Results from LHCb in 3-body Charmless $B$ meson Decays

Jeremy Dalseno

on behalf of the LHCb collaboration

J.Dalseno [at] bristol.ac.uk

29 November 2016
1. Recent Experimental Results

\[ B^+ \to K^+ K^+ \pi^-, \pi^+ \pi^+ K^- \]

2. Manifestation of Direct $CP$ Violation in the Dalitz Plot

- Short/long-distance effects, rescattering

3. Recent Developments in Charmless Amplitude Analyses

- Rescattering, K-matrix, quasi-model-independent approaches to the $S$-wave

4. Summary

Results from LHCb in 3-body Charmless $B$ meson Decays
Motivation

Rare processes $b \rightarrow ssd\bar{d}$ and $b \rightarrow dd\bar{s}$ proceeding by $W$-exchange box

Branching fractions $\mathcal{O}(10^{-11})$ in the SM at most depending on phase between $t$ and $c$ quarks

Amongst the most suitable to observe New Physics effects

MSSM with and without $R$-Parity Violation, variations of the two Higgs doublet model, $Z'$ scenario


Could enhance branching ratio of $b \rightarrow ssd\bar{d}$ and $b \rightarrow dd\bar{s}$ transitions up to $10^{-8}$ and $10^{-7}$

Results from LHCb in 3-body Charmless $B$ meson Decays
**LHCb Detector**

*pp* collisions

*b* quark tends to forward/backward direction

---

Forward spectrometer

Vertex Locator (VeLo)
  Precision tracking
  20 µm IP resolution

Tracking Stations (TT & T)
  \[ \Delta p/p = 0.4\% - 0.6\% \]
  for 5 – 100 GeV tracks

Ring Imaging Cherenkov (RICH)
  \( K, \pi \) ID

Electromagnetic Calorimeter (ECAL)
  \( e, \gamma \) ID

Hadronic Calorimeter (HCL)
  Hadron ID

Muon Stations

Dipole magnet polarity reversal

---

Data set: 1 fb\(^{-1}\) @ 7 TeV and 2 fb\(^{-1}\) @ 8 TeV

Results from LHCb in 3-body Charmless *B* meson Decays
Analysis performed with $3.0 \text{ fb}^{-1}$

Data collected from $pp$ collisions with centre-of-mass energies of 7 and 8 TeV

$$B^+ \rightarrow K^+ K^+ \pi^-$$

No evidence for signal at this time

Branching fractions determined relative to non-suppressed normalisation channels

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ K^+ \pi^-)}{\mathcal{B}(B^+ \rightarrow K^+ K^- \pi^+)} = (-7.5 \pm 4.9 \pm 1.0) \times 10^{-3}$$

$$\frac{\mathcal{B}(B^+ \rightarrow \pi^+ \pi^+ K^-)}{\mathcal{B}(B^+ \rightarrow \pi^+ \pi^- K^+)} = (1.1 \pm 4.0 \pm 0.1) \times 10^{-4}$$
Employ the frequentist Feldman-Cousins approach

Intervals constructed from simulation accounting for relevant biases and systematic uncertainties

Solid line shows the expected true branching fraction as a function of the measured signal yield

Upper (lower) dashed line shows previous (new) best upper limit at 90% CL

\[ \mathcal{B}(B^+ \rightarrow K^+ K^+ \pi^-) < 1.1 \times 10^{-8} (1.8 \times 10^{-8}) \text{ at } 90\% (95\%) \text{ CL} \]

\[ \mathcal{B}(B^+ \rightarrow \pi^+ \pi^+ K^-) < 4.6 \times 10^{-8} (5.7 \times 10^{-8}) \text{ at } 90\% (95\%) \text{ CL} \]

Close to where NP models predict branching fractions to be
1. Recent Experimental Results

- $B^+ \rightarrow K^+ K^+ \pi^-, \pi^+ \pi^+ K^-$

2. Manifestation of Direct $CP$ Violation in the Dalitz Plot

- Short/long-distance effects, rescattering

3. Recent Developments in Charmless Amplitude Analyses

- Rescattering, K-matrix, quasi-model-independent approaches to the $S$-wave

4. Summary

Results from LHCb in 3-body Charmless $B$ meson Decays
Dalitz plot contains all kinematic and dynamic information of decay

Amplitude analysis one of the most powerful techniques

Extract amplitude-level information rather than amplitude-squared information

Interference between intermediate states allows measurement of relative magnitudes and phases

