems should appear as parity-doubled, i.e. in pairs differing for parity and transforming according to a linear representation of chiral symmetry. In particular, the doublet composed by the states having $J^P = (0^+, 1^+)$ can be considered as the chiral partner of that with $J^P = (0^-, 1^-)$ [40].

It is possible to build an effective lagrangian for those two doublets and their interactions with light pseudoscalar mesons, based on both heavy quark and chiral symmetries. A consequence is that the coupling $g_\pi$ governing the $(0^+, 1^+) \rightarrow (0^-, 1^-) P$ transitions, $P$ being a generic light pseudoscalar meson, obeys a Goldberger-Treiman relation:

$$g_\pi = \frac{\Delta M}{f_\pi}$$  \hspace{1cm} (2)
with $\Delta M = M(0^+) - M(0^-)$. This relation is analogous to the one involving the pion-nucleon coupling constant, $g_{NN\pi} = \frac{m_N}{f_\pi}$. Since in heavy-light system there is a single light constituent quark, while the nucleon contains three, one could expect $g_\pi \simeq \frac{g_{NN\pi}}{3}$ and $\Delta M \simeq \frac{m_N}{3}$. Identifying the BaBar state with the $0^+ c\bar{s}$ state, one has: $\Delta M \simeq 349$ MeV and $g_\pi \simeq 3.73$.

In this scheme, by suitably choosing the parameters entering in the terms of the lagrangian responsible of the hyperfine splitting in each multiplet, one can obtain $M_{D_{s0}^*} - M_{D_{s0}^*} = M_{D_{s1}'} - M_{D_{s1}'}$, in agreement with the observation. One would also obtain the relation $M_{D_{s0}^*} - M_{D} = M_{D^*} - M_{D_{s0}^*}$, but the experimental results in Table 3 are only marginally compatible with it.

It is worth mentioning that, since chiral partners are split by dynamically generated quark mass, they could give information on the chiral symmetry property of the medium in which they are observed. In particular, the mass splitting between chiral partners is expected to vanish in hot matter when the chiral phase transition is approached [41].

A test of this picture relies on computing the decay rates of $D_{sJ}(2317)$ and $D_{sJ}(2460)$, as discussed in Section 4.

### 3.4 Unitarized chiral models

A different approach to interpret the new $c\bar{s}$ states is based on the investigation of the singularities in the s-wave meson-meson scattering amplitude. An extension to the charm sector of a unitarized quark model applied to light scalar mesons is analyzed in [42]. The generalization is obtained replacing one of the effective quark mass parameters used in light meson systems by the mass of the charm quark. Including the coupling to the OZI allowed DK channel, a scalar meson is found with mass 2.28 GeV. Analogously, in s-wave $D\pi$ amplitude a scalar state with mass 2.030 GeV is found. Conventional $c\bar{q}$ states are found with higher mass: $M_{D_{s0}^*} \simeq 2.64$ GeV and $M_{D_{s0}^*} \simeq 2.79$ GeV, both with $\Gamma \simeq 200$ MeV [42].

By a similar approach, heavy-light $J^P = 0^+, 1^+$ mesons have been studied using a chiral SU(3) lagrangian involving heavy-light $0^-, 1^-$ fields transforming non linearly under the chiral SU(3) group. Charmed mesons with $J^P = 0^+, 1^+$ forming antitriplet and sextet representations of the SU(3) group are predicted; on the contrary, the linear realization of the chiral symmetry leads to anti-triplet states only [43]. The masses of the states to be identified with $D_{sJ}(2317)$ and $D_{sJ}(2460)$ turn out to be 2303 MeV and 2552 MeV, respectively, and the existence of several new mesons is predicted, the experimental evidence
of which is missing. Including subleading terms in the chiral expansion and adjusting three new input parameters to reproduce the observed spectrum, the values 2352 MeV and 2416 MeV for the $0^+$ and the $1^+$ state are obtained together with the prediction of a scalar $I = 1/2, S = 0$ state with mass 2389 MeV [44].

However, no evidence has been collected, so far, of the new predicted states enriching the open charm spectroscopy.

