Open charm Spectroscopy and exotic states at LHCb

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We present a summary of new experimental results on the status of the charm spectroscopy using inclusive approaches and Dalitz plot analyses of \( B \) and \( B_s \) decays. We also report on a new determination of the \( X(3872) \) quantum numbers.

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1 Introduction: Charm meson spectroscopy

The quark model predicts many states with different quantum numbers in limited mass regions \([1,2]\). New progress in the understanding of the \(D_J\) and \(D_{sJ}\) spectra in LHCb experiment come from:

- Inclusive studies: study of the reactions \(pp \rightarrow D_J/D_{sJ}X\);
- Exclusive studies in Dalitz plot analyses of \(B\) and \(B_s\) decays.

In the following, we remind that states having \(J^P = 0^+, 1^-, 2^+, 3^-, \ldots\) are defined as having “Natural Parity”, while states having \(J^P = 0^-, 1^+, 2^-\), ... are defined as having “Unnatural Parity”. A resonance decaying to \(D\pi\) has “Natural Parity”. Labeled with \(D^*\). The \(D^*(\pi/K)\) system can access to both “Natural Parity” and “Unnatural Parity” states, except for \(J^P = 0^+\) which is forbidden.

In the following, inclusive studies make use of \(1 \text{ fb}^{-1}\) while Dalitz analyses of \(3 \text{ fb}^{-1}\) integrated luminosities.

2 Results on \(D_J\) mesons spectroscopy

2.1 Inclusive studies

![Figure 1: Left: \(D^{*+}\pi^-\) mass spectrum with enhanced natural parity selections. Right: \(D^0\pi^+\) mass spectrum. Note the crossfeed (in red) from the high mass \(D_J\) resonances into the \(D\pi\) mass spectra.](image)

The BaBar \([3]\) and LHCb \([4]\) experiments observe two new natural parity resonances, \(D^*(2650)\) and \(D^*(2760)\), both decaying to \(D\pi\) and \(D^*\pi\). While the parameters of the \(D^*(2760)\) are consistent within the two experiments, the mass of the \(D^*(2650)\) state is shifted down by \(\approx 40\) MeV in the BaBar analysis due to different handling
of the $D^*\pi$ feedthrough into the $D\pi$ final states. The two states are candidates for being the $J^P = 1^- D_1^0(2S)$ and $J^P = 1^- D_1^0(1D)$.

Adding statistical and systematic uncertainties in quadrature, we obtain a weighted mean values for $D_J(2770)$ parameters.

$$m(D_J(2770)) = 2768.8 \pm 1.7 \text{ MeV}, \quad \Gamma(D_J(2770)) = 63.2 \pm 5.3 \text{ MeV}$$

The $D^{*+}\pi^-$ angular distributions in terms of the helicity angle for the $D_J^*(2650)$ and $D^*(2760)$ are shown in fig. 2. They are well fitted by the $\sin^2 \theta_H$ functions and therefore are consistent with having natural parity. LHCb experiment also observes three unnatural parity states, $D_J(2580)^0$, $D_J(2740)^0$, and $D_J(3000)^0$, whose angular distributions are shown in fig. 3. The weighted mean values for $D_J(2580)$ parameters, consistent with a $J^P = 0^-$ assignment, are

$$m(D_J(2580)) = 2564.0 \pm 5.1 \text{ MeV}, \quad \Gamma(D_J(2580)) = 135.6 \pm 16.9 \text{ MeV}$$

The weighted mean values for the $D_J(2740)$ parameters are

$$m(D_J(2740)) = 2751.3 \pm 3.1 \text{ MeV}, \quad \Gamma(D_J(2740)) = 71.4 \pm 11.4 \text{ MeV}$$

and is a candidate for being a $J^P = 2^-$ state. The broad structures observed in the 3000 MeV mass region could be a superposition of several states.
2.2 First observation and Dalitz plot analysis of $B^- \to D^+K^-\pi^-$

