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# Dalitz Plot Analyses of $B \to \bar{D}DK$ Decays

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Dalitz plot analyses of $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$ decays based on a data sample of $471 \times 10^6\,\mathrm{B\bar{B}}$ pairs recorded with the *BABAR* experiment at SLAC are presented. The $D^*_{s1}(2700)^+$ resonance is observed, and $M(D^*_{s1}(2700)^+) = 2699^{+14}_{-7}\,\mathrm{MeV}/c^2$ and $\Gamma(D^*_{s1}(2700)^+) = 127^{+24}_{-19}\,\mathrm{MeV}/c^2$ are measured. In both decays, enhancements are observed in the $D^0 K^+$ invariant mass spectra at around $2350 - 2500\,\mathrm{MeV}/c^2$, which require further interpretation.

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Dalitz plot analyses of $B \to \bar{D}DK$ decays enable to access the resonant substructure of intermediates involving $\bar{D}D$ and $DK$ finale states, providing sensitive probes for spectroscopy of heavy hadrons in the $c\bar{c}$ and $c\bar{s}$ systems. On quark level, $B \to \bar{D}DK$ decays receive contributions from the Feynman diagrams shown in Figure 1. Depending on the internal or external emission of the W boson, $B \to \bar{D}DK$ decays can involve intermediate $\psi$ and $D_{sJ}$ states, which can be studied in detail by a Dalitz amplitude analysis of these three-body decays.

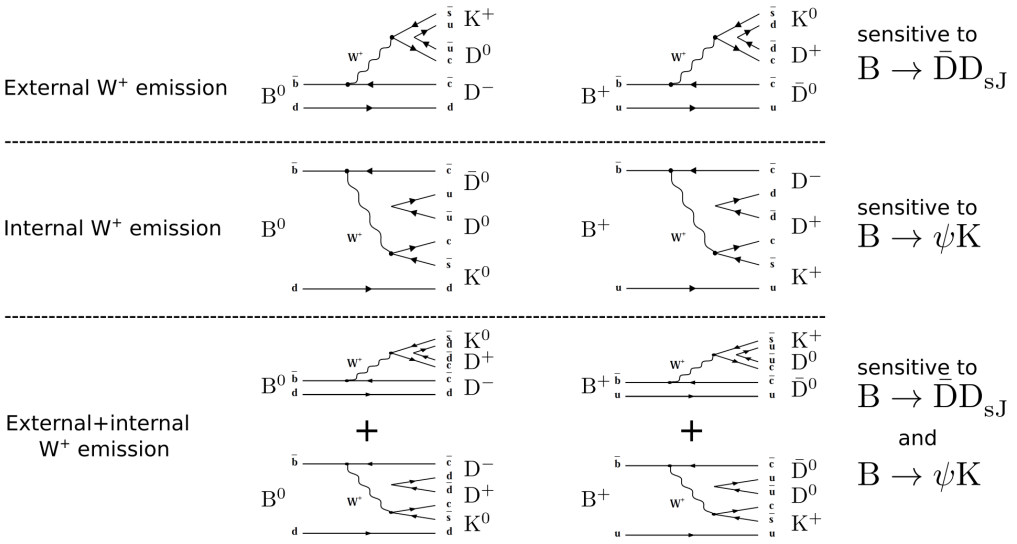


**Figure 1:** Feynman diagrams contributing to $B \to \bar{D}DK$ decays and sensitivity to intermediate $\psi$ and $D_{sJ}$ states. Excited states are neglected for clarity.