Resolve trigonometric ambiguities in phases that plague 2-body measurements

Results from LHCb in 3-body Charmless $B$ meson Decays
Conditions for Direct $CP$ Violation

In charged $B$ decays, presence of multiple amplitudes may lead to direct $CP$ violation

$$A(B \to f) = \sum_i |A_i| e^{i(\delta_i + \phi_i)}$$
$$\bar{A}(\bar{B} \to \bar{f}) = \sum_i |A_i| e^{i(\delta_i - \phi_i)}$$

Strong phase ($\delta$) invariant under $CP$, while weak phase ($\phi$) changes sign under $CP$

$$\mathcal{A}_{CP}(B \to f) \equiv \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} \propto \sum_{i,j} |A_i| |A_j| \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j)$$

3 conditions required for direct $CP$ violation

At least 2 amplitudes

Non-zero strong phase difference, $\delta_i - \delta_j \neq 0$

Non-zero weak phase difference, $\phi_i - \phi_j \neq 0$

Source of weak phase differences come from different CKM phases of each amplitude
Short-Distance Contributions

Direct $CP$ violation more complicated in $B \to 3h$ decay channels compared to 2-body decays

There are at least 4 possible sources of strong phase

1. Short-distance contributions (quark level)

   BSS mechanism, PRL 43 242 (1979)

   Tree contribution (a)

   Penguin diagram (b) contains 3 quark generations in loop

   $S$-matrix unitarity, $CPT$ require absorptive amplitude

   If gluon in penguin is timelike (on-shell)

     Momentum transfer $q^2 > 4m_i^2$ where $i = u, c$

     Imaginary part depends on quark masses

     Particle rescattering (c) generates a phase difference

   $CP$ violation in 2-body processes caused by this effect

     eg. $B^0 \to K^+\pi^-$

Results from LHCb in 3-body Charmless $B$ meson Decays
Long-Distance Contributions

Remaining sources unique to multibody decays

Long-distance contributions ($q\bar{q}$ level)

2. Breit-Wigner phase

Propagator represents intermediate resonance states

$$F_{R}^{BW}(s) = \frac{1}{m_{R}^{2} - s - im_{R}\Gamma_{R}(s)}$$

Phase varies across the Dalitz plot

3. Relative $CP$-even phase in the isobar model

$$A(B \rightarrow f) = \sum_{i} |A_{i}| e^{i(\delta_{i} + \phi_{i})}$$

$$\bar{A}(\bar{B} \rightarrow \bar{f}) = \sum_{i} |\bar{A}_{i}| e^{i(\delta_{i} - \phi_{i})}$$

Related to final state interactions between different resonances

Results from LHCb in 3-body Charmless $B$ meson Decays
Manifestation of $CP$ Violation

Each source of strong phase leaves a unique signature in the Dalitz plot.

Illustrate with series of examples.

Consider $B^\pm \to K^\pm \pi^+ \pi^-$ with only 2 isobars:

$B^\pm \to \rho^0 K^\pm$ and flat non-resonant (NR) component.

$\rho^0$ lineshape a Breit-Wigner, $F_{\rho}^{BW}$.

$\rho^0$ is a vector resonance, so angular distribution follows $\cos \theta$.

$$
A_+ = |a_+^{\rho}| e^{i\delta_+} F_{\rho}^{BW} \cos \theta + |a_+^{NR}| e^{i\delta_+}^{NR}
$$

$$
A_- = |a_-^{\rho}| e^{i\delta_-} F_{\rho}^{BW} \cos \theta + |a_-^{NR}| e^{i\delta_-}^{NR}
$$

$$
A_{CP} \propto |A_-|^2 - |A_+|^2
\propto (|a_-^{\rho}|^2 - |a_+^{\rho}|^2) |F_{\rho}^{BW}|^2 \cos^2 \theta...
- 2(m_{\rho}^2 - s) |F_{\rho}^{BW}|^2 \cos \theta...
+ 2 m_{\rho} \Gamma_{\rho} |F_{\rho}^{BW}|^2 \cos \theta...
$$

