CP violation in charmless multi-body beauty decays

Cayo Costa Sobral, on behalf of the LHCb collaboration

XXXIII Rencontres de Physique de la Vallée d'Aoste – 12/03/2019
Charmless multi-body decays

• Tree-level $b \to u$ transitions are comparable to loop-level $b \to s, d$ amplitudes
  • Potential new physics in loops
  • Potential for large CP violation (CPV) in tree-penguin interference
  • Tests/input to QCD

• Multi-body decays can proceed via a number of intermediate states
  • Resonant + non-resonant contributions can interfere $\to$ variation in phase
  • CP asymmetry ($A_{CP}$) as a function of phase-space ($+$ phase-space integrated $A_{CP}$)
  • Many techniques available: Amplitude analyses, binned phase-space asymmetries, triple-product asymmetries

\[ B^{\pm} \to \pi^{\pm} K^{+} K^- \]
Charmless multi-body decays

• LHCb is able to study the whole family of $b$-hadrons: $B^0, B^\pm, B_s^0, \Lambda_b^0$, etc...

• **Some recent results:**
  • Amplitude analysis of the $B^0 \rightarrow K^*0 \bar{K}^*0$ decay and measurement of its relative branching fraction with the $B_s^0 \rightarrow K^*0 \bar{K}^*0$ decay [LHCb-PAPER-2019-004, in preparation]
  • Study of the $B^0 \rightarrow \rho(770)^0 K^*(892)^0$ mode with an amplitude analysis of $B^0 \rightarrow (\pi^\pm \pi^\mp)(K^+\pi^-)$ decays [arxiv:1812.07008, submitted to JHEP]
  • Measurement of CP asymmetries in charmless four-body $\Lambda_b^0$ and $\Xi_b^0$ decays [LHCb-PAPER-2018-044, in preparation]
  • Amplitude analysis of $B^\pm \rightarrow \pi^\pm K^+ K^-$ decays [LHCb-PAPER-2018-051, in preparation]
  • Amplitude analysis of $B_s^0 \rightarrow K_s^0 K^\pm \pi^\mp$ decays [arxiv:1902.07955, submitted to JHEP]
Isobar model

- Amplitude analyses (AA) are usually carried out via the “isobar model” – full decay amplitude as coherent sum of individual amplitudes

\[ A(m^2_{ij}, m^2_{jk}) = \sum_{r=1}^{N} c_r F_r(m^2_{ij}, m^2_{jk}) \]

- \( c_r \) – complex coefficient describing relative contribution of the different intermediate states
- \( F_r \) – describes the dynamics of the intermediate states (lineshape + angular distribution)

- Extract from the fit: \( \text{Re}(c_r), \text{Im}(c_r) \) or \( |c_r|, \text{arg}(c_r) \)
  - And the corresponding values for \( \bar{c}_r \), the coefficient of the charge conjugate decay
- Other quantities are derived from these e.g. branching fractions, \( A_{CP} \)

\[ A_{CP} = \frac{|\bar{c}_r|^2 - |c_r|^2}{|\bar{c}_r|^2 + |c_r|^2} \]

Fit fraction:
\[ FF_r = \frac{\int |c_r F_r|^2 \, dm^2_{ij} dm^2_{jk}}{\int |A|^2 \, dm^2_{ij} dm^2_{jk}} \]
$B^\pm \rightarrow \pi^\pm K^+ K^-$

- Previously studied by LHCb [Phys. Rev. D90 (2014) 112004]
  - Inclusive $A_{CP} = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$
  - Phase-space regions with even larger $A_{CP}$
  - Model independent – no information on contributing intermediate states

- First amplitude analysis of this channel
  - Using 2011+2012 data corresponding to 3.0fb$^{-1}$
  - Follow up to binned $A_{CP}$ measurement
  - 2052 $B^+$ and 1566 $B^-$ signal candidates in the fit region

- Signal PDF includes:
  - Resonant contributions from $K^*(892)^0, K^*_0(1430)$ in $K\pi$ and $ho(1450), f_2(1270), \phi(1020)$ in $KK$
  - A single-pole form factor to describe non-resonant $K\pi$ contribution
  - Dedicated amplitude for $\pi\pi \leftrightarrow KK$ rescattering
$B^\pm \rightarrow \pi^\pm K^+ K^-$

