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Spectroscopy of the excited D_s mesons

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Abstract. The discoveries of the $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$ mesons challenge our understanding of quantum chromodynamics. After almost 20 years, the nature of these hadrons is still subject of debate and many models have been proposed to explain their unexpected masses: standard charmed-strange mesons, DK molecules and tetraquarks. The LHCb experiment has studied the production of excited D^+_s meson in prompt proton-proton collisions and from b-hadron decays. Precise measurement of their properties and observation of new D^+_s states have been reported. The latest results on the spectroscopy of the charmed-strange mesons and the prospect to investigate their nature will be presented.

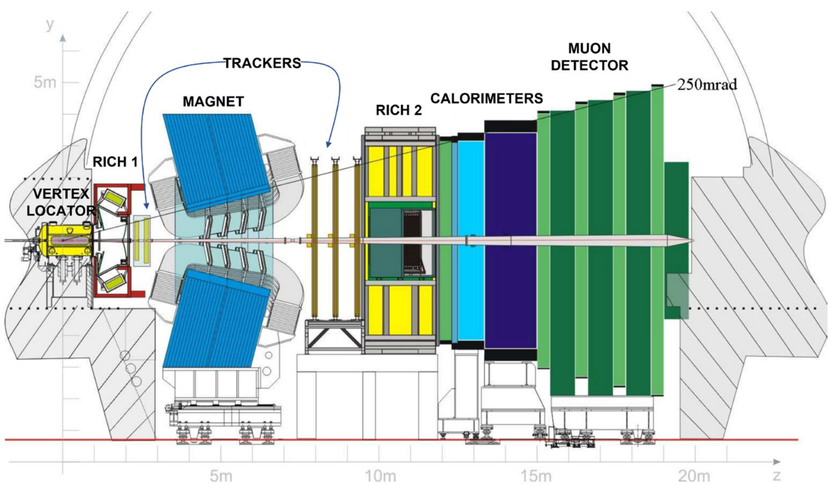

Figure 1. The LHCb apparatus during LHC Run 1 ($\sqrt{s} = 7 \div 8$ TeV) and Run 2 ($\sqrt{s} = 13$ TeV). pp collisions happen in the vertex locator.

1 The LHCb contribution to the spectrum of the excited D^+_s states

The LHCb experiment has largely contributed to the D^+_s spectroscopy in Run 1 and Run 2 with 9/fb integrated luminosity [1] by exploiting its high detection performance [2] and a large D^+_s production cross-section at LHC equal to $\sigma(pp \to D^+_s X) = 353 \pm 9 \pm 76\ \mu\mathrm{b}$ [3]. As shown in Fig.1 the apparatus is a single-arm forward spectrometer [2]. At upstream, the

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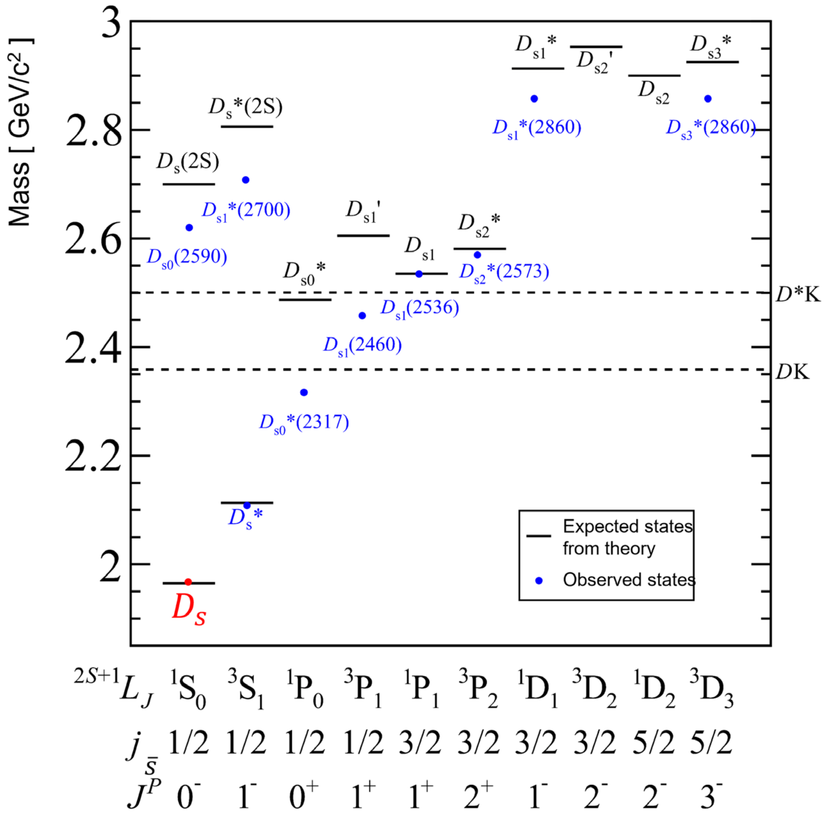

