Dalitz Plot Analyses with $B \to D_{hh}$ decays at LHCb

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on behalf of the LHCb Collaboration

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General view of Dalitz plot analyses with $B \rightarrow Dhh$

Results of excited D mesons

Light meson structure studies

Conclusion
Analyses with $B \to D_{hh}$

<table>
<thead>
<tr>
<th>Decay Channels</th>
<th>Branching fractions ($\times 10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to \overline{D}^0 \pi^+ \pi^-$</td>
<td>$8.46 \pm 0.14 \pm 0.29 \pm 0.40$</td>
</tr>
<tr>
<td>$B_s^0 \to \overline{D}^0 f_0(980)$</td>
<td>$0.017 \pm 0.010 \pm 0.005 \pm 0.001$</td>
</tr>
<tr>
<td>$B^0 \to \overline{D}^0 K^+ \pi^-$</td>
<td>$0.92 \pm 0.06 \pm 0.07 \pm 0.06$</td>
</tr>
<tr>
<td>$B_s^0 \to \overline{D}^0 K^- \pi^+$</td>
<td>$0.47 \pm 0.09 \pm 0.06 \pm 0.05$</td>
</tr>
<tr>
<td>$B^0 \to \overline{D}^0 K^- K^+$</td>
<td>$0.42 \pm 0.19$</td>
</tr>
<tr>
<td>$B_s^0 \to \overline{D}^0 K^- K^+$</td>
<td></td>
</tr>
<tr>
<td>$B^- \to D^+ K^- \pi^-$</td>
<td>$0.731 \pm 0.019 \pm 0.022 \pm 0.039$</td>
</tr>
</tbody>
</table>

... ……

Rich physics programs with $B \to D_{hh}$ decays at LHCb:

➢ Understand excited D meson spectroscopy

➢ Understand ππ, Kπ, KK spectrum

➢ can be used for further studies to extract CKM angle $\gamma$, $\beta(s)$

arXiv: 1505.01710; 3 fb⁻¹

arXiv: 1505.01654; 3 fb⁻¹

arXiv: 1505.01505; 3 fb⁻¹

PRD 90, 072003 (2014); 3 fb⁻¹

PRD 91, 092002 (2015); 3 fb⁻¹

PRL 109, 131801 (2012); 0.62 fb⁻¹
Dalitz plot analyses strategy (1)

Similar Dalitz plot analysis strategy applied:

> Optimized selection to achieve clean environment for Dalitz plot analyses

\[ B^0 \rightarrow \bar{D}^0 \pi^+ \pi^- \]

arXiv: 1505.01710; 3 fb⁻¹

\[ B^0 \rightarrow \bar{D}^0 K^+ \pi^- \]

arXiv: 1505.01505; 3 fb⁻¹
Dalitz plot analyses strategy (2)

Similar Dalitz plot analysis strategy applied:

➢ Efficiency obtained from Monte Carlo with data-driven method to correct for data and Monte Carlo difference

\[ \text{arXiv: 1505.01710; 3 fb}^{-1} \quad B^0 \rightarrow \overline{D}^0 \pi^+ \pi^- \]

\[ \text{arXiv: 1505.01505; 3 fb}^{-1} \quad B^0 \rightarrow \overline{D}^0 K^+ \pi^- \]

➢ Combinatorial background modeled from sidebands

➢ Peaking background either suppressed to negligible level or modeled using Dalitz model obtained from other analyses
Dalitz formalism with $B \to Dhh$

Modeled by Isobar formalism: total amplitude as coherent sum of quasi-two-body contributions ($\pi\pi$ S-wave also uses K-matrix formalism)

\[ A(s_{12}, s_{23}) = \sum_j A_j = \sum_j a_j F_j(s_{12}, s_{23}) \]

$\Rightarrow$ $s_{12}, s_{23}$ are the invariant mass squared of two of the three decay particles

$\Rightarrow$ sum over all resonant contributions

$\Rightarrow$ $a_j$: complex fit parameters to describe relative contributions between resonances

$\Rightarrow$ $F_j(s_{12}, s_{23})$: strong dynamics including resonant line shapes, angular distributions etc.

Output of Dalitz plot analyses

$\Rightarrow$ Resonant contributions, relative amplitudes and phases of resonances, fit fractions, resonant properties etc.
Spectroscopy of charmed mesons

- Tests of HQET, potential models, Lattice QCD, ...
- Inputs for other studies, exotic states, R(D^{(*)}), ...