We report a Dalitz amplitude analysis of $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$ decays based on a data sample of $471 \times 10^6$ B$\bar{\text{B}}$ pairs recorded with the *BABAR* experiment at the PEP-II asymmetric-energy $e^+e^-$ collider at SLAC. The measurement applies the same selection as employed in previous analyses. The selection includes requirements on quantities for particle identification, invariant masses and event shape variables, and is described in detail in Reference [1]. $D$ mesons are reconstructed in the decay modes $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^0$, $D^0 \to K^-\pi^+\pi^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$. $B$ mesons are reconstructed in the decay modes $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$. For intermediate reconstructed $D^0$, $D^+$ and $\pi^0$ mesons a kinematic fit with a mass-constraint is applied to improve the resolution on the reconstructed momenta and on the invariant masses of the resonances to be studied. $B$ mesons are selected by the beam-energy-substituted mass $m_{\text{ES}} = \sqrt{(E^*_{\text{beam}}/c^2)^2 - (p^*_B/c)^2}$ and the energy difference $\Delta E = E^*_B - E^*_{\text{beam}}$, where $p^*$ and $E^*$ denote the momentum and energy of the $B$ meson candidate, and $E^*_{\text{beam}}$ is the energy of the beam in the center-of-mass frame. A yield of $635 \pm 47$ signal events is obtained for $B^0 \to D^- D^0 K^+$ decays, and a yield of $901 \pm 54$ signal events is obtained for $B^+ \to \bar{D}^0 D^0 K^+$ decays.

The data distributions for the Dalitz plots of $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$ decays are shown in Figure 2. To model the resonant substructure of the Dalitz plots and to extract the physical parameters of the individual contributions, an isobar formalism is applied. The Lorentz-invariant matrix elements $\mathscr{M}$ for $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$ decays are modeled by coherent sums

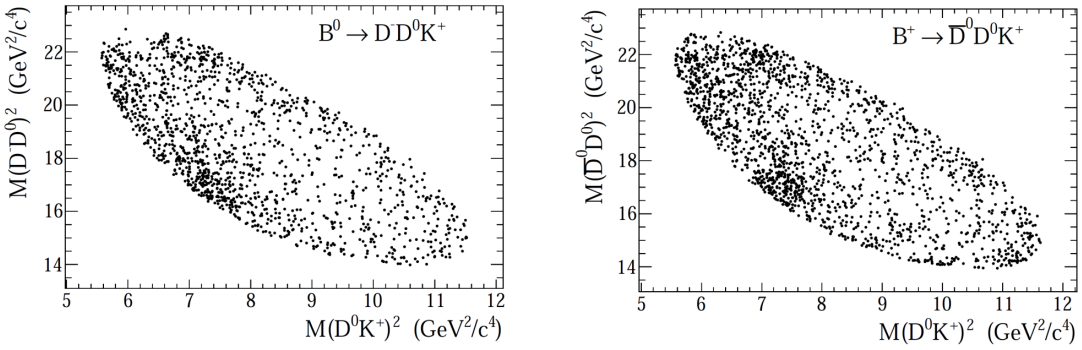


**Figure 2:** Dalitz plot data distributions of $B^0 \to D^-D^0K^+$ decays (left) and $B^+ \to \bar{D}^0D^0K^+$ decays (right) [2].

of the amplitudes representing the individual resonant and nonresonant contributions:

$$\mathscr{M} = \sum_i c_i A_i \tag{1}$$

The amplitudes $A_i$ account for the decay dynamics, form factors and angular factors, and the complex coefficients $c_i$ quantify the individual contributions. The measurements are performed by an unbinned maximum likelihood fit to the data distributions of the Dalitz plots. The likelihood function accounting for efficiency corrections $\varepsilon$ and including background $B$ is given by:

$$\mathscr{L} = \prod_{j=1}^{N_{\text{events}}} \left[ f \times \frac{\varepsilon(m_{12}^2, m_{23}^2)|\mathscr{M}|^2}{\int \varepsilon(m_{12}^2, m_{23}^2)|\mathscr{M}|^2 dm_{12}^2 dm_{23}^2} + (1-f) \times \frac{B(m_{12}^2, m_{23}^2)}{\int B(m_{12}^2, m_{23}^2) dm_{12}^2 dm_{23}^2} \right] \tag{2}$$

