First observation of several sources of CP violation in $B^+ \rightarrow \pi^+\pi^+\pi^-$ decays at LHCb

EPS-HEP 2019

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11 July 2019
$B^\pm \to K^\pm h^+h^-, \pi^\pm h^+h^-$

Observed large $CP$ violating effects in the phase space with Run 1 data


$B^\pm \to K^\pm \pi^+\pi^-$

$LHCb$ (a)

$B^\pm \to K^\pm K^+K^-$

$LHCb$ (b)

$B^\pm \to \pi^\pm \pi^+\pi^-$

$LHCb$ (c)

$B^\pm \to \pi^\pm K^+K^-$

$LHCb$ (d)

First observation of several sources of $CP$ violation in $B^+ \to \pi^+\pi^+\pi^-$ decays at LHCb
Conditions for \( CP \) Violation in Decay

In charged \( B \) decays, presence of multiple amplitudes may lead to (direct) \( CP \) violation in decay

\[
\begin{align*}
\bar{A}(B \rightarrow f) &= \sum_i |A_i| e^{i(\delta_i + \phi_i)} \\
A(\bar{B} \rightarrow f) &= \sum_i |A_i| e^{i(\delta_i - \phi_i)}
\end{align*}
\]

Strong phase (\( \delta \)) invariant under \( CP \)

Weak phase (\( \phi \)) changes sign under \( CP \)

\[
A_{CP}(B \rightarrow f) \equiv \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} \propto \sum_{i,j} |A_i| |A_j| \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j)
\]

3 conditions required for \( CP \) violation in decay

At least 2 competitive amplitudes

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

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

Weak phase comes from Unitarity Triangle contributions to each amplitude

First observation of several sources of \( CP \) violation in \( B^+ \rightarrow \pi^+ \pi^+ \pi^- \) decays at LHCb
Project onto $m_{\pi\pi}$ of $B^\pm \rightarrow \pi^\pm \pi^+ \pi^-$, Phys. Rev. D 90, 112004 (2014)

Sign-flip in raw asymmetry and zero around $\rho^0$ pole
Opposite behaviour of raw asymmetry in each helicity half
Characteristic of $CP$ asymmetry generated by S-P interference
\( \pi\pi \leftrightarrow KK \) rescattering region: 1.0 – 1.5 GeV/c\(^2\)


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

\( KK \leftrightarrow \pi\pi \) rescattering generates a strong phase

CPT conservation constrains hadron rescattering

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

Clear opposite sign \( CP \) asymmetry in \( KK/\pi\pi \) - related channels

First observation of several sources of CP violation in \( B^+ \rightarrow \pi^+\pi^+\pi^- \) decays at LHCb
Physics Parameters

Dalitz Plot position, $\Phi_3$

Construct amplitude model

Isobar coefficients $c_i$, free parameters of the model

$$A(\Phi_3) = \sum_i A_i(\Phi_3) = \sum_i c_i F_i(\Phi_3)$$

$CP$ conjugate: $\bar{\Phi}_3 \equiv \Phi_3 \Rightarrow \bar{F}_i(\bar{\Phi}_3) = F_i(\Phi_3)$

Form factor $F_i$, contains only strong dynamics

$$\bar{A}(\bar{\Phi}_3) = \sum_i \bar{c}_i F_i(\Phi_3)$$

$CP$ violation parametrised in free parameters

$$c_i = (x_i + \Delta x_i) + i(y_i + \Delta y_i)$$

$$\bar{c}_i = (x_i - \Delta x_i) + i(y_i - \Delta y_i)$$

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Physics Parameters

Derived physical quantities

Fit fraction, essentially gives branching fractions

\[ \mathcal{F}_i \equiv \frac{\int d\Phi_3 |A_i(\Phi_3)|^2 + \int d\Phi_3 |\bar{A}_i(\Phi_3)|^2}{\int d\Phi_3 |A(\Phi_3)|^2 + \int d\Phi_3 |\bar{A}(\Phi_3)|^2} \]

\( CP \) violation in decay

\[ \mathcal{A}_{CP}^i \equiv \frac{\int d\Phi_3 |\bar{A}_i(\Phi_3)|^2 - \int d\Phi_3 |A_i(\Phi_3)|^2}{\int d\Phi_3 |\bar{A}_i(\Phi_3)|^2 + \int d\Phi_3 |A_i(\Phi_3)|^2} \]