3.5 Are $D_{sJ}(2317), D_{sJ}(2460)$ unconventional states?

It has been also considered the possibility of a sizeable four-quark component in $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$. Four-quark states could be baryonium-like or molecular-like, if they result from bound states of quarks or of hadrons, respectively, and examples of the second kind of states are the often discussed $f_0(980)$ and $a_0(980)$ when interpreted as $K\bar{K}$ molecules.

A possible baryonium structure for $D_{sJ}^*(2317)$ is $c\bar{s}q\bar{q}$ with $I = 0$ ($q=u,d$); in that case the observed transition to $D_s^+\pi^0$ would be isospin violating, explaining the observed narrowness. On the other hand, $c\bar{s}q\bar{q}$ with $I = 1$, predicted with nearby mass, would be broad [45].

In a molecular interpretation, $D_{sJ}^*(2317)$ could be viewed as a $DK$ molecule, an interpretation supported by the mass very close to the DK threshold [46, 47, 48]. Although the preferred assignment for a DK molecule would be $I = 0$, it is also possible that a mixing occurs with a $I = 1, I_z = 0$ molecule, analogously to what is supposed for $f_0(980)$ and $a_0(980)$. However, the existence of such a state would imply isospin partners in the $D_s^+\pi^\pm$ invariant mass distributions: CDF Collaboration has looked for such states without finding any evidence [13]. The corresponding interpretation for $D_{sJ}(2460)$, would be a $D^*K$ molecule.

The mechanism for producing a molecular state could be a strong flavour-singlet attraction between a pion and a $c\bar{s}$ meson, leading to the capture of the pion by the latter [49]. Numerical estimates are in favour of a molecular state with mass close to 2317 MeV, and of two other scalar resonances ($D_0^*, D_{s0}^*$) with masses and widths of: $M_{D_0^*} = 2.15-2.30$ GeV, $\Gamma(D_0^*) = 7-24$ MeV; $M_{D_{s0}^*} = 2.44-2.55$ GeV, $\Gamma(D_{s0}^*) = 17-42$ MeV, respectively, states that still need to be experimentally confirmed.

It is interesting to mention that a measurement of the meson elastic form factor could, at least in principle, allow to distinguish a two-quark state from a four-quark state, due to the different asymptotic behavior in the space-like momentum transfer dictated by QCD counting rules, namely $1/Q^2$ for $q\bar{q}$ versus $1/Q^6$ in the four-quark picture. However, the
practical feasibility of such a measurement is difficult to assess.

It has also been considered the possibility that a mixing occurs between a $c\bar{s}$ state and a four-quark state, resulting in two mesons, one of which has mass below the $DK$ threshold [50]. For the masses before the mixing, it is assumed a value above the $DK$ threshold for the four-quark state, and of 2.48 GeV for the $c\bar{s}$ state. For several values of the parameters $(\tilde{m}_0, \theta)=$ (mass of the four quark state, mixing angle) one of the two mixed states turns out of mass $\simeq 2317$ MeV. For example, for $\tilde{m}_0$ just above the $DK$ threshold and $\theta = 28.8^\circ$, a mass of 2319.4 MeV is obtained for the lower mixed state. The four-quark states could decay in doubly charged final states, as $D^+K^+$. In such scenario the radiative transition $c\bar{s}q\bar{q} \rightarrow D^*_s\gamma$ would be suppressed by $\sin \theta$, explaining the non observation of such a decay mode. For the $1^+$ state the mixing between the $c\bar{s}$ state and a $D^*K$ state should be analogously considered.

Finally, the possibility that the $D^*_{sJ}(2317)$ is an exotic particle has been discussed. Strong decays of a non exotic $\bar{q}q$ state are suppressed due to the necessity of creating a second $\bar{q}q$ pair, while an exotic state simply falls apart into its constituent non-exotic hadrons without any suppression, hence they should be broad. If $D^*_{sJ}(2317)$ and $D_{sJ}(2460)$ were exotic states, they would be a special case of narrow exotics. A suggestion [51] considers $D^*_{sJ}(2317)$ a superposition of three components:

$$|D^*_{sJ}(2317)\rangle = \alpha |c\bar{s}\rangle + \beta \left| c\bar{s} \left( \frac{\bar{u}u + \bar{d}d}{\sqrt{2}} \right) \right\rangle + \gamma \left| \frac{(K^+D^0 + K^0D^+)}{\sqrt{2}} \right\rangle$$

(3)

giving different contributions when probed at different length scales. At short scales, the pure $c\bar{s}$ component would dominate, while at an intermediate and large scales the second component and the $DK$ bound state would prevail.