- Single-pole form factor provides better description than resonant contributions tested such as $\kappa$
  - Form factor of the form $(1 + m_{\pi K}^2/\Lambda^2)^{-1}, \Lambda = 1\text{GeV}$

- Destructive interference pattern at high $m_{\pi K}^2$ is described by combination of $\rho(1450)$ and $f_2(1270)$

- $\pi\pi \leftrightarrow KK$ rescattering amplitude based on Pelaez and Yndurain [Phys. Rev. D 71 (2005) 074016]
  - Rescattering in the region $1.0 < m_{KK}^2 < 1.5$ GeV/$c^2$ (see next slide)
  - $\mathcal{A}_{\text{rescatt}} = \mathcal{A}_{\text{source}} \cdot f_{\text{scattering}}$, with $\mathcal{A}_{\text{source}} = (1 + m_{KK}^2/\Lambda^2)^{-1}$
  - $f_{\text{scattering}} = \sqrt{1 - \eta^2} e^{2i\delta}$ is the off-diagonal term in the $\pi\pi - KK$ coupled channel S-matrix
$B^\pm \rightarrow \pi^\pm K^+ K^-$

- Fit results:

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Fit Fraction(%)</th>
<th>$A_{CP}(%)$</th>
<th>Amplitude $(B^+/B^-)$</th>
<th>Phase[$\circ$] $(B^+/B^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^0$</td>
<td>7.5 ± 0.6 ± 0.5</td>
<td>12.3 ± 8.7 ± 4.5</td>
<td>0.94 ± 0.04 ± 0.02 / 1.06 ± 0.04 ± 0.02</td>
<td>0 (fixed)</td>
</tr>
<tr>
<td>$K^*_0(1430)$</td>
<td>4.5 ± 0.7 ± 1.2</td>
<td>10.4 ± 14.9 ± 8.8</td>
<td>0.74 ± 0.09 ± 0.09 / 0.82 ± 0.09 ± 0.10</td>
<td>$-176 \pm 10 \pm 16 / 136 \pm 11 \pm 21$</td>
</tr>
<tr>
<td>Single-Pole Form Factor</td>
<td>32.3 ± 1.5 ± 4.1</td>
<td>$-10.7 \pm 5.3 \pm 3.5$</td>
<td>2.19 ± 0.13 ± 0.17 / 1.97 ± 0.12 ± 0.20</td>
<td>$-138 \pm 7 \pm 5 / 166 \pm 6 \pm 5$</td>
</tr>
<tr>
<td>$\rho(1450)$</td>
<td>30.7 ± 1.2 ± 0.9</td>
<td>$-10.9 \pm 4.4 \pm 2.4$</td>
<td>2.14 ± 0.11 ± 0.07 / 1.92 ± 0.10 ± 0.07</td>
<td>$-175 \pm 10 \pm 15 / 140 \pm 13 \pm 20$</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>7.5 ± 0.8 ± 0.7</td>
<td>26.7 ± 10.2 ± 4.8</td>
<td>0.86 ± 0.09 ± 0.07 / 1.13 ± 0.08 ± 0.05</td>
<td>$-106 \pm 11 \pm 10 / -128 \pm 11 \pm 14$</td>
</tr>
<tr>
<td>rescattering</td>
<td>16.4 ± 0.8 ± 1.0</td>
<td>$-66.4 \pm 3.8 \pm 1.9$</td>
<td>1.91 ± 0.09 ± 0.06 / 0.86 ± 0.07 ± 0.04</td>
<td>$-56 \pm 12 \pm 18 / -81 \pm 14 \pm 15$</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>0.3 ± 0.1 ± 0.09</td>
<td>9.8 ± 43.6 ± 26.6</td>
<td>0.20 ± 0.07 ± 0.02 / 0.22 ± 0.06 ± 0.04</td>
<td>$-52 \pm 23 \pm 32 / 107 \pm 33 \pm 41$</td>
</tr>
</tbody>
</table>

$\phi(1020)$ seen at $3\sigma$ level

Largest $A_{CP}$ reported for a single amplitude
$B_S^0 \rightarrow K_S^0 K^\pm \pi^\mp$