Results from LHCb in 3-body Charmless $B$ meson Decays
Short-Distance Effects

\[ A_{CP} \propto \left( |a_{\rho}^-|^2 - |a_{\rho}^+|^2 \right) |F_{\rho}^{\text{BW}}|^2 \cos^2 \theta \ldots \]
\[ -2(m_{\rho}^2 - s)|F_{\rho}^{\text{BW}}|^2 \cos \theta \ldots \]
\[ +2m_{\rho}\Gamma_{\rho}|F_{\rho}^{\text{BW}}|^2 \cos \theta \ldots \]

Only depends on \( \rho \) resonance, maximum difference at \( \rho \) pole, quadratic in helicity

Only short-distance effects can create \( |a_{\rho}^+| \neq |a_{\rho}^-| \)

Results from LHCb in 3-body Charmless \( B \) meson Decays
Long-Distance Effects

\[ A_{CP} \propto (|a^-_\rho|^2 - |a^+_\rho|^2)|F^{BW}_\rho|^2 \cos^2 \theta \ldots \]
\[ -2(m^2_\rho - s)|F^{BW}_\rho|^2 \cos \theta \ldots \]
\[ +2m_\rho \Gamma_\rho |F^{BW}_\rho|^2 \cos \theta \ldots \]

Interference term from real part of Breit-Wigner, zero at \( \rho \) pole, linear in helicity

Caused by long-distance effects from final state interactions
Long-Distance Effects

\[ A_{CP} \propto (|a^-_\rho|^2 - |a^+_\rho|^2)|F^{BW}_\rho|^2 \cos^2 \theta \ldots 
-2(m^2_\rho - s)|F^{BW}_\rho|^2 \cos \theta \ldots 
+2m_\rho \Gamma_\rho |F^{BW}_\rho|^2 \cos \theta \ldots \]

Interference term from imaginary part of Breit-Wigner, maximum at \( \rho \) pole, linear in helicity

Caused by long distance effects from Breit-Wigner phase and final state interactions

Results from LHCb in 3-body Charmless \( B \) meson Decays
Rescattering Contributions

Last source of strong phase

4. Final state $KK \leftrightarrow \pi\pi$ rescattering

Can occur between decay channels with the same flavour quantum numbers

eg. $B^\pm \rightarrow K^\pm K^+K^-$ and $B^\pm \rightarrow K^\pm \pi^+\pi^-$

$CPT$ conservation constrains hadron rescattering

For given quantum numbers, sum of partial widths equal for charge-conjugate decays

$KK \leftrightarrow \pi\pi$ rescattering generates a strong phase

Look into rescattering region

If rescattering phase in one decay channel generates direct $CP$ violation in this region

Rescattering phase should generate opposite sign direct $CP$ violation in partner decay channel

Results from LHCb in 3-body Charmless $B$ meson Decays
Recently observed large $CP$ violating effects in the phase space

$B^\pm \rightarrow K^\pm \pi^+ \pi^-$  \hspace{1cm} $B^\pm \rightarrow K^\pm K^+ K^-$

LHCb (a)

$B^\pm \rightarrow \pi^\pm \pi^+ \pi^-$  \hspace{1cm} $B^\pm \rightarrow \pi^\pm K^+ K^-$

LHCb (c)

LHCb (b)

LHCb (d)

Penguin

Tree

Results from LHCb in 3-body Charmless $B$ meson Decays
CP Asymmetry by Interference

Project onto $m_{\pi\pi}$ of $B^\pm \rightarrow \pi^\pm \pi^+\pi^-$

Sign-flip and zero around $\rho^0$ pole, CP asymmetry may be dominated by real part of Breit-Wigner
$\pi \pi \leftrightarrow K K$ rescattering region: $1.0 - 1.5 \text{ GeV}/c^2$

$$B^- \rightarrow K^- \pi^+ \pi^- \quad B^+ \rightarrow K^+ \pi^+ \pi^-$$

$$B^- \rightarrow K^- K^+ K^- \quad B^+ \rightarrow K^+ K^+ K^-$$

Clear opposite sign $CP$ asymmetry in $K K/\pi \pi$ - related channels

$KK \leftrightarrow \pi \pi$ rescattering would require this by $CPT$ conservation
1. Recent Experimental Results
   \(-B^+ \rightarrow K^+ K^+ \pi^-, \pi^+ \pi^+ K^-\)

2. Manifestation of Direct \(CP\) Violation in the Dalitz Plot
   - Short/long-distance effects, rescattering

3. Recent Developments in Charmless Amplitude Analyses
   - Rescattering, K-matrix, quasi-model-independent approaches to the \(S\)-wave