To conclude the Section, one can remark that a common feature of descriptions based on a multiquark content of the new resonances is the requirement of additional states in the spectrum, with their own decays and typical widths. The study of the decay modes is an important tool to discriminate among different descriptions, as we discuss below.

4 Decays of $D_0^*$, $D_1'$, and $D^*_{sJ}(2317)$, $D_{sJ}(2460)$.

In order to understand the structure of the newly observed charmed resonances, in particular the ones with strangeness, it is necessary to analyze their decays modes and their branching fractions. The different interpretations are indeed constrained to provide predictions in agreement with the experimental observations.
Considering the resonances as ordinary quark-antiquark states, one can use the heavy quark theory together with chiral symmetry to describe low energy interactions between heavy mesons and pseudoscalar light mesons. A lagrangian invariant under heavy spin-flavour transformations and under chiral transformations for the pseudo Goldstone K, π and η bosons \[52\]

\[
\mathcal{L} = igTr\{P_a H_b \gamma_\mu \gamma_5 A^\mu_{ba}\} + \{ihTr\{S_b \gamma_\mu \gamma_5 A^\mu_{ba}\} + h.c.\} \tag{4}
\]

involves the fields H and S representing \(1^-\) and \(1^+\) doublets, respectively:

\[
H_a = \frac{1+ \beta}{2} [P_a \gamma_\mu - P_\mu a] \quad , \quad S_a = \frac{1+ \beta}{2} [P^a_\mu \gamma_\mu - P_{0a}] \tag{5}
\]

where \(v\) is the meson four-velocity and \(a\) is a light quark flavour index. Light meson fields are included in Lagrangian (4) through

\[
A^\mu_{\alpha} = \frac{1}{2} (\xi^\dagger \partial^\mu \xi - \xi \partial^\mu \xi^\dagger), \quad \xi = exp(\frac{\sqrt{2} \tilde{\pi}}{f})
\]

with \(f \simeq f_\pi\). The relevant coupling in the strong decays of \(s_{P}^{F} = \frac{1}{2}^{+}\) resonances is \(h\).

QCD sum rule analyses, based on both the light-cone expansion, both on the short-distance expansion in the soft pion limit, allowed to estimate this coupling: \(h \simeq -0.6 \ [53]\) and the leading heavy quark mass corrections. Using this value, together with the meson masses in Table 1, one obtains \(\Gamma(D_0^{*0} \rightarrow D^+\pi^-) = 260 \pm 54\) MeV and \(\Gamma(D_1^{*} \rightarrow D^{++}\pi^-) = 160 \pm 25\) MeV. If the modes with one pion essentially saturate the decay widths, one predicts \(\Gamma(D_0^{*0}) = 390 \pm 80\) MeV and \(\Gamma(D_1^{*}) = 240 \pm 40\) MeV, consistent with the measurements in Table 1.

One can look at the analogous predictions for the strange states. However, in this case the corresponding (isospin conserving) decays cannot occur, since the masses of \(D_s^{*J}(2317)\) and \(D_{sJ}(2460)\) are below the \(DK\) and \(D^*K\) thresholds, respectively. Therefore, one has to invoke a mechanism inducing isospin breaking \(D_{s0}^{*} \rightarrow D_s\pi_0\) and \(D_{s1}^{*} \rightarrow D_s\pi_0\) decays with the emission of a neutral pion. The \(\eta - \pi^0\) mixing which appears in the light meson chiral lagrangian when the light quark masses are different from zero:

\[
\mathcal{L}_m = \frac{\bar{\mu}f^2}{4} Tr \left[ \xi m_q \xi + \xi^\dagger m_q \xi^\dagger \right], \tag{7}
\]