States appear in doublet with similar widths: one with “natural” parity \((0^+, 1^-, 2^+, \ldots)\) and one with “unnatural” parity \((0^-, 1^+, 2^-, \ldots)\)

Similar for D^{*0}, D^{*+}, Ds^{*+}

Excited D meson states

States in $B^0 \rightarrow \overline{D}^0 \pi^+ \pi^-$, $B^0 \rightarrow \overline{D}^0 K^+ \pi^-$, $B^- \rightarrow D^+ K^- \pi^-$, Dalitz plot analysis

$\theta(D\pi)$ is helicity angle defined between directions of two pions in the rest frame of resonance

- $D_0(2400)$, $D_2(2460)$ dominant in all analyses
- Many new $D^*$ states observed in inclusive D spectroscopy: $D^*(2650)$, $D^*(2760)$, $D^*(3000)$
- A $D^*$ with spin 3 and mass around 2800 MeV observed in $B^0 \rightarrow \overline{D}^0 \pi^+ \pi^-$ analysis
- A $D^*$ with spin 1 and mass around 2791 MeV observed in $B^- \rightarrow D^+ K^- \pi^-$ analysis

$B^0 \rightarrow \overline{D}^0 \pi^+ \pi^-$

\[ \begin{align*}
D_3^* (2806) & \quad 3^- \\
D_2(2806) & \quad 2^- \\
D_2(2801) & \quad 2^- \\
D_3^* (2796) & \quad 1^+ \\
D_4^* (3084) & \quad 4^+ \\
D_3(3079) & \quad 3^+ \\
D_3(3074) & \quad 3^+ \\
D_2^* (3074) & \quad 2^+ \\
D_1^* (2618) & \quad 1^+ \\
D_0(2558) & \quad 0^+ \\
D_0^* (2380) & \quad 0^+ \\
D_2^* (2479) & \quad 2^+ \\
D_1(2469) & \quad 1^+ \\
D_1(2419) & \quad 1^+ \\

\end{align*} \]
Excited $D_s$ meson states

<table>
<thead>
<tr>
<th>State</th>
<th>Mass</th>
<th>Width</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{s1}^*(2700)^-$</td>
<td>$2710 \pm 2^{+12}_{-7}$</td>
<td>$149 \pm 7^{+39}_{-52}$</td>
<td>Seen in $DK$ and $D^*K$</td>
</tr>
<tr>
<td>$D_{sJ}^*(2860)^-$</td>
<td>$2862 \pm 2^{+5}_{-2}$</td>
<td>$48 \pm 3 \pm 6$</td>
<td>Seen in $DK$ and $D^*K$</td>
</tr>
<tr>
<td>$D_{sJ}(3040)^-$</td>
<td>$3044 \pm 8^{+30}_{-4}$</td>
<td>$239 \pm 35^{+46}_{-42}$</td>
<td>Seen in $D^*K$ only</td>
</tr>
<tr>
<td>$D_{s1}^*(2700)^-$</td>
<td>$2709.2 \pm 1.9 \pm 4.5$</td>
<td>$115.8 \pm 7.3 \pm 12.1$</td>
<td>Only $DK$ studied</td>
</tr>
<tr>
<td>$D_{sJ}^*(2860)^-$</td>
<td>$2866.1 \pm 1.0 \pm 6.3$</td>
<td>$69.9 \pm 3.2 \pm 6.6$</td>
<td></td>
</tr>
</tbody>
</table>

$\Rightarrow$ Many new $D_s^*$ states also observed in inclusive $D_s$ spectroscopy: $D_s^*(2700)$, $D_s^*(2860)$, $D_s^*(3040)$

$\Rightarrow$ A structure around 2860 MeV with both spin 1 and spin 3 resonant contributions is found

$B_s^0 \rightarrow \bar{D}^0 K^- \pi^+$
Excited D meson masses and widths

- Spin 3 D* meson around 2800 MeV from $B^0 \rightarrow \bar{D}^0 \pi^+ \pi^-$

<table>
<thead>
<tr>
<th>Isobar</th>
<th>K-matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_3^*(2760)$</td>
<td>$m$</td>
</tr>
<tr>
<td></td>
<td>$\Gamma$</td>
</tr>
</tbody>
</table>

