First observation and amplitude analysis of $B^- \rightarrow D^+ K^- \pi^-$

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IoP 2015
31$^{st}$ March 2015
Introduction and Overview

• Motivation

• Introduction to Spectroscopy and Dalitz plot analysis

• Status of $D^{**}$ spectroscopy

• $B^- \rightarrow D^+K^-\pi^-$ branching fraction measurement

• $B^- \rightarrow D^+K^-\pi^-$ amplitude analysis

arXiv:1503.02995
submitted to PRD
Motivation

- Excited charmed mesons offer a way to study QCD effects
- $D^{**}$ states have been studied at B-factories in the past
  - Only a few predicted states have been observed
- Amplitude analyses allow the measurement of quantum numbers
- $B^- \to D^{**}K^-$ decay mode could be used to measure CKM angle $\gamma$ in the future
Dalitz plot analysis is a powerful tool
- Previously used by B-factories to study charm spectroscopy
- Used at LHCb for $D_s$ spectroscopy ($B_s^0 \rightarrow \bar{D}^0 K^- \pi^+$) [Phys. Rev. D90 (2014) 072003, Phys. Rev. Lett. 113 (2014) 162001]
- Clean and constrained method compared to inclusive production studies
- Allows determination of quantum numbers for states

$B^- \rightarrow D^+ K^- \pi^-$ is an interesting mode to study $D^{**}$ states
- Decay previously unobserved, first measure branching fraction
- No resonances expected to decay to $D^+ K^-$ or $K^- \pi^-$

Use Laura++ Dalitz plot fitting software
- Available on Hepforge
Dalitz plot of $B^- \rightarrow D^+ K^- \pi^-$

- See resonant structures in invariant mass of pairs of daughters
- Reflections visible in other invariant mass pairs
- 2D representation is “Dalitz plot”
- Interference effects visible
Charm spectrum predicted \cite{Godfrey:1985xj}.

Experimental results come from Dalitz plot analyses and prompt production.

Some discrepancies between predicted and measured values.

Evidence for higher mass states, but not yet possible to assign quantum numbers.

Parameters of orbitally excited (1P) states measured at B-factories and LHCb.

- JHEP 1309 (2013) 145
Evidence for several high mass states but no spin-parity information yet

- Spectrum can be studied with a Dalitz plot analysis of $B^- \rightarrow D^+ K^- \pi^-$
- Only states with natural spin-parity ($J^P$) can decay to $D^+ \pi^-$
- $D_0^*(2400)^0$, $D_2^*(2460)^0$ and higher mass states expected to contribute
- Amplitude analysis techniques give spin-parity information
Branching fraction measurement

- Events selected with loose cuts and neural network used to reduce backgrounds

- \( \sim 2000 \, B^- \rightarrow D^+ K^- \pi^- \) candidate events (> 60\(\sigma\) observation!)

- Branching fraction measured wrt to \( B^- \rightarrow D^+ \pi^- \pi^- \)

\[
\mathcal{B}(B^- \rightarrow D^+ K^- \pi^-) = (7.92 \pm 0.23 \pm 0.24 \pm 0.42) \times 10^{-5}
\]

Uncertainties are statistical, systematic and due to PDG uncertainty on \( B^- \rightarrow D^+ \pi^- \pi^- \) BF
Dalitz plot model