- First amplitude analysis of these decays
  - Untagged, decay-time-integrated
  - Novel approach – simultaneous amplitude fit of two final states
  - Using 3.0 fb$^{-1}$ of data (2011+2012)
- The two final states $K_S^0 K^+ \pi^-$ and $K_S^0 K^- \pi^+$ are both accessible by $B_S^0$ and $\bar{B}_S^0$
- Previously observed by LHCb
- Measurements of resonant contributions also performed
  - $B_S^0 \rightarrow K^{*\pm} K^\mp$ [New J. Phys. 16 (2014) 123001]
  - $B_S^0 \rightarrow K^{*0} K_S^0$ [JHEP 01 (2016) 012]
  - Potential for time-dependent CP violation measurements with larger samples

La Thuile – 12/03/2019
\[ B_{s}^{0} \rightarrow K_{s}^{0}K^{\pm}\pi^{\mp} \]

- Event selection follows closely from updated BF measurement \[ \text{JHEP 11 (2017) 027} \]
  - Criteria have been reoptimized for an AA
- Data sample divided into 24 sub-samples
  - Four final states: \( K_{s}^{0}K^{\pm}\pi^{\mp}, K_{s}^{0}\pi^{+}\pi^{-}, K_{s}^{0}K^{+}K^{-} \)
  - Two \( K_{s}^{0} \) reconstruction categories
  - Three data-taking periods
- Simultaneous, unbinned, extended maximum-likelihood fit to all sub-samples to extract signal yields
  - Signal yields of \( 431.1(489.4) \) in \( K_{s}^{0}K^{+}\pi^{-} (K_{s}^{0}K^{-}\pi^{+}) \) in the region used for the AA
\[ B_s^0 \rightarrow K_S^0 K^\pm \pi^\mp \]

- Both \( B_s^0 \) and \( \bar{B}_s^0 \) contribute to each final state \( f \) but the two amplitudes need not be the same: \( A_f \neq \bar{A}_f \)

- Untagged analysis means that the \( B_s^0 \) and \( \bar{B}_s^0 \) contributions cannot be untangled

- Amplitude fit is performed using an effective amplitude that is some combination of \( A_f \) and \( \bar{A}_f \)
  - Akin to CP-averaged amplitude fits

- Method validated by generating pseudoexperiments with full decay-time-dependent model
  - Amplitude parameters based on expected BFs + range of CP violation hypotheses
  - Effective model results for fit fractions are found to be robust
$B_S^0 \rightarrow K_S^0 K^\pm \pi^{\mp}$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Fit fraction (%)</th>
<th>Resonance</th>
<th>Fit fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^-$</td>
<td>15.6 ± 1.5</td>
<td>$K^+(892)^+$</td>
<td>13.4 ± 2.0</td>
</tr>
<tr>
<td>$K^*(1430)^-$</td>
<td>30.2 ± 2.6</td>
<td>$K^*(1430)^+$</td>
<td>28.5 ± 3.6</td>
</tr>
<tr>
<td>$K_2^0(1430)^-$</td>
<td>2.9 ± 1.3</td>
<td>$K_2^*(1430)^+$</td>
<td>5.8 ± 1.9</td>
</tr>
<tr>
<td>$K^*(892)^0$</td>
<td>13.2 ± 2.4</td>
<td>$K^*(892)^0$</td>
<td>19.2 ± 2.3</td>
</tr>
<tr>
<td>$K^*_0(1430)^0$</td>
<td>33.9 ± 2.9</td>
<td>$K^*_0(1430)^0$</td>
<td>27.0 ± 4.1</td>
</tr>
<tr>
<td>$K_2^*(1430)^0$</td>
<td>5.9 ± 4.0</td>
<td>$K_2^*(1430)^0$</td>
<td>7.7 ± 2.8</td>
</tr>
</tbody>
</table>

- Contributions in $m_{K^+K_S}^2$ such as $a_2(1320)\pm$ were considered but found to be negligible
- Vector and tensor states modelled with Breit—Wigner functions
- $K\pi$ S-wave modelled with LASS lineshape, combines $K_0^*(1430)$ + non-resonant shape
- $K_0^*(1430)$ contributions observed at $> 10\sigma$ level for the first time
- No significant CP violation seen
$B^0_S \rightarrow K^0_S K^\pm \pi^\mp$