- Spin 1 D* meson around 2791 MeV from $B^- \rightarrow D^+ K^- \pi^-$

| $D_1^*(2760)$ | $m$ | 2791 ± 18 ± 11 ± 6 |
| | $\Gamma$ | 177 ± 32 ± 20 ± 7 |

- Spin 1 and spin 3 mixture of $D_s^*$ meson around 2860 MeV from $B_{s0}^0 \rightarrow \bar{D}^0 K^- \pi^+$

| $D_s^*(2860)$ | $m$ | 2859 ± 12 ± 6 ± 23 |
| | $\Gamma$ | 159 ± 23 ± 27 ± 72 |
| $D_{s3}^*(2860)$ | $m$ | 2860.5 ± 2.6 ± 2.5 ± 6.0 |
| | $\Gamma$ | 53 ± 7 ± 4 ± 6 |

- More precise and accurate also for other D* states like $D_0^*(2400), D_2^*(2460)$ etc compared to previous measurements
Dalitz fit display: $B^0 \rightarrow \bar{D}^0 \pi^+ \pi^-$

larger subcomponent due to interference
Dalitz fit display: $B^0 \rightarrow \bar{D}^0 \pi^+ \pi^-$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Isobar ($\times 10^{-5}$)</th>
<th>K-matrix ($\times 10^{-5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(500)$</td>
<td>$11.2 \pm 0.8 \pm 0.5 \pm 2.1 \pm 0.5$</td>
<td>n/a</td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>$1.34 \pm 0.25 \pm 0.10 \pm 0.46 \pm 0.06$</td>
<td>n/a</td>
</tr>
<tr>
<td>$f_0(2020)$</td>
<td>$1.35 \pm 0.31 \pm 0.14 \pm 0.85 \pm 0.06$</td>
<td>n/a</td>
</tr>
<tr>
<td>S-wave</td>
<td>$14.1 \pm 0.5 \pm 0.6 \pm 1.3 \pm 0.7$</td>
<td>$14.2 \pm 0.6 \pm 1.5 \pm 0.9 \pm 0.7$</td>
</tr>
<tr>
<td>$\rho(770)$</td>
<td>$32.1 \pm 1.0 \pm 1.2 \pm 0.9 \pm 1.5$</td>
<td>$31.0 \pm 1.0 \pm 2.1 \pm 0.7 \pm 1.5$</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>$0.42 \pm 0.11 \pm 0.02 \pm 0.03 \pm 0.02$</td>
<td>$0.43 \pm 0.11 \pm 0.02 \pm 0.02 \pm 0.02$</td>
</tr>
<tr>
<td>$\rho(1450)$</td>
<td>$1.36 \pm 0.28 \pm 0.08 \pm 0.19 \pm 0.06$</td>
<td>$1.91 \pm 0.37 \pm 0.73 \pm 0.19 \pm 0.09$</td>
</tr>
<tr>
<td>$\rho(1700)$</td>
<td>$0.33 \pm 0.11 \pm 0.06 \pm 0.05 \pm 0.02$</td>
<td>$0.73 \pm 0.18 \pm 0.53 \pm 0.10 \pm 0.03$</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>$9.5 \pm 0.5 \pm 0.4 \pm 1.0 \pm 0.4$</td>
<td>$9.1 \pm 0.6 \pm 0.8 \pm 0.5 \pm 0.4$</td>
</tr>
<tr>
<td>$D^*_0(2400)^-$</td>
<td>$7.7 \pm 0.5 \pm 0.3 \pm 0.3 \pm 0.4$</td>
<td>$8.0 \pm 0.5 \pm 0.8 \pm 0.4 \pm 0.4$</td>
</tr>
<tr>
<td>$D^*_2(2460)^-$</td>
<td>$24.4 \pm 0.7 \pm 1.0 \pm 0.4 \pm 1.2$</td>
<td>$23.8 \pm 0.7 \pm 1.2 \pm 0.5 \pm 1.1$</td>
</tr>
<tr>
<td>$D^*_3(2760)^-$</td>
<td>$1.03 \pm 0.16 \pm 0.07 \pm 0.08 \pm 0.05$</td>
<td>$1.34 \pm 0.19 \pm 0.16 \pm 0.06 \pm 0.06$</td>
</tr>
</tbody>
</table>

arXiv: 1505.01710; 3 fb$^{-1}$
Light meson structure (1)

2-q model

\[ |f_0(500)⟩ = \frac{1}{\sqrt{2}} (|\bar{u}u⟩ + |\bar{d}d⟩) \equiv |\bar{n}n⟩, \]
\[ |f_0(980)⟩ = |\bar{s}s⟩. \]