3 approaches to analysis differing by S-wave description

Isobar Approach

Each contribution has clear physical meaning

K-matrix Approach

Interface with results from scattering experiments

QMI Approach

Binned amplitude determined directly from data

First observation of several sources of CP violation in \( B^+ \rightarrow \pi^+\pi^+\pi^- \) decays at LHCb
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,

$$\hat{S} = 1 + 2i\hat{T}$$

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

First observation of several sources of CP violation in $B^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays at LHCb
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 $\eta(s)$


Rescattering vs phase space

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

K-Matrix

From unitarity of the $S$-matrix, physical transition amplitude given by

$$
\hat{T} = (\hat{I} - i\hat{K}\rho)^{-1}\hat{K}
$$

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

$$(\rho\hat{K})_{ij}(s) \equiv \sqrt{\rho_i\rho_j}\left(\sum_R \frac{g_i^R g_j^R}{m_R^2 - s} + f_{ij}^{\text{scat}} \frac{c - s_0^{\text{scat}}}{s - s_0^{\text{scat}}}\right)f_{A0}(s)
$$

Parameters taken from global fit to scattering data


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

$$
\hat{P}_j(s) \equiv \sum_R \beta_{R}^{\text{prod}} \frac{g_j^R}{m_R^2 - s} + f_{j}^{\text{prod}} \frac{c - s_0^{\text{prod}}}{s - s_0^{\text{prod}}}
$$

$j$: $\pi\pi$, $KK$, $4\pi$, $\eta\eta$, $\eta\eta'$; $\beta_{R}^{\text{prod}}$ and $f_{j}^{\text{prod}}$ are the complex free parameters of the model
K-Matrix

Elastic scattering on the physical boundary, inelastic scattering inside

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

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

Transition amplitude intensity

Phase shift

Resonances don’t necessarily manifest as Breit-Wigner structure

First observation of several sources of CP violation in \( B^+ \rightarrow \pi^+ \pi^+ \pi^- \) decays at LHCb
Quasi-Model-Independent Approach

Construct spin-1 and spin-2 resonances with the isobar model as usual
Model $\pi\pi$ S-waves with adaptive binning method
Equal number of events in each bin
1D bins in $m^2(\pi^+\pi^-)$, 15 bins below charm veto, 2 bins above
In each bin, float amplitude magnitude and phase, 83 free parameters in total
Bose-symmetric amplitude implied

First observation of several sources of CP violation in $B^+ \rightarrow \pi^+\pi^+\pi^-$ decays at LHCb
Quasi-Model-Independent Approach

Quasi-model-independent method

Reminiscent of partial wave analysis

Divide the data into bins

Free magnitude/phase in each bin

Data points: Fit results

Blue Curve: Generated $f_0(500)$ Breit-Wigner

First observation of several sources of CP violation in $B^+ \rightarrow \pi^+\pi^+\pi^-$ decays at LHCb
Dalitz plot analysis performed in the signal region, \(5.249 < m(\pi^\pm\pi^+\pi^-) < 5.317 \text{ GeV}/c^2\)

- Sample correspond to 3fb\(^{-1}\) from Run 1.
- Charm veto.
- \(f_2(1270)\) region.
- \(\rho(770)\) region.
- Low scalar \(m(\pi\pi)\).
Phases

**B^+**

<table>
<thead>
<tr>
<th>Component</th>
<th>Isobar</th>
<th>K-matrix</th>
<th>QMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega(782)$</td>
<td>$-19 \pm 6 \pm 1$</td>
<td>$-15 \pm 6 \pm 4$</td>
<td>$-25 \pm 6 \pm 27$</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>$+5 \pm 3 \pm 12$</td>
<td>$+19 \pm 4 \pm 18$</td>
<td>$+13 \pm 5 \pm 21$</td>
</tr>
<tr>
<td>$\rho(1450)^0$</td>
<td>$+127 \pm 4 \pm 21$</td>
<td>$+155 \pm 5 \pm 29$</td>
<td>$+147 \pm 7 \pm 152$</td>
</tr>
<tr>
<td>$\rho_3(1690)^0$</td>
<td>$-26 \pm 7 \pm 14$</td>
<td>$+19 \pm 8 \pm 34$</td>
<td>$+8 \pm 10 \pm 24$</td>
</tr>
</tbody>
</table>