The $D^+K^-\pi^-$ mass spectrum [5] is shown in fig. 4 (Left) and contains $\approx 2K$ events in the $B^-$ signal region. To obtain a high $B^-$ signal purity we make use of neural network’s trained by control samples, especially the $B^- \to D^+\pi^-\pi^-$ final state which contains $\approx 49K$ events and shown in fig. 4 (Right). We perform a standard Dalitz plot analysis of the $B^- \to D^+K^-\pi^-$ system. In this final state, resonance production can only occur in the $D^+\pi^-$ system. We plot, in fig. 5, the efficiency corrected and background subtracted $D^+\pi^-$ mass spectrum, weighted by Legendre polynomial moments and compare with Dalitz plot fit results. We note that $P_1$ is related to the S-P interference, while $P_3$ is related to the P-D interference. We also observe, as expected, a Clear D-wave in $P_4$ due to the $D^*_s(2460)^0$. In the Dalitz analysis a better fit is obtained introducing virtual $D^*_s(2007)^0$, $B^{*0}$ and nonresonant contributions. We also observe a clear spin-2 $D^*_2(2460)^0$ signal and a $D^*_J(2760)^0$ spin-1 resonance. The

Figure 4: Left: $D^+K^-\pi^-$ mass spectrum. Right: $B^- \to D^+\pi^-\pi^-$ mass spectrum.

Figure 5: $B^- \to D^+K^-\pi^-$. $D^+\pi^-$ mass spectrum, weighted by Legendre polynomial moments.
| Resonance    | Spin | Parameters                        | Fit fraction       |
|--------------|------|-----------------------------------|--------------------|
| $D_0^*(2400)^0$ | 0    | PDG                              | 8.3 ± 2.6 ± 0.6 ± 1.9 |
| $D_2^0(2460)^0$ | 2    | $m = 2464.0 ± 1.4$, $\Gamma = 43.8 ± 2.9$ MeV | 31.8 ± 1.5 ± 0.9 ± 1.4 |
| $D_2^+(2760)^0$ | 1    | $m = 2781 ± 18$, $\Gamma = 177 ± 32$ MeV | 4.9 ± 1.2 ± 0.3 ± 0.9 |

Table 1: $B^- \rightarrow D^+K^-\pi^-$. Resonances parameters from the Dalitz analysis.

resulting resonance parameters and fitted fractions are given in Table 1. The $D^+\pi^-$ fit projection with fit result is shown in Fig. 6. No evidence for a $D_2^+(2760)$ spin-3 resonance is found in this final state.

2.3 Dalitz plot analysis of $B^0 \rightarrow \bar{D}^0 \pi^+\pi^-$

The $\bar{D}^0 \pi^+\pi^-$ mass spectrum is shown in Fig. 7 (Left) and 6. The $B^0$ signal contains 9565 events with 97.8% purity. The $B^0 \rightarrow \bar{D}^0 \pi^+\pi^-$ Dalitz plot is shown in Fig. 7 (Right). We observe the spin-2 $D_2^+(2460)^-$ signal along the $\bar{D}^0 \pi^-$ axis and the spin-1 $\rho(770)$ signal along the $\pi^+\pi^-$ axis. The Dalitz plot analysis has been performed using the isobar model and a K-matrix description of the $\pi^+\pi^-$ S-wave. Both methods give a good description of the data. The $m^2(\pi^+\pi^-)$ fit projection are shown in Fig. 8. We observe a signal of $\rho/\omega$ interference. The $m^2(\bar{D}^0 \pi^-)$ fit projection is shown in Fig. 9. The decay is dominated, in the $\pi^+\pi^-$ system, by S-wave $(16.51 ± 0.70 ± 1.68 ± 1.10)%$ and $\rho(770) (36.15±1.00±2.13±0.79)%$. In the $\bar{D}^0 \pi^-$ system, the largest contribution comes from the $D_2^+(2460)^-$ resonance $(28.13 ± 0.72 ± 1.06 ± 0.54)%$. The Dalitz plot analysis requires the presence of an additional $J^P = 3^-$ resonance with a K-matrix model fitted fraction of $(1.58 ± 0.22 ± 0.18 ± 0.07)%$. The fitted resonances parameters are given in Table 2.
Figure 7: Left: $D^0 \pi^+ \pi^-$ mass spectrum. The green line represents the background contribution. Right: $B^0 \rightarrow D^0 \pi^+ \pi^-$ Dalitz plot.