\(m_q\) being the light quark mass matrix, can provide such a mechanism as in \(D_s^{*} \rightarrow D_s\pi^0\) transitions \[54\]; indeed, it has been applied to analyze \(D_{sJ}(2317) \rightarrow D_s\pi^0\) and
$D_{sJ}(2460) \rightarrow D_s^*\pi^0$ [40, 55, 56, 25, 57]. The model is based on the decay chain

$$D_{sJ}^*(2317) \rightarrow D_s\eta \rightarrow D_s\pi^0 \quad , \quad D_{sJ}(2460) \rightarrow D_s^*\eta \rightarrow D_s^*\pi^0$$

where the virtual $\eta$ is mixed to $\pi^0$. In the heavy quark limit the couplings of positive and negative parity states to pions and Kaons are all related to the same coupling $h$, and therefore the same value used for the analysis of the broad mesons can be used. The resulting amplitude depends on an isospin violating factor, the difference $m_u - m_d$ between up and down quark masses:

$$\Gamma (D_{s0}^* \rightarrow D_s\pi^0) = \frac{1}{16\pi} \frac{h^2}{f^2} \frac{M_{D_s}}{M_{D_{s0}}^*} \left( m_{\pi^0}^2 + |\vec{q}|^2 \right) |\vec{q}| \left( \frac{m_u - m_d}{m_u + m_d} - m_s \right)^2$$

($\vec{q}$ is the pion three-momentum in the $D_{s0}^*$ rest frame), which shows why the state is narrow. The amplitude $D_{s1}^* \rightarrow D_s^*\pi^0$ is similar. The resulting numerical predictions, collected in Table 7, are compatible with hadronic decay widths of a few (or several) KeV, well below the resolution of the experiments that have observed the mesons. If, instead of using the computed value of the coupling, one uses existing information on other modes, such as $h_c \rightarrow J/\psi\pi_0$ [55] or $\psi(2S) \rightarrow J/\psi\pi^0$, $\psi(2S) \rightarrow J/\psi\eta$, or $D^+_0 \rightarrow D^\pm\pi^0$ [57], one predicts again narrow hadronic widths. Measurement of hadronic widths as in Table 7 is not an easy task; however, comparison of radiative and hadronic decays can be used to get further information.

To analyze radiative decays, the electric dipole matrix elements governing the transitions $D_{sJ}^*(2317) \rightarrow D_s^*\gamma$ and $D_{sJ}(2460) \rightarrow D_s^{(*)}\gamma$ must be determined, and quark model [40, 55], VMD [56] and relations with radiative decays of other mesons have been used. In particular, if Dominance of the Vector $\phi$ Meson is assumed as in [56], one can use the strong coupling $g_{D_s^*D_s^*\phi}$ derived through a low energy lagrangian formalism with the heavy fields coupled to light vector mesons [58]. The results collected in Table 7 present the common feature of predicting a suppressed radiative mode of the scalar state with respect to the hadronic mode. Such a suppression is observed experimentally; however, since the radiative mode is not forbidden, observation at the tipical level predicted in Table 7 is expected, otherwise different interpretations have to be invoked. For the axial-vector state $D_{sJ}(2460)$, the branching fraction of the radiative decay into $D_s\gamma$ has been measured by Belle Collaboration. It is interesting to compare the results based on $q\bar{q}$ interpretation with those coming from the view-point of considering $D_{sJ}^*(2317)$ as a four-quark state [59]. A scalar four-quark state might be lighter than a scalar $q\bar{q}$ state with $\ell = 1$ because of the absence of the orbital angular momentum barrier. Multiplets of the kind $c\bar{q}_1 q_2\bar{q}_3$
with \( q = u, d, s \) can be built and the isosinglet \( D^*_s0 \) can be identified with \( D^*_{sJ}(2317) \). Assuming that \( D^*_s0 \rightarrow D_s \pi^0 \) proceeds through \( D_{sJ} \rightarrow D_s \eta(\eta') \), followed by \( \eta(\eta') - \pi^0 \) mixing, invoking \( \eta - \eta' \) mixing, and using for the \( D^*_s0D_s\eta \) coupling either the vertex \( kK\pi \) and SU(4) symmetry, or QCD sum rules [53], a prediction of a larger hadronic width than in the standard interpretation is obtained.