**B^-**

<table>
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</tr>
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<tbody>
<tr>
<td>$\omega(782)$</td>
<td>$+8 \pm 6 \pm 1$</td>
<td>$+8 \pm 7 \pm 4$</td>
<td>$-2 \pm 7 \pm 11$</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>$+53 \pm 2 \pm 12$</td>
<td>$+80 \pm 3 \pm 17$</td>
<td>$+68 \pm 3 \pm 66$</td>
</tr>
<tr>
<td>$\rho(1450)^0$</td>
<td>$+154 \pm 4 \pm 6$</td>
<td>$-166 \pm 4 \pm 51$</td>
<td>$-175 \pm 5 \pm 171$</td>
</tr>
<tr>
<td>$\rho_3(1690)^0$</td>
<td>$-47 \pm 18 \pm 25$</td>
<td>$+5 \pm 8 \pm 46$</td>
<td>$+36 \pm 26 \pm 46$</td>
</tr>
</tbody>
</table>

Phases given in degrees, measured relative to the $\rho(770)^0$

Broad agreement between different S-wave approaches

Largest phase difference between $B^+$ and $B^-$ in $f_2(1270)$

Responsible for some of the large $CP$ seen in the Dalitz plot

First observation of several sources of $CP$ violation in $B^+ \to \pi^+\pi^+\pi^-$ decays at LHCb
Fit fractions and $CP$ asymmetries

$CP$ conserving fit fractions

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<tr>
<td>$\rho(770)^0$</td>
<td>55.5 ± 0.6 ± 0.7 ± 2.5</td>
<td>56.5 ± 0.7 ± 1.5 ± 3.1</td>
<td>54.8 ± 1.0 ± 1.9 ± 1.0</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>0.50 ± 0.03 ± 0.03 ± 0.04</td>
<td>0.47 ± 0.04 ± 0.01 ± 0.03</td>
<td>0.57 ± 0.10 ± 0.12 ± 0.12</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>9.0 ± 0.3 ± 0.8 ± 1.4</td>
<td>9.3 ± 0.4 ± 0.6 ± 2.4</td>
<td>9.6 ± 0.4 ± 0.7 ± 3.9</td>
</tr>
<tr>
<td>$\rho(1450)^0$</td>
<td>5.2 ± 0.3 ± 0.4 ± 1.9</td>
<td>10.5 ± 0.7 ± 0.8 ± 4.5</td>
<td>7.4 ± 0.5 ± 3.9 ± 1.1</td>
</tr>
<tr>
<td>$\rho_3(1690)^0$</td>
<td>0.5 ± 0.1 ± 0.1 ± 0.4</td>
<td>1.5 ± 0.1 ± 0.1 ± 0.4</td>
<td>1.0 ± 0.1 ± 0.5 ± 0.1</td>
</tr>
<tr>
<td>S-wave</td>
<td>25.4 ± 0.5 ± 0.7 ± 3.6</td>
<td>25.7 ± 0.6 ± 2.6 ± 1.4</td>
<td>26.8 ± 0.7 ± 2.0 ± 1.0</td>
</tr>
</tbody>
</table>

First error: statistical, Second: systematic, Third: Model uncertainty

$\rho(770)^0$ and S-wave dominant, significant $f_2(1270)$ contribution

Direct $CP$ asymmetries

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<tr>
<td>$\rho(770)^0$</td>
<td>+0.7 ± 1.1 ± 1.2 ± 1.5</td>
<td>+4.2 ± 1.5 ± 2.6 ± 5.8</td>
<td>+4.4 ± 1.7 ± 2.3 ± 1.6</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>−4.8 ± 6.5 ± 6.6 ± 3.5</td>
<td>−6.2 ± 8.4 ± 5.6 ± 8.1</td>
<td>−7.9 ± 16.5 ± 14.2 ± 7.0</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>+46.8 ± 6.1 ± 3.6 ± 4.4</td>
<td>+42.8 ± 4.1 ± 2.1 ± 8.9</td>
<td>+37.6 ± 4.4 ± 6.0 ± 5.2</td>
</tr>
<tr>
<td>$\rho(1450)^0$</td>
<td>−12.9 ± 3.3 ± 7.0 ± 35.7</td>
<td>+9.0 ± 6.0 ± 10.8 ± 45.7</td>
<td>−15.5 ± 7.3 ± 14.3 ± 32.2</td>
</tr>
<tr>
<td>$\rho_3(1690)^0$</td>
<td>−80.1 ± 11.4 ± 13.5 ± 24.1</td>
<td>−35.7 ± 10.8 ± 8.5 ± 35.9</td>
<td>−93.2 ± 6.8 ± 8.0 ± 38.1</td>
</tr>
<tr>
<td>S-wave</td>
<td>+14.4 ± 1.8 ± 2.1 ± 1.9</td>
<td>+15.8 ± 2.6 ± 2.1 ± 6.9</td>
<td>+15.0 ± 2.7 ± 4.2 ± 7.0</td>
</tr>
</tbody>
</table>