The preliminary Dalitz models for $B^0 \to D^-D^0K^+$ and $B^+ \to \bar{D}^0D^0K^+$ decays include amplitudes from expected contributions. These are the $D_{s1}^*(2700)^+$ and the $D_{s2}^*(2573)^+$ resonances and nonresonant decays. For $B^+ \to \bar{D}^0D^0K^+$ decays, additional expected charmonia contributions from the $\psi(3770)$ and $\psi(4160)$ resonances are included. The fits of these preliminary Dalitz models show enhancement at low $D^0K^+$ masses that are not well described by the model. These enhancements don't originate from the background or from reflections of known resonances. A similar excess has also seen in $B^+ \to \bar{D}^0D^0K^+$ decays by the Belle experiment [3].

Various models have been tested to account for the enhancements. The best experimental model description is not achieved by a new resonance, but by an exponential function starting at the $D^0K^+$ threshold. The results for the final Dalitz models accounting for the enhancements and projections of the fits are shown in Figure 3 and are summarized in Tables 1 and 2. The $D_{s1}^*(2700)^+$ resonance is observed for the first time in $B^0 \to D^-D^0K^+$, and $M(D_{s1}^*(2700)^+) = 2699^{+14}_{-7}\,\text{MeV}/c^2$ and $\Gamma(D_{s1}^*(2700)^+) = 127^{+24}_{-19}\,\text{MeV}/c^2$ are measured. To improve the description of the data, the model needs to include $B^+ \to \psi(4160)K^+$ decays followed by $\psi(4160) \to \bar{D}^0D^0$ decays.

In summary, enhancements are observed in the $D^0K^+$ invariant mass spectra at around $2350-2500\,\text{MeV}/c^2$ for both, $B^0 \to D^-D^0K^+$ and $B^+ \to \bar{D}^0D^0K^+$ decays, which requires further expla-