- Efficiency and background distributions studied and used as input

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Spin</th>
<th>DP axis</th>
<th>Model</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_0^*(2400)^0$</td>
<td>0</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>$m = 2318 \pm 29$ MeV/c$^2$, $\Gamma = 267 \pm 40$ MeV</td>
</tr>
<tr>
<td>$D_2^*(2460)^0$</td>
<td>2</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>Floated</td>
</tr>
<tr>
<td>$D_J^*(2760)^0$</td>
<td>1</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>Floated</td>
</tr>
<tr>
<td>Nonresonant $^0$</td>
<td>0</td>
<td>$m^2(D\pi)$</td>
<td>EFF</td>
<td>Floated</td>
</tr>
<tr>
<td>Nonresonant $^0$</td>
<td>1</td>
<td>$m^2(D\pi)$</td>
<td>EFF</td>
<td>Floated</td>
</tr>
<tr>
<td>$D_v^*(2007)^0$</td>
<td>1</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>$m = 2006.98 \pm 0.15$ MeV/c$^2$, $\Gamma = 2.1$ MeV</td>
</tr>
<tr>
<td>$B_v^{*0}$</td>
<td>1</td>
<td>$m^2(DK)$</td>
<td>RBW</td>
<td>$m = 5325.2 \pm 0.4$ MeV/c$^2$, $\Gamma = 0.0$ MeV</td>
</tr>
</tbody>
</table>

- $D_0^*(2400)^0$ and $D_2^*(2460)^0$ states expected
- High mass $D_J^*(2760)^0$ state included, previously unknown spin
- Two virtual states
- Relativistic Breit-Wigner shape used to model resonances
- Two non-resonant components (S-wave and P-wave), exponential model
  - Model independent tests support need for both
Dalitz plot fit

**LHCb (d)**

- Candidates / (46 MeV)
- $m(D^+ K^-)$ [GeV]

**LHCb (f)**

- Candidates / (40 MeV)
- $m(K^- \pi^+)$ [GeV]

- **Data**
- **Full fit**
- **Nonresonant S-wave**
- **Nonresonant P-wave**
- **Background**

**LHCb (b)**

- Candidates / (40 MeV)
- $m(D^+ \pi^-)$ [GeV]
Dalitz plot fit

Candidates / (46 MeV)

Candidates / (40 MeV)

Data

Full fit

Background

$D_0^*(2400)^0$

$D_2^*(2460)^0$

$D_s^*(2760)^0$

$B_s^*$

$D_0^*(2007)^0$

Nonresonant S-wave

Nonresonant P-wave

LHCb (d)

LHCb (b)

LHCb (f)
Dalitz plot fit

- (Bottom) helicity angle distributions for (top) interesting $m(D^+ \pi^-)$ regions
Dalitz plot analysis results

- $D_1^*(2760)^0$ determined to have spin-1
  - Other hypotheses rejected with high significance

- Masses and widths of $D_2^*(2460)^0$ and $D_1^*(2760)^0$ reported:

  \[
  \begin{align*}
  m(D_2^*(2460)^0) &= (2464.0 \pm 1.4 \pm 0.5 \pm 0.2) \text{ MeV}/c^2 \\
  \Gamma(D_2^*(2460)^0) &= (43.8 \pm 2.9 \pm 1.7 \pm 0.6) \text{ MeV} \\
  m(D_1^*(2760)^0) &= (2781 \pm 18 \pm 11 \pm 6) \text{ MeV}/c^2 \\
  \Gamma(D_1^*(2760)^0) &= (177 \pm 32 \pm 20 \pm 7) \text{ MeV}
  \end{align*}
  \]

  Previous world averages:
  \[
  \begin{align*}
  m(D_2^*(2460)^0) &= (2462.6 \pm 0.6) \text{ MeV}/c^2 \\
  \Gamma(D_2^*(2460)^0) &= (49.0 \pm 1.3) \text{ MeV}
  \end{align*}
  \]

  Uncertainties are statistical, experimental systematic and model uncertainties

- Product branching fractions ($\times 10^{-4}$) measured:

  \[
  \begin{array}{|c|c|}
  \hline
  \text{Resonance} & \text{Branching fraction} \\
  \hline
  D_0^*(2400)^0 & 6.6 \pm 2.1 \pm 0.5 \pm 1.5 \pm 0.4 \\
  D_2^*(2460)^0 & 25.2 \pm 1.2 \pm 0.7 \pm 1.1 \pm 1.7 \\
  D_1^*(2760)^0 & 3.9 \pm 1.0 \pm 0.3 \pm 0.7 \pm 0.3 \\
  \text{S-wave nonresonant} & 30.1 \pm 5.9 \pm 1.2 \pm 8.6 \pm 2.0 \\
  \text{P-wave nonresonant} & 18.9 \pm 4.4 \pm 1.6 \pm 2.9 \pm 1.3 \\
  D_0^*(2007)^0 & 6.0 \pm 1.8 \pm 1.0 \pm 1.2 \pm 0.4 \\
  B_v^* & 2.9 \pm 1.5 \pm 0.7 \pm 1.3 \pm 0.2 \\
  \hline
  \end{array}
  \]