Figure 8: $B^0 \rightarrow D^0 \pi^+ \pi^-$. $m^2(\pi^+ \pi^-)$ fit projection with two different binnings.

Comparing the $D^*_J$(2760) parameters between inclusive and $B$ decays production, we observe some disagreement. Both $J^P = 1^-$ and $J^P = 3^-$ resonances are expected in this mass region and inclusive data cannot separate the two natural parity contributions.

2.4 Dalitz plot analysis of $B^0 \rightarrow D^0 K^+ \pi^-$

The $D^0 K^+ \pi^-$ mass spectrum is shown in Fig. 10 (Left). The $B^0$ signal region contains 2344 events. The fit projections are shown in Fig. 11. The decay is dominated by intermediate resonance production of $K^*(892)^0$ (37.4 ± 1.5)%, $D^*_0(2400)^-$ (19.3 ± 2.8)% and $D^*_2(2460)^-$ (23.1 ± 1.2)%. These Dalitz analyses obtain new parameters for the broad $D^*_0(2400)^-$ resonance which are summarized in Table 3. No evidence is found for additional spin-1 or spin-3 $D^*_J$ resonances.
Figure 9: $B^0 \to \overline{D}^0 \pi^+ \pi^-$. $m^2(D^0 \pi^-)$ fit projection with two different binnings.

| Isobar             | K-matrix          |
|--------------------|-------------------|
| $D_0^*(2400)$      | $m$ 2349 ± 6 ± 4  |
|                    | $\Gamma$ 2354 ± 11 ± 2 |
| $D_2^*(2460)$      | $m$ 2468.6 ± 0.6 ± 0.3 |
|                    | $\Gamma$ 2468.1 ± 0.4 ± 0.3 |
| $D_3^*(2760)$      | $m$ 2798 ± 7 ± 7  |
|                    | $\Gamma$ 2802 ± 10 ± 3  |

Table 2: $B^0 \to \overline{D}^0 \pi^+ \pi^-$. Resonances parameters from the Dalitz analysis.

| Final state         | Method    | Mass   | Width   |
|---------------------|-----------|--------|---------|
| $B^0 \to \overline{D}^0 K^+ \pi^-$ | Free      | 2360 ± 15 | 255 ± 26 |
| $B^0 \to \overline{D}^0 \pi^+ \pi^-$ | Free      | 2354 ± 7  | 230 ± 15 |
| $B^- \to D^+ K^- \pi^-$          | (PDG)     | 2318 ± 29 | 267 ± 40 |

Table 3: $D_0^*(2400)$ resonances parameters from the different Dalitz analyses.
3 Results on $D_{sJ}$ mesons spectroscopy

3.1 Inclusive studies

Using samples of $3.6 \times 10^6 D^+ K^0_S$ and $3.15 \times 10^6 D^0 K^+$ inclusive candidates, the $D^{*+}_{s1}(2710)^+$ and $D^{*+}_{sJ}(2860)^+$ have been observed with parameters consistent with previous measurements \cite{8}. The background subtracted $D^+ K^0_S$ and $D^0 K^+$ mass spectra are shown in Fig. 12.