Table 7: Estimated width (KeV) of \( D^*_s0 \) and \( D'_s1 \), using the \( cs \) picture (first five columns) or a composite picture (last two columns). The results for \( D'_s1 \) in column [56] are new. The results in column [57] are obtained using \( D^*_0 \) decay width as measured by Belle (Focus).

| Decay mode          | [40] | [55] | [56] | [25]      | [57]        | [59]   | [61]       |
|---------------------|------|------|------|-----------|-------------|--------|------------|
| \( D^*_s0 \rightarrow D_s \pi^0 \) | 21.5 | 7 ± 1 | 16   | 129 ± 43(109 ± 16) | 10-100 | 155 ± 70  |
| \( D^*_s0 \rightarrow D^*_s \gamma \) | 1.74 | 0.85 ± 0.05 | 0.2  | ≤ 1.4     | 21        |        |            |
| \( D'_s1 \rightarrow D_s \pi^0 \) | 21.5 | 7 ± 1 | 32   | 187 ± 73(7.4 ± 2.3) | 155 ± 70 |        |            |
| \( D'_s1 \rightarrow D_s \gamma \) | 5.08 | 6.2  | 3.3 ± 0.6 | ≤ 5       |           |        |            |
| \( D'_s1 \rightarrow D^*_s \gamma \) | 4.66 | 5.5  | 1.5  |           | 93        |        |            |

Experimental information concerning ratios of radiative to hadronic decay rates can be obtained indirectly, using the branching fractions of B decays. Although such an estimate is admittedly uncertain, due to the correlations between various measurements of B decay rates into positive parity charmed mesons, nevertheless it can help to get hints on the role of radiative modes of \( D^*_s0 \), \( D'_s1 \) versus the hadronic ones. In Table 8 we have estimated ratios of branching fractions using B decay data collected in Table 4, neglecting any correlation among experimental measurements. The overall comparison of measurements with predictions seems to support the description of the charmed resonances as ordinary \( q\bar{q} \) mesons.

5 The case of beauty

In the simple \( q\bar{q} \) picture, predictions for the mass of the \( 0^+, 1^+ b\bar{s}, b\bar{q} \) states can be obtained using data in the charm sector together with eq.(1). They are collected in Table 9. The main feature of such estimates is that the \( b\bar{s} \) mesons are predicted below the \( BK \) and \( B^*K \) thresholds (with the exception of [29]); consequently, narrow resonances in \( B_s \pi^0 \) and \( B^*_s \pi^0 \) mass distributions are expected to be observed at the hadron colliders.
Table 8: Decay fractions of $c\bar{s}\frac{1}{2}^+$ states. The values labelled by ($\star$) are obtained from B decay data in Table 4 and from [15]. The other ones result from Belle [10] and Cleo [11] continuum analyses. Few predictions are also reported.

|                    | Belle                  | BaBar      | Cleo | Ref. |
|--------------------|------------------------|------------|------|------|
| $\Gamma(B_{s0}^+\to D_s^{*+}\gamma)$ | ($\star$) $0.29\pm0.26\ (<0.9)$ | $<0.18$ | $<0.059$ | 0.1 0.08 0.2 |
| $\Gamma(B_{s0}^+\to D_s\pi^0)$          |                         | $--$      | $<0.49$ | 0.5 0.24 0.6 |
| $\Gamma(B_{s1}^+\to D_s\gamma)$         | ($\star$) $0.38\pm0.11\pm0.04$ | $0.55\pm0.13\pm0.08$ | ($\star$) $0.44\pm0.17$ | $<0.16$ 0.2 0.2 0.6 |
| $\Gamma(B_{s1}^+\to D_{s1}\pi^0)$        |                         | $<0.31$   | $<0.16$ | 0.4 0.9 0.9 |

Table 9: Recent predictions for the masses of $p$-wave $b\bar{s}$ ($b\bar{q}$) mesons with $s_l^p = \frac{1}{2}^+$.