  Final errors due to uncertainty on $DK\pi$ BF result
Conclusions

• New $D^{**}$ results from Dalitz plot analysis of $B^- \rightarrow D^+ K^- \pi^-$ decays

• First observation of $B^- \rightarrow D^+ K^- \pi^-$ decay

• $D_1^*(2760)^0$ determined to have spin-1

• Masses and widths of $D_2^*(2460)^0$ and $D_1^*(2760)^0$ measured

• Product branching fractions of resonances measured

• Work on-going to study $D^{**}$ states in other decay modes with higher statistics
• Long lived heavy hadrons are predominantly produced in the forward direction
• LHCb geometry exploits this fact

• Vertex Locator (VELO) – precise tracking very close to the interaction point
• Two Ring Imaging Cherenkov (RICH) detectors – separation of kaons and pions
Trigger categories at LHCb

- **Trigger On Signal** – particle from signal decay fires trigger
  - HCAL deposits

- **Trigger Independent of Signal** – particle from rest of the event fires trigger
  - HCAL deposits and muon hits
Square Dalitz plot

- Coordinate transform of Dalitz plot to give a square phase space

- In this choice of SDP representation, $m'$ is related to $m(D\pi)$ in reverse and $\theta'$ is the $D\pi$ helicity angle
  - Resonances decaying to $D^+\pi^-$ appear vertically at high $m'$
$B^- \rightarrow D^+ K^- \pi^-$ branching fraction

- Systematics evaluated:

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c^+$ veto</td>
<td>0.2</td>
</tr>
<tr>
<td>Fit model</td>
<td>2.0</td>
</tr>
<tr>
<td>Particle identification</td>
<td>2.1</td>
</tr>
<tr>
<td>Efficiency modelling</td>
<td>0.8</td>
</tr>
<tr>
<td>Total</td>
<td>3.0</td>
</tr>
</tbody>
</table>

- BF measured w.r.t. topologically similar $B^- \rightarrow D^+ \pi^- \pi^-$

\[
\frac{\mathcal{B}(B^- \rightarrow D^+ K^- \pi^-)}{\mathcal{B}(B^- \rightarrow D^+ \pi^- \pi^-)} = 0.0702 \pm 0.0020 \pm 0.0021
\]

$\mathcal{B}(B^- \rightarrow D^+ K^- \pi^-) = (7.92 \pm 0.23 \pm 0.24 \pm 0.42) \times 10^{-5}$

Uncertainties are statistical, systematic and due to PDG uncertainty on $B^- \rightarrow D^+ \pi^- \pi^-$ BF
$B^- \rightarrow D^+K^-\pi^-$ selection

- Identical selection applied to $D\pi\pi$ and $DK\pi$ candidates apart from Particle Identification (PID) requirement on the one different track.

- $D$ candidates reconstructed as $D^+ \rightarrow K^-\pi^+\pi^+$

- Loose initial requirements applied to suppress background contributions

- $D\pi\pi$ data used to train two neural networks – first to clean up D candidates, second to suppress combinatorial background
  - sPlot technique used to statistically separate signal and background events
  - Combinatorial background reduced by an order of magnitude, 90% signal kept

- PID requirements applied to all 5 final state tracks
Backgrounds

- Signal region is taken as $\pm 2.5\sigma$

- Signal region is 93.2% pure – three backgrounds contribute:
  - $B^- \rightarrow D_s^+ K^- \pi^-$ (1.4%),
  - $B^- \rightarrow D^+ \pi^- \pi^-$ (1.7%),
  - combinatorial (3.5%)
Efficiency and background distributions

