Studies of multibody charmless B decays at LHCb

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The 2013 European Physical Society Conference on High Energy Physics
1. \( CP \) Violation in \( B^{\pm} \rightarrow K^{\pm} h^+ h^- \) decays

2. \( CP \) asymmetries and dynamics in \( B^{\pm} \rightarrow p\bar{p} h^\pm \)

3. Branching fraction measurements of \( B^0_{(s)} \rightarrow K^0_s h^\pm h^{\mp'} \)

4. Search for \( \Lambda^0_b \rightarrow \Lambda\eta' \)
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CPV in $B^\pm \rightarrow K^\pm h^+ h^-$

Motivated by large $CP$ violation (CPV) observed in $B^{0}_{(S)} \rightarrow K^{\pm(\mp)} \pi^{\pm(\mp)}$

- Source of strong phase difference unknown
- Final state hadron rescattering ($\pi^+\pi^- \rightarrow K^+K^-$)

Measure $CP$ asymmetries in $B^\pm \rightarrow K^\pm\pi^+\pi^-$ and $B^\pm \rightarrow K^\pm K^+K^-$

Using 1 fb$^{-1}$ 2011 data recorded by LHCb ($\approx$ 33% total data)

$$A_{CP}(B^\pm \rightarrow f^\pm) = \frac{\Gamma(B^-\rightarrow f^-)\Gamma(B^+\rightarrow f^+)}{\Gamma(B^-\rightarrow f^-)+\Gamma(B^+\rightarrow f^+)}$$

Actually measure:

$$A_{\text{raw}} = A_{CP} + A_{\Delta}$$
$$A_{\Delta} = A_D(K^\pm) + A_P(B^\pm)$$

$A_{\Delta}$ measured using a sample of $B^\pm \rightarrow J/\psi (\mu^+\mu^-)K^\pm$

$$A_{CP}(J/\psi K) = (0.1 \pm 0.7)\%$$

\[ A_{CP}(B^\pm \rightarrow K^\pm \pi^+ \pi^-) = 0.032 \pm 0.008 \text{ (stat)} \pm 0.004 \text{ (syst)} \pm 0.007(A_{CP}(J/\psi K)) \]

\[ A_{CP}(B^\pm \rightarrow K^\pm K^+ K^-) = -0.043 \pm 0.009 \text{ (stat)} \pm 0.003 \text{ (syst)} \pm 0.007(A_{CP}(J/\psi K)) \]

- Significance of asymmetry:

\[ A_{CP}(K^\pm \pi^+ \pi^-) : 2.8\sigma \]

\[ A_{CP}(K^\pm K^+ K^-) : 3.7\sigma \]
Study of phase space

- Study $A_{CP}^{N}$ in Dalitz plane, where $A_{CP}^{N} = \Phi[N(B^+), N(B^-)]$

\[ B^\pm \rightarrow K^\pm \pi^+ \pi^- \] 
\[ B^\pm \rightarrow K^\pm K^+ K^- \]

\begin{align*}
A_{CP}^{\text{reg}}(B^\pm \rightarrow K^\pm \pi^+ \pi^-) &= 0.678 \pm 0.078 \text{ (stat)} \pm 0.032 \text{ (syst)} \pm 0.007(A_{CP}(J/\psi K)) \\
A_{CP}^{\text{reg}}(B^\pm \rightarrow K^\pm K^+ K^-) &= -0.226 \pm 0.020 \text{ (stat)} \pm 0.004 \text{ (syst)} \pm 0.007(A_{CP}(J/\psi K))
\end{align*}


1. *CP* Violation in $B^{\pm} \rightarrow K^{\pm} h^{+} h^{-}$ decays

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Study of $B^{\pm} \rightarrow K^{\pm} p\bar{p}$ and $B^{\pm} \rightarrow \pi^{\pm} p\bar{p}$

- Very similar to $B^{\pm} \rightarrow K^{\pm} h^{+} h^{-}$
- Hadron rescattering ($hh \rightarrow pp$) not expected to play a large role
  - Test of this model
  - $A_{CP}$ should be small
- Uses same dataset and similar selection to previous analysis

$N(p\bar{p}K^{\pm}) = 7029 \pm 139$

$N(p\bar{p}\pi^{\pm}) = 656 \pm 70$

- Measuring the dynamics and $CP$ asymmetry of the decay
Differential production spectra as a function of $m_{p\bar{p}}$

- Charmonium contribution removed:
  - $B^\pm \rightarrow K^\pm J/\psi$, $B^\pm \rightarrow K^\pm \eta_c$, $B^\pm \rightarrow K^\pm \psi(2S)$ and $B^\pm \rightarrow \pi^\pm J/\psi$