Figure 2. Spectrum of the excited D_s^+ mesons. The D_s ground state is shown in red. The classification is based on masses and quantum numbers. L is the orbital angular momentum between constituent quarks (S, P, D correspond to $L = 0, 1, 2$ respectively); $S = 0, 1$ is the sum of quark spins and J is the total spin of meson; P is the parity.

Vertex Locator detects particles near pp collision point. Momentum measurements are made by tracker stations thanks to a magnet that deflects charged particles. RICH detectors are instead used for the particle identification, distinguishing kaons from pions and calorimeters are used for energy particle measurements. At downstream of the apparatus, the muon detector is devoted to muon identification.

The spectrum of the excited D_s^+ states is shown in Fig.2, where expected and observed excited states are identified according to their mass and quantum numbers. The LHCb collaboration has reported the recent observation of the new state $D_{s0}(2590)^+$ (Fig.2) in the $B^0 \to D^- D^+ K^+ \pi^-$ decay [9], which is interpreted as the radially excitation of the D_s^+ ground state. Another remarkable observation is the $D_{s3}^*(2860)^+$ resonance, the first spin-3 meson ever observed in the B-meson production. In particular, the $D_{s1}^*(2860)^+$ and $D_{s3}^*(2860)^+$ resonances have been distinguished in a broad structure at 2.86 GeV/c^2 by fitting the Dalitz plot of exclusive three-body decays $B_s^0 \to \overline{D}^0 K^- \pi^+$ [4, 5].

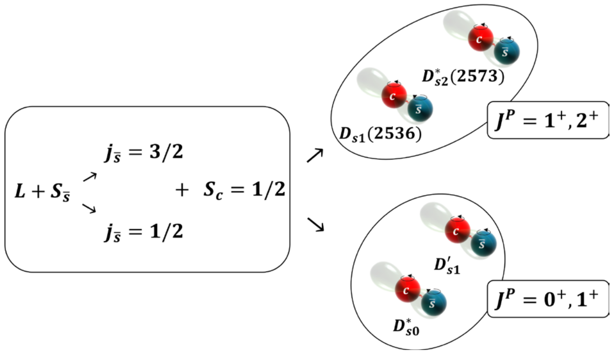

Figure 3. Excited P-wave states ($\vec{L} = 1$) in the heavy quark limit model.

2 The heavy quark limit model and unresolved puzzles

A D_s^+ meson state, composed of heavy c and light $\bar{s}$ quarks, is well described by the heavy quark limit model in the QCD theory pattern. Indeed, according to the QCD theory, the strong coupling constant α_S is small at high energy scale of the heavy c quark, causing interactions at short distance scale $<< R_{had}$[1] perturbatively described. At the contrary, α_S is large at small energy scale of the light $\bar{s}$ quark, causing interactions with non perturbative confinement phenomena of quarks and gluons at large length scale $\approx R_{had}$. Considering the two mass scales bound together in the heavy quark limit, the heavy c quark is much smaller than the hadron size and it is surrounded by a strongly interacting cloud of light quarks, antiquarks, and gluons with which the light $\bar{s}$ interacts without seeing the heavy quark spin effect. In this way the heavy quark spin decouples and the bounding energy of the states depends on spin-orbit coupling of the light $\bar{s}$ quark only.