4. Summary
Rescattering Lineshape

Inspired by $\pi\pi \leftrightarrow KK$ scattering in 2-body interactions

In the context of 3-body decays, production of one pair of mesons can affect the coupled channel

Attempt to account for this with phenomenological form factor

$$A(s) = \frac{\hat{T}}{1 + \frac{s}{\Delta_{PP}^2}}$$


Intended to describe the partonic interaction that produces $\pi\pi$ and $KK$ in 3-body final state

$\hat{T}$ is the observable amplitude related to the unitary $S$-matrix as, $\hat{S} = 1 + 2i\hat{T}$

$$\hat{S}(s) = \begin{pmatrix}
\eta(s)e^{2i\delta_{\pi\pi}(s)} & i\sqrt{1 - \eta^2(s)}e^{i(\delta_{\pi\pi}(s) + \delta_{KK}(s))} \\
\frac{i}{\sqrt{1 - \eta^2(s)}}e^{i(\delta_{\pi\pi}(s) + \delta_{KK}(s))} & \eta(s)e^{2i\delta_{KK}(s)}
\end{pmatrix}$$

Results from LHCb in 3-body Charmless $B$ meson Decays
Rescattering Lineshape

Only off-diagonal elements are relevant for amplitude analysis.

Use models for the phase shifts $\delta_{\pi\pi}(s)$, $\delta_{KK}(s)$ and inelasticity $\eta(s)$

Phys. Rev. D 71, 074016 (2005);

Also tested on LHCb asymmetry $\rho, f_0(980)$ considered in addition

Reproduces the main features

Results from LHCb in 3-body Charmless $B$ meson Decays
From unitarity of the $S$-matrix, physical transition amplitude given by $\hat{T} = (\hat{I} - i\hat{K}\rho)^{-1}\hat{K}$

For observed final state $i$, $\hat{F}_i = (\hat{I} - i\hat{K}\rho)^{-1}\hat{P}^j$

$\hat{K}$ parametrised by summation of base mass poles and a slowly varying part for non-resonant

$$(\rho\hat{K})_{ij}(s) \equiv \sqrt{\rho_i\rho_j}\left(\sum_R g_i^R g_j^R \frac{m_R^2 - s}{m_R^2 - s} + f_{ij}^{\text{scat}} \frac{c - s_o^{\text{scat}}}{s - s_o^{\text{scat}}}\right)f_{A0}(s)$$

Parameters taken from scattering data

The production vector $\hat{P}$ takes on an analogous form to $\hat{K}$

$$\hat{P}_j(s) \equiv \sum_R \beta_R^{\text{prod}} g_j^R \frac{m_R^2 - s}{m_R^2 - s} + f_j^{\text{prod}} \frac{c - s_o^{\text{prod}}}{s - s_o^{\text{prod}}}$$

$j: \pi\pi, KK, 4\pi, \eta\eta, \eta\eta'; \beta_R^{\text{prod}}$ and $f_j^{\text{prod}}$ are the complex free parameters of the model.

Results from LHCb in 3-body Charmless $B$ meson Decays
K-Matrix

Elastic scattering on the physical boundary, inelastic scattering inside

Inelasticity, \( \eta = |2T - I|| = |S| \)

Transition amplitude \( T; S = I + 2T \)

Transition amplitude intensity

Phase shift

Resonances don’t necessarily manifest as Breit-Wigner structure

Results from LHCb in 3-body Charmless \( B \) meson Decays
Data-Driven Approach

Quasi-model-independent method
   Reminiscent of partial wave analysis
Divide the data into bins
Free magnitude and phase in each bin
Data points: Fit results
Blue Curve: Generated $f_0(500)$ Breit-Wigner

MC sample generated with $\rho$, $f_0(500)$

Results from LHCb in 3-body Charmless $B$ meson Decays
Summary

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

New results with the full LHCb data set
Branching fractions highly sensitive to NP effects
World’s best upper limits achieved
Nearing the region of NP predictions

\[ B^+ \rightarrow h^+ h'^+ h'^- \]

Large \( CP \) violating effects observed in the phase space
Arises from a variety of potential sources that need to be studied
Invoking \( CPT \) constraints to model rescattering effects between \( \pi\pi \) and \( KK \)
Promising method to interface with the wealth of results from scattering experiments
Quasi-model-independent measurement of \( S \)-wave obtained directly from the data
Look forward to amplitude analyses on all these channels