| $B_{s0}^*$ ($B_0'$) (MeV) | $B_{s1}^*$ ($B_1'$) (MeV) | Ref. |
|--------------------------|--------------------------|------|
| $5710\pm25$              | $5770\pm25$              | [26] |
| $5654\ (5576)$           | $5716\ (5640)$           | [27] |
| $5837\pm43\pm22$         | $5803\pm31$              | [62] |
| $5752\pm31$              |                          |      |
| $5718\pm35$              | $5765\pm35$              | [40] |
| $5721\ (5710 - 5736)$    | $5762\ (5744 - 5761)$    | this paper |

6 Conclusions

We have briefly reviewed the experimental status of recently observed positive parity charmed states, as well as several theoretical analyses devoted to determine their masses and decay rates and to interpret the measurements. In particular, in the case of charmed-strange states, we have described various interpretations proposed for their structure.

At present, we believe that there is no compelling evidence that a non-standard scenario, different from simple $q\bar{q}$, is required to explain the nature of $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$, a conclusion mainly based on the analysis of the decay modes.

Nevertheless, unanswered questions remain, namely about the near equality of the masses of strange and non-strange states, as well as the difference between the mass splittings between excited and low-lying $c\bar{q}$ and $c\bar{s}$ states which is not theoretically re-
produced, as shown by a calculation of chiral corrections to the meson masses [63]. The missing evidence of the radiative mode $D_{sJ}^*(2317) \rightarrow D_s^* \gamma$ is another puzzling aspect deserving further experimental investigations.

To gain further information on these states, one could at look at two-body $B$ decays into $D_{sJ}^*(2317)$ or $D_{sJ}(2460)$ [64]-[69]. As a matter of fact, the modes $B \rightarrow D_{sJ} M$ decays, with $M = D, \pi, K$, can further discriminate between quark-antiquark and multiquark scenarios. In the $\bar{q}q$ case the $B \rightarrow D_{sJ} M$ branching ratios are expected to be of the same order of magnitude as $B \rightarrow D_s^{(*)} M$, since the $D_{sJ}$ meson decay constants are expected to be close to those of low-lying $D_s^{(*)}$ mesons. On the other hand, in multiquark case the decay amplitude would receive additional contributions from hard scattering of all the four valence quarks, and the branching fractions would be suppressed by the coupling constant and by inverse powers of heavy meson masses. A dedicated analysis of a complete set of data, such as that reported in Table 4, is required in this context. A different test is based on $B_s \rightarrow D_{sJ} M$ transitions ($M = \pi, \rho, K$, etc.) that are not currently accessible at $B$ factories but can be investigated at the hadron machines [67]. The ratios of branching fractions involving strange and non-strange positive parity charm resonances:

$$T_{D_{sJ}^*(2317)} = \frac{\mathcal{B}(B_s \rightarrow D_{sJ}^*(2317) M)}{\mathcal{B}(B_d \rightarrow D_s^0 M)}, \quad T_{D_{sJ}(2460)} = \frac{\mathcal{B}(B_s \rightarrow D_{sJ}(2460) M)}{\mathcal{B}(B_d \rightarrow D_s^0 M)} \quad (10)$$

are equal to one in the heavy quark and SU(3) limit, but deviate from that in composite models for the two $D_{sJ}$. Finally, looking at decays of higher charmonium states, e.g. $\psi(4415) \rightarrow D_s^* D_{sJ}(2317)$, one can further investigate the charmed resonances [70].

A detailed analysis of properties and decays of $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$, together with their non-strange partners, undoubtly has become a part of the present and future Physics programme of many currently operating experiments, for further enriching our knowledge of flavour Physics and, in the end, of QCD mechanisms of confinement.

Acknowledgments. One of us (PC) thanks CPhT, École Polytechnique, where this work was completed and, in particular, Prof. T.N. Pham for discussions. We acknowledge partial support from the EC Contract No. HPRN-CT-2002-00311 (EURIDICE).
References

[1] For a recent review on pentaquarks see: S-H. Zhu, hep-ph/0406204 and references therein.

[2] Recent results on heavy quarkonium are described in: T. Skwarnicki, *Int. J. Mod. Phys.* A19, 1030 (2004) and in references therein.

[3] M. Mattson et al. [SELEX Collaboration], *Phys. Rev. Lett.* 89, 112001 (2002).