The heavy quark limit model is able to predict the existence of D_s^+ excited states, according to the sum rules of the quarks orbital momentum and spin. In Fig.3 the excited P-wave states ($L = 1$) prediction scheme is shown: after the spin-orbit coupling is made, involving only the spin $\vec{S}_{\bar{s}} = 1/2$ of the light quark, the total angular momentum of that quark is $\vec{j}_{\bar{s}} = \vec{L} + \vec{S}_{\bar{s}}$ that can be equal to $1/2$ or $3/2$. Then the spin of the meson is obtained summing $\vec{j}_{\bar{s}}$ to the spin $\vec{S}_c = 1/2$ of the heavier quark. Four new possible states emerge: the resonances $D_{s1}(2536)$ and $D^*_{s2}(2573)$ with spin parity 1^+ and 2^+, and the resonances D^*_{s0} and D'_{s1} with spin-parity 0^+ and 1^+ respectively. The first state two states have been observed, thus confirmed, by studying the DK and D^*K mass spectra [6, 8].

However a puzzle characterizes $D_{s1}(2536)^+$ particle: since the c quark is not infinitely heavy, the $D_{s1}(2536)^+$ can contain an admixture of another state from $j_{\bar{s}} = 1/2$ and can have a small decay fraction in an S-wave. But the angular analysis of the $D_{s1}(2536)^+ \to D^{*+}K^0_S$ decay [7] shows an unexpected S-wave dominant contribution $\approx 70\%$ against the expectations.

Another more remarkable puzzle concerns the latter two P-wave states, featured by $\vec{j}_{\bar{s}} = 1/2$ quantum number, such that it is not clear that they have been observed. Indeed, the theory predicted them as broad states with masses large enough so that the dominant decays would have been the DK and/or D^*K final states. However, two narrow resonances, named $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$, were observed by the *BABAR* [10] and the *CLEO* [11] collaborations, having mass smaller than all theoretical predictions and decaying to the isospin-violating $D_s^{(*)+}\pi^0$ channels. The observation of such surprising states hinted at either the theoretical models are

[1]Considering the hadron size R_{had}.

inadequate or the $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$ mesons are not $c\bar{s}$ states but 4-quark systems, as corroborated by several observed anomalies.

2.1 The puzzle of the $D_{s1}(2460)^+$

We focus now on the $D_{s1}(2460)^+$ state, trying to explain well some its anomalies. For instance, in the heavy quark limit model, the following ratio R is expected ≈ 1, contrary to the measured value [12, 13]:

$$R = \frac{BR(B \to DD_{s1}(2460))}{BR(B \to DD^*_s)} \approx \frac{1}{3} \neq 1$$

The discrepancy could be explained by interpreting the $D_{s1}(2460)$ meson as a 4-quark state whose production is suppressed in $B \to DD_{s1}(2460)$ decays, than the D^*_s production, with only two quarks. Another anomaly is evident comparing the D^{*+}_s and $D_{s1}(2460)^+$ decay modes, shown in Tab. 1. For the D^{*+}_s meson, the radiative decay mode is much more likely

Table 1. Known decay modes and measured decay rates of the D^{*+}_s and $D_{s1}(2460)^+$ states [13].