• Signal efficiency distribution for events triggered by (left) particles in the candidate decay, (right) other particles in the event

• Signal region is 93% pure – three backgrounds contribute: (left) $B^- \rightarrow D_s^+ K^- \pi^-$, (middle) $B^- \rightarrow D^+ \pi^- \pi^-$, (right) combinatorial
Previous $D^{**}$ spectroscopy measurements

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV/$c^2$)</th>
<th>Width (MeV)</th>
<th>$J^P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_0^*(2400)^0$</td>
<td>2318 ± 29</td>
<td>267 ± 40</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$D_1(2420)^0$</td>
<td>2421.4 ± 0.6</td>
<td>27.4 ± 2.5</td>
<td>1$^+$</td>
</tr>
<tr>
<td>$D_1'(2430)^0$</td>
<td>2427 ± 26 ± 20 ± 15</td>
<td>384 $^{+107}_{-75}$ ± 24 ± 70</td>
<td>1$^+$</td>
</tr>
<tr>
<td>$D_2^*(2460)^0$</td>
<td>2462.6 ± 0.6</td>
<td>49.0 ± 1.3</td>
<td>2$^+$</td>
</tr>
<tr>
<td>$D^*(2600)$</td>
<td>2608.7 ± 2.4 ± 2.5</td>
<td>93 ± 6 ± 13</td>
<td>natural</td>
</tr>
<tr>
<td>$D^*(2650)$</td>
<td>2649.2 ± 3.5 ± 3.5</td>
<td>140 ± 17 ± 19</td>
<td>natural</td>
</tr>
<tr>
<td>$D^*(2760)$</td>
<td>2763.3 ± 2.3 ± 2.3</td>
<td>60.9 ± 5.1 ± 3.6</td>
<td>natural</td>
</tr>
<tr>
<td>$D^*(2760)$</td>
<td>2760.1 ± 1.1 ± 3.7</td>
<td>74.4 ± 3.4 ± 19.1</td>
<td>natural</td>
</tr>
</tbody>
</table>

### Fit results

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Real part</th>
<th>Imaginary part</th>
<th>Magnitude</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^*_0(2400)^0$</td>
<td>$-0.04 \pm 0.07 \pm 0.03 \pm 0.28$</td>
<td>$-0.51 \pm 0.07 \pm 0.02 \pm 0.13$</td>
<td>$0.51 \pm 0.09 \pm 0.02 \pm 0.15$</td>
<td>$-1.65 \pm 0.16 \pm 0.06 \pm 0.50$</td>
</tr>
<tr>
<td>$D^*_2(2460)^0$</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$D^*_1(2760)^0$</td>
<td>$-0.32 \pm 0.06 \pm 0.03 \pm 0.03$</td>
<td>$-0.23 \pm 0.07 \pm 0.03 \pm 0.03$</td>
<td>$0.39 \pm 0.05 \pm 0.01 \pm 0.03$</td>
<td>$-2.53 \pm 0.24 \pm 0.08 \pm 0.08$</td>
</tr>
<tr>
<td>Nonresonant (S-wave)</td>
<td>0.93 $\pm 0.09 \pm 0.03 \pm 0.17$</td>
<td>$-0.58 \pm 0.08 \pm 0.03 \pm 0.15$</td>
<td>1.09 $\pm 0.09 \pm 0.02 \pm 0.20$</td>
<td>$-0.56 \pm 0.09 \pm 0.04 \pm 0.11$</td>
</tr>
<tr>
<td>Nonresonant (P-wave)</td>
<td>$-0.43 \pm 0.09 \pm 0.03 \pm 0.34$</td>
<td>0.75 $\pm 0.09 \pm 0.05 \pm 0.68$</td>
<td>0.87 $\pm 0.09 \pm 0.03 \pm 0.11$</td>
<td>2.09 $\pm 0.15 \pm 0.05 \pm 0.95$</td>
</tr>
<tr>
<td>$D^*_v(2007)^0$</td>
<td>0.16 $\pm 0.08 \pm 0.03 \pm 0.56$</td>
<td>0.46 $\pm 0.09 \pm 0.04 \pm 0.77$</td>
<td>0.49 $\pm 0.07 \pm 0.04 \pm 0.05$</td>
<td>1.24 $\pm 0.17 \pm 0.07 \pm 0.60$</td>
</tr>
<tr>
<td>$B^*_v$</td>
<td>$-0.07 \pm 0.08 \pm 0.22 \pm 0.09$</td>
<td>$0.33 \pm 0.07 \pm 0.02 \pm 0.08$</td>
<td>$0.34 \pm 0.06 \pm 0.03 \pm 0.07$</td>
<td>$1.78 \pm 0.23 \pm 0.11 \pm 0.27$</td>
</tr>
</tbody>
</table>