- Branching fractions can be obtained from the flavour-averaged fit fractions:

$$B \left( B^0_s \rightarrow K^* (892)^\pm K^\mp; \ K^* (892)^\pm \rightarrow \overline{K}^0 \pi^\pm \right) = (12.4 \pm 0.8 \pm 0.5 \pm 2.7 \pm 1.3) \times 10^{-6}$$

$$B \left( B^0_s \rightarrow (\overline{K}^0 \pi^\mp)_0 K^\mp \right) = (24.9 \pm 1.8 \pm 0.5 \pm 20.0 \pm 2.6) \times 10^{-6}$$

$$B \left( B^0_s \rightarrow K_{s}^0(1430)^\pm K^\mp; \ K_{s}^0(1430)^\pm \rightarrow \overline{K}^0 \pi^\pm \right) = (3.4 \pm 0.8 \pm 0.4 \pm 5.4 \pm 0.4) \times 10^{-6}$$

$$B \left( B^0_s \rightarrow \overline{K}^0(892)^0 \overline{K}^0; \ \overline{K}^0(892)^0 \rightarrow K^\mp \pi^\pm \right) = (13.2 \pm 1.9 \pm 0.8 \pm 2.9 \pm 1.4) \times 10^{-6}$$

$$B \left( B^0_s \rightarrow (K^\mp \pi^\pm)_0 \overline{K}^0 \right) = (26.2 \pm 2.0 \pm 0.7 \pm 7.3 \pm 2.8) \times 10^{-6}$$

$$B \left( B^0_s \rightarrow \overline{K}_{s}^0(1430)^0 \overline{K}^0; \ \overline{K}_{s}^0(1430)^0 \rightarrow K^\mp \pi^\pm \right) = (5.6 \pm 1.5 \pm 0.6 \pm 7.0 \pm 0.6) \times 10^{-6}$$

- Largest systematic uncertainty comes from alternative $K\pi$ S-wave parameterisation

- $(K\pi)_0^*$ refers to the total $K\pi$ S-wave
Summary

• Charmless multi-body decays are a crucial area for studying CP violation

• LHCb continues to provide many interesting results
  • Motivation for Run 2 analyses + LHCb upgrade
  • Some areas exclusive to LHCb in the near future: $B_s^0, b$-baryons

• $B^\pm \to \pi^\pm K^+K^-$ reports largest $A_{CP}$ for a single amplitude
  • Inclusion of rescattering amplitude highlights constructive dialogue between theory and experiment in developing new models
  • Potentially important for channels with larger datasets
  • Size of rescattering hints towards need of coupled-channel analyses

• $B_s^0 \to K_S^0 K^+\pi^-$ analysis:
  • Observation of $K_0^*(1430)$ states, with $> 10\sigma$ significance
  • Full flavour-tagged, decay-time-dependent analysis only possible following LHCb upgrade
Backup
$K\pi$ S-wave

$K^*(892)$

$D_{s2}^*(2573)^-$
Previous $B^\pm \to \pi^\pm K^+ K^-$ measurements:

<table>
<thead>
<tr>
<th></th>
<th>$\mathcal{B}$F</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>$(5.0 \pm 0.5 \pm 0.5) \times 10^{-6}$</td>
<td>$-$</td>
</tr>
<tr>
<td>LHCb</td>
<td>$-$</td>
<td>$-0.123 \pm 0.017 \pm 0.012 \pm 0.007$</td>
</tr>
<tr>
<td>Belle</td>
<td>$(5.38 \pm 0.40 \pm 0.35) \times 10^{-6}$</td>
<td>$-0.170 \pm 0.073 \pm 0.017$</td>
</tr>
</tbody>
</table>