Large $CP$ violation in $f_2(1270)$ and S-wave

First observation of several sources of CP violation in $B^+ \rightarrow \pi^+\pi^+\pi^-$ decays at LHCb
$B^+ \rightarrow \pi^+\pi^+\pi^-$ has two identical pions

$m_{\text{low}}$ is the lower $\pi^+\pi^-$ invariant mass combination

Enhances resonance visibility

$m_{\text{high}}$ is the higher $\pi^+\pi^-$ invariant mass combination

Shows spin structure

First observation of several sources of CP violation in $B^+ \rightarrow \pi^+\pi^+\pi^-$ decays at LHCb
\( \rho(770)^0 \) Region: \( m(\pi^+\pi^-) \)

Clear \( \rho - \omega \) interference

Rapid sign flips of \( A_{CP} \) in small region, attribute to \( \rho - \omega \) mixing

No charge asymmetry observed as a function of \( m(\pi^+\pi^-) \)
Described well by all 3 S-wave approaches
Large amounts of direct $CP$ violation seen
Opposite behaviour in helicity between $B^+$ and $B^-$
Characteristic of $CP$ violation in interference between broad and dominant S- and P-waves

$A_{CP}$ linear in helicity, yet invisible in full $m(\pi^+\pi^-)$ projection

Over 25$\sigma$ statistical significance
First observation of $CP$ violation in S-P interference
Poorly described by all 3 S-wave approaches, can be fixed in 2 ways

Free $f_2(1270)$ pole parameters

Inconsistent with PDG values, disagreement between 3 approaches

Additional D-wave contribution

Fit with additional D-wave, $f_2(1430)$ state not well established

Very large $CP$ asymmetry well-described by all 3 S-wave approaches

First observation of several sources of CP violation in $B^+ \rightarrow \pi^+\pi^+\pi^-$ decays at LHCb
Quantify quasi-two-body CP violation by plotting isobar parameters in the Argand plane.

Magnitude and phase for $B^+ \to f_2(1270)\pi^+$ and $B^- \to f_2(1270)\pi^-$

Black ellipse: Nominal fit
Coloured ellipses: Various systematic variations
Observation of CPV ranges from $14 - 19\sigma$ (statistical only)

First observation of CP violation in any process involving a tensor.
S-wave Comparison

Green data points: QMI S-wave
Blue curve: Isobar S-wave, Orange curve: K-matrix S-wave
Total uncertainties shown
Good agreement on structures in $|A|^2$
Structure in phase motion qualitatively agreed on
Deviation from QMI indicates more theoretical work needed
S-wave Amplitude

Isobar

KMatrix

QMI

Red: $B^+$, Blue: $B^-$, Dark (light) shading: Statistical (Total) error

First $CP$ violation in S-wave, over 10$\sigma$ statistical significance

Elastic region, could be generated by short-distance effects

If phase difference non-constant, could indicate new dynamics

First observation of several sources of $CP$ violation in $B^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays at LHCb
Summary

Amplitude analysis of $B^+ \rightarrow \pi^+\pi^+\pi^-$

3 approaches to the complicated S-wave, which broadly agree

  Isobar: Each lineshape has physical meaning
  K-matrix: Interface with results from scattering experiments
  QMI: Determine directly from the data

Theoretical speculation on cause of large localised $CP$ violation

  Low-mass S-wave interference with $\rho(770)^0$: yes
  $\rho - \omega$ mixing: no
  $KK \rightarrow \pi\pi$ rescattering: not yet

3 different kinds of $CP$ violation observed for the first time

  In S-P interference around the $\rho(770)^0$ pole
  In the $f_2(1270)$
  In the S-wave at low $m(\pi^+\pi^-)$

Significant new insight into $CP$ violation in multi-body $B$-hadron decays

Motivates further study into the processes that govern $CP$ violation


First observation of several sources of CP violation in $B^+ \rightarrow \pi^+\pi^+\pi^-$ decays at LHCb
Para empregos institucionais e en contextos de alta representación, o sigillum acompañará as siglas do xeito indicado. O sigillum inscríbese nun cadrado azul de igual tamaño que o cadrado azul das siglas, separados por unha canle de cor branca como se indica nas especificacións de construción.
$f_2(1270)$ Region

Bad fit in $f_2(1270)$ region can be fixed in 2 ways

Left: Free $f_2(1270)$ pole parameters
   Inconsistent with PDG values, disagreement between 3 approaches

Right: Additional D-wave contribution
   Fit with additional $f_2(1430)$, state not well established

LHCb-PAPER-2019-017

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