### Fit fraction

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Fit fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^*_0(2400)^0$</td>
<td>8.3 $\pm 2.6 \pm 0.6 \pm 1.9$</td>
</tr>
<tr>
<td>$D^*_2(2460)^0$</td>
<td>31.8 $\pm 1.5 \pm 0.9 \pm 1.4$</td>
</tr>
<tr>
<td>$D^*_1(2760)^0$</td>
<td>4.9 $\pm 1.2 \pm 0.3 \pm 0.9$</td>
</tr>
<tr>
<td>Nonresonant (S-wave)</td>
<td>38.0 $\pm 7.4 \pm 1.5 \pm 10.8$</td>
</tr>
<tr>
<td>Nonresonant (P-wave)</td>
<td>23.8 $\pm 5.6 \pm 2.1 \pm 3.7$</td>
</tr>
<tr>
<td>$D^*_v(2007)^0$</td>
<td>7.6 $\pm 2.3 \pm 1.3 \pm 1.5$</td>
</tr>
<tr>
<td>$B^*_v$</td>
<td>3.6 $\pm 1.9 \pm 0.9 \pm 1.6$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_S$</td>
<td>0.36 $\pm 0.03$</td>
</tr>
<tr>
<td>$\alpha_P$</td>
<td>0.36 $\pm 0.04$</td>
</tr>
</tbody>
</table>
Legendre moments for $B^- \rightarrow D^+ K^- \pi^-$

- Angular distributions are Legendre Polynomials
- Allows angular moments to be calculated from Legendre polynomials
  - Done up to an order of $2 \times$ maximum spin of resonances
- Weighting with Legendre polynomials exploits their orthogonality
  - $N \langle P_l \rangle = \sum_j^N w_j P_l(\cos(\theta_{D\pi}))$ for $N$ events in each bin of $m(D\pi)$
  - Contributions of different spins can be accessed
- In general, the moment $\langle P_l \rangle$ contains
  - for odd $l$: interference terms between even and odd partial waves
  - for even $l$: partial waves with $J \geq l/2$ and interference terms between even and even or odd and odd partial waves
Legendre moments for $B^- \to D^+ K^- \pi^-$

- Moments for $m(D\pi)$
- Data and fit model
- No structure in $P_5$ and $P_6$ suggest no spin-3 contribution in data
Goodness of fit for $B^- \rightarrow D^+ K^- \pi^-$ Dalitz plot fit

- Adaptive binning – equal number of events per bin
- $1.38 < \chi^2/\text{ndf} < 1.68$
  - ndf between nbins-1 and nbins-npars-1
- Fits to toy data support result of $\chi^2/\text{ndf} = 1.68$ for binning choice
- Pulls across SDP shown:
$B^- \rightarrow D^+ K^- \pi^-$ DP systematics

• Extensive systematic studies performed
  • Systematic uncertainties calculated for all reported fit parameters
  • All systematics have varying effects on measured quantities but systematics that tend to dominate are shown in red

• Experimental systematics
  • Signal and background yields
  • Efficiency distribution
  • Background distributions
  • Fit bias

• Model uncertainties
  • Fixed parameters in DP model
  • Test model (add/remove marginal components)
  • Alternative models for non-resonant and virtual components