D^{*+}_s		$D_{s1}(2460)^+$	
Decay mode	Branching fraction (%)	Decay mode	Branching fraction (%)
$D^+_s\gamma$	93.5 ± 0.7	$D^+_s\gamma$	18 ± 4
$D^+_s\pi^0$	5.8 ± 0.7	$D^{*+}_s\pi^0$	48 ± 11
$D^+_s e^+e^-$	0.67 ± 0.16	$D^+_s\pi^+\pi^-$	4.3 ± 1.3
		Total	70 ± 12

because it is not isospin-violating, unlike the $D^+_s\pi^0$ mode that violates the isospin conservation. Same remarks should be also valid for the $D_{s1}(2460)^+$ in a $c\bar{s}$ scenario, but its behavior is practically the opposite. Indeed, the isospin-violating $D^{*+}_s\pi^0$ decay mode is much more frequent than radiative $D^+_s\gamma$ mode, suggesting a 4-quark component ($c\bar{s}u\bar{u}$ or $c\bar{s}d\bar{d}$). It can also be noticed that the $D_{s1}(2460)^+$ decay channel spectrum is not complete. New decay channels, not observed so far, could be studied, such as Dalitz decays featured by two leptons in the final state, produced from a virtual photon.

3 LHCb Upgrades and Prospects

During the LHCb Upgrade I, new detectors and new data acquisition electronics systems have been installed, upgrading all the apparatus for the future LHC Run 3 and Run 4 [14]. However, the future of the LHCb experiment is characterized by the LHC luminosity increase up to $1.5\times10^{34}\ cm^{-2}sec^{-1}$ planned for Run 5. It is a great opportunity to improve the precision of all the LHCb physics reach [15], contributing also to disentangle puzzles in the excited D^+_s states described so far. Several analysis prospects could be considered, profiting from the large D^+_s production cross-section and D^+_s signal purity as evident in Fig.4. For instance, some analysis that could be mentioned are:

- Search for muonic Dalitz decay $D_{s1}(2460) \to D_s + \gamma^* \to D_s + \mu^+\mu^-$
  with muons in the final state generated by the virtual photon. The analysis is inspired by the observed $\chi_{c1}, \chi_{c2} \to J/\psi\mu^+\mu^-$ decays [16], justifying the feasibility of the search.

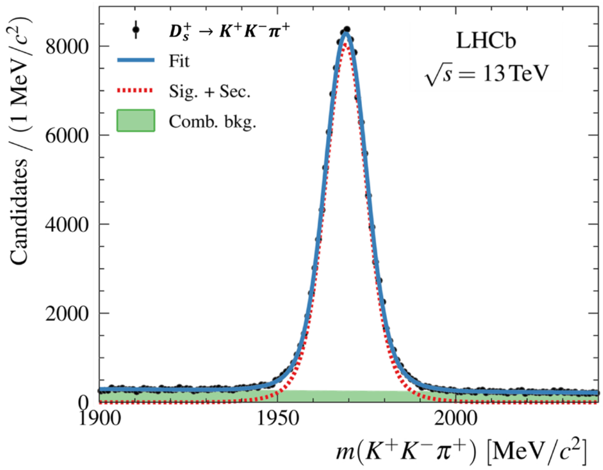

Figure 4. D_s^+ signal in $K^+K^-\pi^+$ decay at LHCb [3].

- Production measurement of the $D_{s1}(2460)^+$ state via $D_s^+\gamma$ decay.

- Quantum numbers measurement of the $D_{s0}^*(2317)^+$ state. In particular spin-parity measurement by studying the decay $B_s^0 \to D_{s0}^*(2317)^-\pi^+ \to D_s^-\pi^0\pi^+$

In conclusion, the debate on the D_s^+ excited states is still open, in particular on the P-wave $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ particles. Their properties disagree from the heavy quark limit model that is suitable instead for the most of the other D_s^+ excited states.
The LHCb experiment has largely contributed to the spectroscopy of the D_s^+ mesons and it will continue more thanks to its detection capability and to the high statistics in the new LHC luminosity era, trying to disentangle the debates on the described puzzles.

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