Charmless $b$ Decays

Jeremy Dalseno

on behalf of the LHCb collaboration

J.Dalseno [at] bristol.ac.uk

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1. Types of $CP$ violation
   - Direct, mixing-induced

2. 2-body
   - $B^0 \rightarrow K^+\pi^-, \pi^+\pi^-, B_s^0 \rightarrow K^+K^-$

3. 3-body
   - $B^0 \rightarrow K_S^0\pi^+\pi^-$

4. 4-body
   - $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-, \Lambda_b^0 \rightarrow pK^-h^+h^- \text{ New!}, \Xi_b^0 \rightarrow pK^-\pi^+K^- \text{ New!}$
   - $B_s^0 \rightarrow \phi\phi, K^*\bar{K}^*$
In charged $B$ decays, presence of multiple amplitudes may lead to direct $CP$ violation

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

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

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

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

3 conditions required for 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
Multiple 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. $B^0 \rightarrow K^+ \pi^-$
Long-Distance Contributions

Remaining sources endemic 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

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

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

Related to final state interactions between different resonances
Neutral Meson Mixing

Mixing arises from a difference between the mass and flavour eigenstates

$$|P_H\rangle = p|P^0\rangle + q|\bar{P}^0\rangle, \quad |P_L\rangle = p|P^0\rangle - q|\bar{P}^0\rangle$$

$p, q$ are complex mixing parameters

Mixing can be described by the effective 2x2 Hamiltonian

$$H_{ij} = M_{ij} - i\Gamma_{ij}/2$$

$M$ is the mass term

$\Gamma$ provides the decay term due to the $-i$

Solving the Schrödinger Equation

3 mixing physical observables

$$\Delta m \equiv m_H - m_L:$$ mixing frequency in time evolution

$$\Delta \Gamma \equiv \Gamma_H - \Gamma_L:$$ lifetime difference

$$\phi_{mix} = -\arg(M_{12}/\Gamma_{12}): CP$$-violating mixing phase

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Charmless $b$ Decays
**CP Violation in Neutral Mesons**

*CP* violation in neutral meson system governed by complex parameter

\[ \lambda_{CP} \equiv \frac{q \bar{A}(\bar{P}^0 \to f_{CP})}{p A(P^0 \to f_{CP})} \]

Access experimentally through time-dependent rate asymmetry in neutral mesons

\[ a_{CP}(t) = \frac{\Gamma(\bar{P}^0 \to f_{CP}) - \Gamma(P^0 \to f_{CP})}{\Gamma(\bar{P}^0 \to f_{CP}) + \Gamma(P^0 \to f_{CP})} = \frac{-C_{CP} \cos(\Delta mt) + S_{CP} \sin(\Delta mt)}{\cosh(\Delta \Gamma t/2) + A_{\Delta \Gamma} \sinh(\Delta \Gamma t/2)} \]

Sensitive to 3 physical observables

- **C<sub>CP</sub>**: *CP* violation in the decay, \(|\bar{A}| \neq |A|\)

  \[ C_{CP} \equiv \frac{|\lambda_{CP}|^2 - 1}{|\lambda_{CP}|^2 + 1} \]

- **S<sub>CP</sub>**: Mixing-induced *CP* violation, \(\arg(\lambda_{CP}) \neq 0\)

  \[ S_{CP} \equiv -\eta_{CP} \frac{2\Im(\lambda_{CP})}{|\lambda_{CP}|^2 + 1} \]

- **A<sub>\Delta \Gamma</sub>**: Admixture of \(P_H\) and \(P_L\) that decay to final state

  \[ A_{\Delta \Gamma} \equiv -\frac{2\Re(\lambda_{CP})}{|\lambda_{CP}|^2 + 1} \]
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   - $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$, $\Lambda_b^0 \rightarrow pK^-h^+h^-$ \text{New!}$\,$, $\Xi_b^0 \rightarrow pK^-\pi^+K^-$ \text{New!}$
   - $B_s^0 \rightarrow \phi\phi, K^*\bar{K}^*$

Charmless $b$ Decays
Simultaneous analysis includes $B^0 \rightarrow K^- \pi^+, \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$

Based on 2011+2012 data ($3.0 \text{ fb}^{-1}$)

Sensitive to direct and mixing-induced $CP$ violation

Constrain $\alpha$, $\gamma$ and $-2\beta_s$

Requires time-dependent and flavour-tagged analysis
Decay times precisely measured due LHCb VELO vertex measurements

Time distribution affected by acceptance effects due to trigger and selection criteria

Shape determined from $B^0 \rightarrow K^+\pi^-$ data
Transformation to other final states from simulation
Decay Time Resolution