[4] For reviews see: M. Neubert, *Phys. Rep.* 245, 259 (1994); F. De Fazio, in ”At the Frontier of Particle Physics - Handbook of QCD”, edited by M. A. Shifman, (World Scientific, 2001), page 1671.

[5] S. Eidelman et al. [Particle Data Group Collaboration], *Phys. Lett.* B592, 1 (2004).

[6] S. Anderson et al. [CLEO Collaboration], *Nucl. Phys.* A663, 647 (2000).

[7] K. Abe et al. [Belle Collaboration], arXiv:hep-ex/0307021.

[8] J. M. Link et al. [FOCUS Collaboration], *Phys. Lett.* B586, 11 (2004).

[9] B. Aubert et al. [BABAR Collaboration], *Phys. Rev. Lett.* 90, 242001 (2003).

[10] Y. Mikami et al. [Belle Collaboration], *Phys. Rev. Lett.* 92, 012002 (2004).

[11] D. Besson et al. [CLEO Collaboration], *Phys. Rev.* D68, 032002 (2003).

[12] E. W. Vaandering [FOCUS Collaboration], arXiv:hep-ex/0406044.

[13] F. C. Porter [BABAR Collaboration], arXiv:hep-ex/0312019; A. Pompili [BABAR Collaboration], Proceedings of QCD@Work 2003, International Workshop on QCD: Theory and Experiment, Conversano (Italy) 2003, P. Colangelo, F. De Fazio, R.A. Fini, E. Nappi, G. Nardulli editors, eConf C030614 (2003) 027.

[14] B. Aubert et al. [BABAR Collaboration], *Phys. Rev.* D69, 031101 (2004).

[15] P. Krokovny et al. [Belle Collaboration], *Phys. Rev. Lett.* 91, 262002 (2003); P. Krokovny [Belle Collaboration], arXiv:hep-ex/0310053.

[16] G. Calderini [BABAR Collaboration], arXiv:hep-ex/0405081.

[17] S. Godfrey and R. Kokoski, *Phys. Rev.* D43, 1679 (1991).
[18] J. Zeng, J. W. Van Orden and W. Roberts, Phys. Rev. D52, 5229 (1995).

[19] S. N. Gupta and J. M. Johnson, Phys. Rev. D51, 168 (1995).

[20] D. Ebert, V. O. Galkin and R. N. Faustov, Phys. Rev. D57, 5663 (1998) [Erratum ibid. D59, 019902 (1999)].

[21] T. A. Lahde, C. J. Nyfalt and D. O. Riska, Nucl. Phys. A674, 141 (2000).

[22] M. Di Pierro and E. Eichten, Phys. Rev. D64, 114004 (2001).

[23] J. Charles, A. Le Yaouanc, L. Oliver, O. Pene and J. C. Raynal, Phys. Lett. B425, 375 (1998) [Erratum ibid. B433, 441 (1998)].

[24] R. N. Cahn and J. D. Jackson, Phys. Rev. D68, 037502 (2003).

[25] Fayyazuddin and Riazuddin, Phys. Rev. D69, 114008 (2004).

[26] A. Deandrea, G. Nardulli and A. D. Polosa, Phys. Rev. D68, 097501 (2003).

[27] M. Sadzikowski, Phys. Lett. B579, 39 (2004).

[28] W. Lucha and F. F. Schoberl, Mod. Phys. Lett. A18, 2837 (2003).

[29] G. S. Bali, Phys. Rev. D68, 07150 (2003).

[30] C. Michael and J. Peisa [UKQCD Collaboration], Phys. Rev. D58, 034506 (1998).

[31] G. S. Bali et al. [SESAM Collaboration], Phys. Rev. D62, 054503 (2000); B. Bolder et al. [SESAM Collaboration], Phys. Rev. D63, 074504 (2001).

[32] J. Hein et al., Phys. Rev. D62, 074503 (2000).

[33] R. Lewis and R. M. Woloshyn, Phys. Rev. D62, 114507 (2000).

[34] P. Boyle [UKQCD Collaboration], Nucl. Phys. Proc. Suppl. 63, 314 (1998); Nucl. Phys. Proc. Suppl. 53, 398 (1997).