- Differential production spectra as a function of $m^2_{(ph)_0}$ for $B^\pm \rightarrow p\bar{p}K^\pm$
Differential production spectra

- Differential signal yields as a function of $\cos \theta_p$
  \[ B^\pm \rightarrow K^\pm p\bar{p} \]
  \[ B^\pm \rightarrow \pi^\pm p\bar{p} \]

- Measure Forward-Backward asymmetry, $A_{FB}$
  \[
  A_{FB} = \frac{N_{\text{RAW}}^{\text{pos}} - f \times N_{\text{RAW}}^{\text{neg}}}{N_{\text{RAW}}^{\text{pos}} + f \times N_{\text{RAW}}^{\text{neg}}} , \quad f = \frac{\epsilon_{\text{pos}}}{\epsilon_{\text{neg}}}
  \]

  \[ A_{FB}(p\bar{p}K^\pm) = 0.370 \pm 0.018 \text{ (stat)} \pm 0.016 \text{ (syst)} \]
  \[ A_{FB}(p\bar{p}\pi^\pm) = -0.392 \pm 0.117 \text{ (stat)} \pm 0.015 \text{ (syst)} \]
Measure $CP$ asymmetries in $B^\pm \rightarrow p\bar{p}K^\pm$
Perform simultaneous fit to $B^+$ and $B^-$ samples to extract $B^\pm$ yields
Extract $A_{CP}$ again using $B^\pm \rightarrow J/\psi K^\pm$
$A_{CP}$ measured in different regions:
- Full $p\bar{p}K^\pm$ spectrum
- $m_{p\bar{p}} < 2.85 \text{ GeV}/c^2$
- Charmonia resonances

\begin{align*}
A_{CP}(p\bar{p}K^\pm) &= -0.022 \pm 0.031 \text{ (stat)} \pm 0.007 \text{ (syst)} \\
A_{CP}(p\bar{p}K^\pm) &= -0.047 \pm 0.036 \text{ (stat)} \pm 0.007 \text{ (syst)} \\
A_{CP}(\eta_c K^\pm) &= 0.046 \pm 0.057 \text{ (stat)} \pm 0.007 \text{ (syst)} \\
A_{CP}(\psi(2S)K^\pm) &= -0.002 \pm 0.123 \text{ (stat)} \pm 0.007 \text{ (syst)}
\end{align*}

- No significant $CP$ asymmetries found in any region!
Observation of $B^+ \rightarrow \Lambda(1520)\bar{p}$

- Resonance observed in the $m^2_{(Kp)^0}$ spectrum, corresponding to $\Lambda(1520)$ mass.
- Investigate signal in the region $1.44 < m_{pK} < 1.585$ GeV/$c^2$.
- 2D fit to $m_B - m_{Kp}$, projected below $\Lambda(1520)$.

$$\frac{\mathcal{B}(B^+ \rightarrow \Lambda(1520)\bar{p})}{\mathcal{B}(B^+ \rightarrow J/\psi K^+)} = 0.041^{+0.011}_{-0.010} \text{ (stat)} \pm 0.001 \text{ (syst)}$$

$$\mathcal{B}(B^+ \rightarrow \Lambda(1520)\bar{p}) = (3.9^{+1.0}_{-0.9} \text{ (stat)} \pm 0.1 \text{ (syst)} \pm 0.3 \text{(BF)}) \times 10^{-7}$$

**NEW!**
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Towards a full amplitude analysis of 3-body decays

Today present update of branching fraction measurements

<table>
<thead>
<tr>
<th>Decay</th>
<th>Observed?</th>
<th>Favoured?</th>
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<tbody>
<tr>
<td>$B^0 \rightarrow K^0_S K^+ K^-$</td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>$B^0 \rightarrow K^0_S K^\pm \pi^\mp$</td>
<td>✔</td>
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<tr>
<td>$B^0 \rightarrow K^0_S \pi^+ \pi^-$</td>
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</tbody>
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Boosted Decision Tree (BDT) used to separate signal and background.

Selection separated depending where $K^0_S$ decays:
- Upstream of the VELO: Long-Long (LL)
- Downstream of the VELO: Downstream-Downstream (DD)

Optimisation of BDT performed differently for favoured modes:
Branching fraction measurements of $B^0_{(s)} \rightarrow K^0_S h^\pm h^\mp$

Loose BDT Selection.  