13

\[ |f_0(500)⟩ = |\bar{s}s⟩ \cos θ + |\bar{n}n⟩ \sin θ, \]
\[ |f_0(980)⟩ = -|\bar{s}s⟩ \sin θ + |\bar{n}n⟩ \cos θ. \]

4-q model

\[ |f_0(500)⟩ = |\bar{u}u⟩ |\bar{d}d⟩ \]
\[ |f_0(980)⟩ = |\bar{b}b⟩ |\bar{d}d⟩ \]

➢ Proposals given to use \( B_{(s)} \rightarrow J/ψππ \) to understand nature of light mesons \( f_0(500) \) and \( f_0(980) \) and has been performed by LHCb to set upper limits on mixing angles

➢ Similar studies can also be done for \( B_{(s)} \rightarrow D^0ππ \) decays
Light meson structure (2)

\[
\begin{align*}
\mathcal{B}(B^0 \rightarrow \overline{D}^0 f_0) & \quad \mathcal{B}(B_s^0 \rightarrow \overline{D}^0 f_0) \\
 f_0(500) & : (11.2 \pm 0.8 \pm 0.5 \pm 2.1 \pm 0.5) \times 10^{-5} \\
f_0(980) & : (1.34 \pm 0.25 \pm 0.10 \pm 0.46 \pm 0.06) \times 10^{-5} \\
 & \quad (1.7 \pm 1.0 \pm 0.5 \pm 0.1) \times 10^{-6}
\end{align*}
\]

2-q model

4-q model

-arXiv: 1505.01710; 3 fb\(^{-1}\)
arXiv: 1505.01654; 3 fb\(^{-1}\)

Mixing angles of 2-q and 4-q model given as a function of form factor ratios

Results from \(B_s^0 \rightarrow \overline{D}^0 f_0(980)\), \(B^0 \rightarrow \overline{D}^0 f_0(980)\) and \(B^0 \rightarrow \overline{D}^0 f_0(500)\) indicate complicated nature of the system
Other results

<table>
<thead>
<tr>
<th>Channels</th>
<th>Isobar x 10^{-5}</th>
<th>K-Matrix x 10^{-5}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)(\pi^+\pi^-)$</td>
<td>$32.1 \pm 1.4 \pm 1.2 \pm 0.9 \pm 1.5$</td>
<td>$31.0 \pm 1.4 \pm 2.1 \pm 0.7 \pm 1.5$</td>
</tr>
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</table>

> Isospin symmetry between three decays: $B^+\rightarrow D^0\rho^+$, $B^0\rightarrow D^-\rho^+$, $B^0\rightarrow \bar{D}^0\rho^0$,

$$A(\bar{D}^0\rho^+) = \sqrt{3}A_{3/2},$$
$$A(D^-\rho^+) = \sqrt{1/3}A_{3/2} + \sqrt{2/3}A_{1/2},$$
$$A(\bar{D}^0\rho^0) = \sqrt{2/3}A_{3/2} - \sqrt{1/3}A_{1/2},$$

In factorization approximation:

$$R_{D\rho} = \frac{|A_{1/2}|}{\sqrt{2}|A_{3/2}|} = 1 + \mathcal{O}(\Lambda_{QCD}/m_b)$$

$$\delta_{D\rho} = \arg\left(\frac{A_{1/2}}{A_{3/2}}\right) \sim \mathcal{O}(\Lambda_{QCD}/m_b)$$

<table>
<thead>
<tr>
<th>Model</th>
<th>$R_{D\rho}$</th>
<th>$\cos\delta_{D\rho}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isobar</td>
<td>$0.69 \pm 0.15$</td>
<td>$0.984^{+0.113}_{-0.048}$</td>
</tr>
<tr>
<td>K-matrix</td>
<td>$0.69 \pm 0.15$</td>
<td>$0.987^{+0.114}_{-0.048}$</td>
</tr>
</tbody>
</table>

> Uncertainties mainly from Br of $D^+\rho^+$ and $D^0\rho^-$

> The results are not different from the prediction of factorization
Conclusion

➢ Rich physics in $B \rightarrow Dhh$ systems using Dalitz plot techniques

➢ Studies have been performed to understand their resonant contributions, excited $D^*$ spectroscopy, light meson structures etc.

➢ Stay tuned for more analyses in the $B \rightarrow Dhh$ system

Thank You