[35] A. Dougall, R. D. Kenway, C. M. Maynard and C. McNeile [UKQCD Collaboration], Phys. Lett. B569, 41 (2003).

[36] M. Neubert, Phys. Rev. D45, 2451 (1992).

[37] P. Colangelo, F. De Fazio and N. Paver, Phys. Rev. D58, 116005 (1998).
[38] Y. B. Dai, C. S. Huang, C. Liu and S. L. Zhu, Phys. Rev. D68, 114011 (2003).

[39] M. A. Nowak, M. Rho and I. Zahed, Phys. Rev. D48, 4370 (1993); W. A. Bardeen and C. T. Hill, Phys. Rev. D49, 409 (1994).

[40] W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D68, 054024 (2003).

[41] M. A. Nowak, M. Rho and I. Zahed, arXiv:hep-ph/0307102.

[42] E. van Beveren and G. Rupp, Phys. Rev. Lett. 91, 012003 (2003).

[43] E. E. Kolomeitsev and M. F. M. Lutz, Phys. Lett. B582, 39 (2004).

[44] J. Hofmann and M. F. M. Lutz, Nucl. Phys. A733, 142 (2004).

[45] K. Terasaki, Phys. Rev. D68, 01150 (2003).

[46] T. Barnes, F. E. Close and H. J. Lipkin, Phys. Rev. D68, 054006 (2003).

[47] H. J. Lipkin, Phys. Lett. B580, 50 (2004).

[48] P. Bicudo, arXiv:hep-ph/0401106.

[49] A. P. Szczepaniak, Phys. Lett. B567, 23 (2003).

[50] T. E. Browder, S. Pakvasa and A. A. Petrov, Phys. Lett. B578, 365 (2004).

[51] S. Nussinov, arXiv:hep-ph/0306187.

[52] M.B. Wise, Phys. Rev. D45, R2188 (1992); G.Burdman and J.F.Donoghue, Phys. Lett. B280, 287 (1992); P.Cho, Phys. Lett. B285, 145 (1992); H.-Y.Cheng, C.-Y.Cheung, G.-L.Lin, Y.C.Lin and H.-L.Yu, Phys. Rev. D46, 1148 (1992). R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio and G. Nardulli, Phys. Lett. B292, 371 (1992).

[53] P. Colangelo, F. De Fazio, G. Nardulli, N. Di Bartolomeo and R. Gatto, Phys. Rev. D52, 6422 (1995); P. Colangelo and F. De Fazio, Eur. Phys. J. C4, 503 (1998).

[54] P. L. Cho and M. B. Wise, Phys. Rev. D49, 6228 (1994).

[55] S. Godfrey, Phys. Lett. B568, 254 (2003).

[56] P. Colangelo and F. De Fazio, Phys. Lett. B570, 180 (2003).
[57] Y. I. Azimov and K. Goeke, arXiv:hep-ph/0403082.

[58] R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio and G. Nar- dulli, Phys. Lett. B299, 139 (1993).

[59] H. Y. Cheng and W. S. Hou, Phys. Lett. B566, 193 (2003).

[60] T. W. Ruijgrok, Acta Phys. Polon. B34, 6005 (2003).

[61] S. Ishida, M. Ishida, T. Komada, T. Maeda, M. Oda, K. Yamada and I. Yamauchi, arXiv:hep-ph/0310061.

[62] A. M. Green, J. Koponen, C. McNeile, C. Michael and G. Thompson [UKQCD Collaboration], Phys. Rev. D69, 094505 (2004).

[63] D. Becirevic, S. Fajfer and S. Prelovsek, arXiv:hep-ph/0406296.

[64] M. Suzuki, arXiv:hep-ph/0307118.

[65] C. H. Chen and H. N. Li, Phys. Rev. D69, 054002 (2004).

[66] H. Y. Cheng, Phys. Rev. D68, 094005 (2003).

[67] A. Datta and P. J. O'Donnell, Phys. Lett. B572, 164 (2003).

[68] M. Q. Huang, Phys. Rev. D69, 114015 (2004).

[69] H. Y. Cheng, C. K. Chua and C. W. Hwang, Phys. Rev. D69, 074025 (2004).

[70] T. Barnes, arXiv:hep-ph/0406327.