La Thuile – 12/03/2019
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{*}(892)^-$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
<td>0.2</td>
<td>–</td>
<td>0.7</td>
<td>5.4</td>
<td>3.1</td>
<td>6.3</td>
</tr>
<tr>
<td>$K_0^*(1430)^-$</td>
<td>0.1</td>
<td>0.2</td>
<td>0.6</td>
<td>0.3</td>
<td>0.1</td>
<td>2.1</td>
<td>22.0</td>
<td>2.9</td>
<td>22.3</td>
</tr>
<tr>
<td>$K_2^*(1430)^-$</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>0.6</td>
<td>0.1</td>
<td>1.8</td>
<td>2.2</td>
<td>0.2</td>
<td>2.9</td>
</tr>
<tr>
<td>$K^{*}(892)^0$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.9</td>
<td>–</td>
<td>0.3</td>
<td>7.0</td>
<td>2.0</td>
<td>7.4</td>
</tr>
<tr>
<td>$K_0^*(1430)^0$</td>
<td>0.2</td>
<td>0.3</td>
<td>0.9</td>
<td>0.4</td>
<td>0.1</td>
<td>4.4</td>
<td>3.3</td>
<td>1.3</td>
<td>5.7</td>
</tr>
<tr>
<td>$K_2^*(1430)^0$</td>
<td>0.1</td>
<td>0.3</td>
<td>0.7</td>
<td>1.3</td>
<td>0.2</td>
<td>4.4</td>
<td>3.6</td>
<td>1.0</td>
<td>6.0</td>
</tr>
<tr>
<td>$K^{*}(892)^+$</td>
<td>0.4</td>
<td>0.1</td>
<td>0.6</td>
<td>0.5</td>
<td>0.1</td>
<td>0.7</td>
<td>1.1</td>
<td>0.7</td>
<td>1.8</td>
</tr>
<tr>
<td>$K_0^*(1430)^+$</td>
<td>0.5</td>
<td>0.4</td>
<td>0.7</td>
<td>0.8</td>
<td>0.2</td>
<td>6.4</td>
<td>13.0</td>
<td>4.5</td>
<td>15.2</td>
</tr>
<tr>
<td>$K_2^*(1430)^+$</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>4.1</td>
<td>4.5</td>
<td>3.2</td>
<td>6.9</td>
</tr>
<tr>
<td>$K^{*}(892)^0$</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
<td>3.0</td>
<td>7.9</td>
<td>8.5</td>
</tr>
<tr>
<td>$K_0^*(1430)^0$</td>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>0.7</td>
<td>0.9</td>
<td>3.9</td>
<td>5.4</td>
<td>6.8</td>
</tr>
<tr>
<td>$K_2^*(1430)^0$</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
<td>0.8</td>
<td>0.1</td>
<td>1.0</td>
<td>5.5</td>
<td>2.7</td>
<td>6.3</td>
</tr>
</tbody>
</table>
Backup $- \Lambda^0_b, \Xi^0_b \rightarrow 4$-body

- CP violation search in 6 modes
- Measure difference in $A_{CP}$ between charmless decay and decay with intermediate charm baryon
  - Cancel out detector+production charge asymmetries
- 18 CP asymmetries considered:
  - Inclusive $A_{CP}$ of the six modes
  - $A_{CP}$ in low two-body mass regions in the large-yield channels
  - $A_{CP}$ in regions containing specific intermediate baryonic/mesonic resonances
- No significant CP violation observed
  - Contrast with evidence ($3.3 \sigma$) seen previously in $\Lambda^0_b \rightarrow p\pi^-\pi^+\pi^-$ using triple-product asymmetries
    - [Nature Physics 13 (2017) 391]
Backup – $B^0 \rightarrow \rho(770)^0 K^*(892)^0$

- First AA of $B^0 \rightarrow (\pi^+\pi^-)(K^+\pi^-)$
  - $300 < m(\pi^+\pi^-) < 1100$ MeV/$c^2$
  - $750 < m(K^+\pi^-) < 1200$ MeV/$c^2$

- Fit model includes 10 decay channels = 14 amplitudes
  - Each Vector-Vector wave contributes 3 amplitudes
  - GPU-based fit framework to deal with high-dimensionality

![B0 fit shown](image)
**Backup – $B^0 \rightarrow \rho(770)^0 K^*(892)^0$**

- Particularly small longitudinal polarisation fraction and significant direct CP asymmetry measured for $B^0 \rightarrow \rho(770)^0 K^*(892)^0$
  
  \[ P_{\rho K^*}^0 = 0.164 \pm 0.015 \pm 0.022 \text{ and } A_{\rho K^*}^0 = -0.62 \pm 0.09 \pm 0.09 > 5\sigma \]

- Parameters for $B^0 \rightarrow \omega K^*0$ also determined
  
  \[ P_{\omega K^*}^0 = 0.68 \pm 0.17 \pm 0.16 \text{ and } A_{\omega K^*}^0 = -0.13 \pm 0.27 \pm 0.13 \]