3.2 Dalitz plot analysis of $B^0_s \to \bar{D}^0 K^+ \pi^-$

Fig. 13 (Left) shows the $\bar{D}^0 K^+ \pi^+$ mass spectrum \cite{9}. The $B^0_s$ signal contains $11302 \pm 159$ signal events. The Dalitz analysis shows that the largest components are: $K^*(892)^0$ (28.6%), $D^{*+}_{s2}(2573)^-$ (25.7%), $K \pi$ S-wave (LASS) (21.4%) $D^0 K^-$ nonresonant (12.4%).

A signal present in the 2860 MeV $\bar{D}^0 K^-$ mass region which is described by a superposition of a spin-1 ($5.0 \pm 1.2 \pm 0.7 \pm 3.3\%$) and a spin-3 ($2.2 \pm 0.1 \pm 0.3 \pm 0.4\%$)
Figure 12: Background subtracted (c) $D^+K_S^0$ and (d) $D^0K^+$ mass spectra.

Figure 13: (Left) $\overline{D}^0K^-\pi^+$ mass spectrum. (Right) $K^-\pi^+$ and $\overline{D}^0K^-$ mass projections.

resonance. The fitted resonances parameters are: $m(D^{*}_{s1}(2860)^-) = 2859 \pm 12 \pm 6 \pm 23$ MeV/$c^2$, $\Gamma(D^{*}_{s1}(2860)^-) = 159 \pm 23 \pm 27 \pm 72$ MeV/$c^2$ $m(D^{*}_{s3}(2860)^-) = 2860.5 \pm 2.6 \pm 2.5 \pm 6.0$ MeV/$c^2$, $\Gamma(D^{*}_{s3}(2860)^-) = 53 \pm 7 \pm 4 \pm 6$ MeV/$c^2$.

3.3 Determination of the $X(3872) \rightarrow J/\psi\rho(770)$ quantum numbers

We study the decay $B^+ \rightarrow X(3872)K^+$ with $X(3872) \rightarrow J/\psi\pi^+\pi^- [10] [10]$. The quantum numbers of $X(3872) \rightarrow J/\psi\rho(770)$ have been determined to be $J^{PC} = 1^{++}$. However it was assumed that the decay is dominated by the lowest values of angular momentum between the $X(3872)$ decay products. The analysis is repeated here using 3-times the statistics and without any assumption on $L_{min}$. The $\Delta M$ signal for $J/\psi\pi^+\pi^-$ is shown in Fig. [14]. The $B^+$ signal for $B^+ \rightarrow X(3872)K^+$ contains $1011 \pm 38$ with 80% signal purity.

The distributions of the test statistic $t \equiv -2 \ln[L(J_{alt}^{lh})/L(1^{++})]$, for the simulated experiments under the $J^{PC} = J_X^{alt}$ hypothesis and under the $J^{PC} = 1^{++}$ hypothesis are shown in Fig. [14]. The $J^{PC} = 1^{++}$ hypothesis gives the highest Likelihood value with an upper limit of $D$-wave contribution of 4% at 95% C.L.
Figure 14: (Left) X(3872) signal. (Right) Distributions of the test statistic for different spin-parity hypothesis.

References

[1] Godfrey and Isgur, Phys.Rev. D32, 189 (1985).
[2] S. Godfrey and I. T. Jardine, Phys. Rev. D89, 074023 (2014).
[3] BaBar collaboration, P. del Amo Sanchez, P. et al., Phys. Rev. D82, 111101 (2010).
[4] LHCb collaboration, R. Aaij et al., JHEP 09, 145 (2013).
[5] LHCb collaboration, R. Aaij et al., Phys. Rev. D91, 092002 (2015).
[6] LHCb collaboration, R. Aaij et al., Phys. Rev. D92, 032002 (2015).
[7] LHCb collaboration, R. Aaij et al., Phys. Rev. D92, 032002 (2015).
[8] LHCb collaboration, R. Aaij et al., JHEP 1210, 151 (2012).
[9] LHCb collaboration, R. Aaij et al., Phys. Rev. D 90, 072003 (2014).
[10] LHCb collaboration, R. Aaij et al., Phys.Rev. bf D92, 011102 (2015).