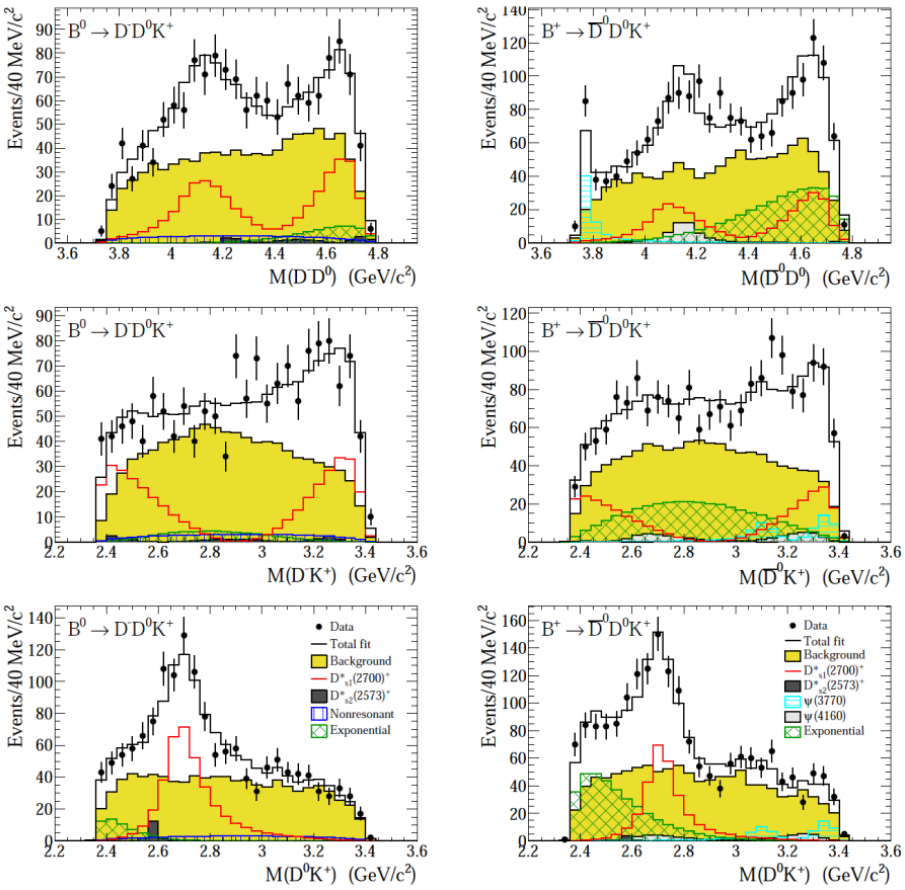


**Figure 3:** Results using the final Dalitz models and fit projections for $B^0 \to D^- D^0 K^+$ decays (left) and for $B^+ \to \bar{D}^0 D^0 K^+$ decays (right). The final Dalitz models include an exponential function starting at the $D^0 K^+$ threshold to account for the enhancements seen at low invariant masses [2].

| Contribution | Amplitude | Phase (°) | Fraction (%) |
|---|---|---|---|
| $D^*_{s2}(2573)^+$ | $0.031 \pm 0.008 \pm 0.002$ | $277 \pm 17^{+6}_{-9}$ | $3.2 \pm 1.6^{+0.3}_{-0.4}$ |
| $D^*_{s1}(2700)^+$ | 1.00 | 0 | $66.7 \pm 7.8^{+3.5}_{-3.8}$ |
| Exponential | $6.94 \pm 1.83^{+0.82}_{-0.43}$ | $269 \pm 33^{+17}_{-15}$ | $9.9 \pm 2.9^{+3.0}_{-3.3}$ |
| Nonresonant | $1.33 \pm 0.63^{+0.46}_{-0.35}$ | $287 \pm 21^{+10}_{-15}$ | $10.9 \pm 6.6^{+7.0}_{-4.3}$ |

**Table 1:** Results for $B^0 \to D^- D^0 K^+$ decays.

nation. At the current experimental sensitivity it is not possible to determine the source of this excess. An *ad hoc* description by an exponential function improves the model description of the data. Further parameters of resonances contributing to $B^0 \to D^- D^0 K^+$ and $B^+ \to \bar{D}^0 D^0 K^+$ decays including the mass and width of the $D^*_{s1}(2700)^+$ resonance are measured. The results are published in Reference [2].

| Contribution | Amplitude | Phase (°) | Fraction (%) |
|---|---|---|---|
| $D^*_{s2}(2573)^+$ | $0.021 \pm 0.010^{+0.009}_{-0.003}$ | $267 \pm 30^{+17}_{-13}$ | $0.6 \pm 1.1^{+0.4}_{-0.2}$ |
| $D^*_{s1}(2700)^+$ | 1.00 | 0 | $38.3 \pm 5.0^{+0.8}_{-6.2}$ |
| $\psi(3770)$ | $1.40 \pm 0.21^{+0.20}_{-0.24}$ | $284 \pm 22^{+26}_{-30}$ | $9.0 \pm 3.1^{+0.4}_{-0.8}$ |
| $\psi(4160)$ | $0.78 \pm 0.20^{+0.18}_{-0.14}$ | $188 \pm 13^{+14}_{-17}$ | $6.4 \pm 3.1^{+1.9}_{-2.4}$ |
| Exponential | $16.15 \pm 2.26^{+1.09}_{-1.74}$ | $308 \pm 8^{+6}_{-5}$ | $44.5 \pm 6.2^{+1.3}_{-2.1}$ |

**Table 2:** Results for $B^+ \to \bar{D}^0 D^0 K^+$ decays.

## References

[1] P. del Amo Sanchez *et al.* (*BABAR* Collaboration), Phys. Rev. D **83**, 032004 (2011).

[2] J.P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. D **91**, 052002 (2015).

[3] J. Brodzicka *et al.* (Belle Collaboration), Phys. Rev. Lett. **100**, 092001 (2008).