Loose BDT cut for favoured modes

$B^0 \rightarrow K^0_S K^+ K^-$  
$B^0_s \rightarrow K^0_S K^\pm \pi^\mp$  
$B^0 \rightarrow K^0_S \pi^+ \pi^-$

Clear first observation of $B^0_s \rightarrow K^0_S K^\pm \pi^\mp$
Branching fraction measurements of $B_{s}^{0}\rightarrow K_{S}^{0}h^{\pm}h^{\mp}$

**Tight BDT Selection.**

- Tight BDT cut for suppressed modes.

$B_{s}^{0}\rightarrow K_{S}^{0}K^{+}K^{-}$

$B^{0}\rightarrow K_{S}^{0}K^{\pm}\pi^{\mp}$

$B_{s}^{0}\rightarrow K_{S}^{0}\pi^{+}\pi^{-}$

No evidence of $B_{s}^{0}\rightarrow K_{S}^{0}K^{+}K^{-}$

Observation of $B_{s}^{0}\rightarrow K_{S}^{0}\pi^{+}\pi^{-}$ at 5.9$\sigma$

Preliminary.
Branching fractions measured relative to $B^0 \to K^0_S \pi^+ \pi^-$.  
90% Confidence belt obtained for $B^0_s \to K^0_S K^+ K^-$ using Feldman Cousins (FC) method.  

\[
\frac{\mathcal{B} (B^0_s \to K^0_S K^{\pm} \pi^\mp)}{\mathcal{B} (B^0 \to K^0_S \pi^+ \pi^-)} = 1.48 \pm 0.11 \text{ (stat.)} \pm 0.08 \text{ (syst.)} \pm 0.11 \text{ (f}_s/f_d\text{)}, \\
\frac{\mathcal{B} (B^0 \to K^0_S K^+ K^-)}{\mathcal{B} (B^0 \to K^0_S \pi^+ \pi^-)} = 0.385 \pm 0.030 \text{ (stat.)} \pm 0.026 \text{ (syst.)}, \\
\frac{\mathcal{B} (B^0_s \to K^0_S \pi^+ \pi^-)}{\mathcal{B} (B^0 \to K^0_S \pi^+ \pi^-)} = 0.29 \pm 0.06 \text{ (stat.)} \pm 0.03 \text{ (syst.)} \pm 0.02 \text{ (f}_s/f_d\text{)}, \\
\frac{\mathcal{B} (B^0 \to K^0_S K^{\pm} \pi^\mp)}{\mathcal{B} (B^0 \to K^0_S \pi^+ \pi^-)} = 0.130 \pm 0.017 \text{ (stat.)} \pm 0.012 \text{ (syst.)}, \\
\frac{\mathcal{B} (B^0_s \to K^0_S K^+ K^-)}{\mathcal{B} (B^0 \to K^0_S \pi^+ \pi^-)} \in [0.004; 0.068] \text{ at 90\% C.L.}.
\]
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New search for baryonic decays to $\eta$ and $\eta'$

- Investigating $\eta-\eta'$ mixing
- No baryonic decays observed in this channel
- Theoretical predictions: $B(\Lambda^0_b \rightarrow \Lambda \eta') \approx (1.8 - 19) \times 10^{-6}$

Ahmady et al.

Dataset recorded in 2012, corresponding to 2.0 fb$^{-1}$
No significant signal observed
Use FC method to place a limit on branching fractions relative to $B^0 \rightarrow K^0_S \eta'$:

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda \eta')}{\mathcal{B}(B^0 \rightarrow K^0_S \eta')} < 9.6 \times 10^{-2} \text{ at 90\% CL}$$

Using $\mathcal{B}(B^0 \rightarrow K^0 \eta') = (66 \pm 4) \times 10^{-6}$

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda \eta') < 6.3 \times 10^{-6} \text{ at 90\% CL}.$$
Summary

- First evidence for $CP$ violation in inclusive $B^\pm \to K^\pm K^+ K^-$ decay
- Studies of $B^\pm \to p\bar{p}h^\pm$
  - No $CP$ asymmetries observed: no hadron rescattering expected
  - First observation of $B^+ \to \bar{\Lambda}(1520)p$
- First observation of $B^{0}_s \to K^{0}_S K^\pm \pi^\mp$ and $B^{0}_s \to K^{0}_S \pi^+ \pi^-$
  - No evidence for $B^{0}_s \to K^{0}_S \pi^+ \pi^-$ in 1 fb$^{-1}$ 2011 data
- Search for the decay $\Lambda^{0}_b \to \Lambda\eta'$
  - No evidence for signal in 2 fb$^{-1}$ 2012 data.
- All analyses will benefit from full 3 fb$^{-1}$ dataset (2011+2012)