Event-dependent decay time resolution $\sigma_t$

Dilutes oscillation amplitudes $D = \exp \left( \frac{1}{2} \Delta m^2 \sigma_t^2 \right)$

Negligible in $B^0$ decays due to small $\Delta m_d$

Linearly dependent on per-event decay time error

Calibrated from time-dependent asymmetry of $B \rightarrow D\pi$ control samples

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Charmless $b$ Decays
Employs Opposite Side (OS) and Same Side (SS) taggers

Algorithm produces per-event tagging decision and associated wrong tag probability

Wrong tag probability linearly calibrated with various control samples

\(B^0\) tagging power: \((4.08 \pm 0.20)\%\), \(B_s^0\) tagging power: \((3.65 \pm 0.21)\%\)
$B \rightarrow h^+ h^-$ Results

First error statistical, second systematic

\begin{align*}
C_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01, \\
S_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01, \\
C_{K^+K^-} &= +0.20 \pm 0.06 \pm 0.02, \\
S_{K^+K^-} &= +0.18 \pm 0.06 \pm 0.02, \\
A_{K^+K^-}^{\Delta \Gamma} &= -0.79 \pm 0.07 \pm 0.10, \\
A_{CP}^{B^0 \rightarrow K^+\pi^-} &= -0.084 \pm 0.004 \pm 0.003, \\
A_{CP}^{B^0_s \rightarrow K^-\pi^+} &= +0.213 \pm 0.015 \pm 0.007
\end{align*}

Most precise single measurement

First determination of $A_{K^+K^-}^{\Delta \Gamma}$

$4\sigma$ evidence for $CP$ violation in $B^0_s \rightarrow K^+K^-$
$B \rightarrow h^+ h^- \text{ World Average}$

Contours give $-2\Delta \ln L = \Delta \chi^2 = 1$, corresponding to 39.3% CL for 2 dof.

### Charmless $b$ Decays

- **HFLAV**
- Moriond 2018
- PRELIMINARY

#### $\pi^+ \pi^- S_{CP}$ vs $C_{CP}$

- **BaBar**
  - PRD 87 (2013) 052009
  - HFLAV correlated average
  - $-0.68 \pm 0.10 \pm 0.03$

- **Belle**
  - PRD 88 (2013) 092003
  - $-0.64 \pm 0.08 \pm 0.03$

- **LHCb**
  - LHCb-PAPER-2018-006
  - $-0.63 \pm 0.05 \pm 0.01$

- **Average**
  - $-0.63 \pm 0.04$

#### $\pi^+ \pi^- C_{CP}$

- **BaBar**
  - PRD 87 (2013) 052009
  - HFLAV correlated average
  - $-0.25 \pm 0.08 \pm 0.02$

- **Belle**
  - PRD 88 (2013) 092003
  - $-0.33 \pm 0.06 \pm 0.03$

- **LHCb**
  - LHCb-PAPER-2018-006
  - $-0.34 \pm 0.06 \pm 0.01$

- **Average**
  - $-0.32 \pm 0.04$
Outline

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Charmless $b$ Decays
$B^0 \rightarrow K^0_S \pi^+ \pi^-$

Mediated by penguin and tree processes

Time-independent amplitude analysis (today)
Sensitive to direct $CP$ violation for intermediate states

Time-dependent amplitude analysis (long-term plan)
Direct measurement of $CP$ violating phase $\beta$ from $CP$ eigenstate intermediates states
Flavour-specific intermediate states contribute information towards $\gamma$ measurement
Analysis performed with 2011+2012 data (3.0 $f b^{-1}$)

Around 3200 signal events in signal region with $\sim 90\%$ purity

arXiv:1712.09320
\[ B^0 \rightarrow K^0_S \pi^+ \pi^- \]

Isobar approach

\[ A = \sum_i c_i F_i(m_{12}^2, m_{23}^2) \]

\( F_i(m_{12}^2, m_{23}^2) \): strong dynamics form factor

Contains lineshape and spin density

\( c_i \): \( CP \)-violating complex fit coefficients

\[ A_{CP}^{\text{Raw}, i} = \frac{|\bar{c_i}|^2 - |c_i|^2}{|\bar{c_i}|^2 + |c_i|^2} \]

Raw \( A_{CP} \) corrections

\( B^0/\bar{B}^0 \) production asymmetry

\((-0.35 \pm 0.81)\%\)

\( \pi^+/\pi^- \) detection asymmetry

\((0.00 \pm 0.25)\%\)

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Parameters</th>
<th>Lineshape</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^*(892)^- )</td>
<td>( m_0 = 891.66 \pm 0.26 ) ( \Gamma_0 = 50.8 \pm 0.9 )</td>
<td>RBW</td>
</tr>
<tr>
<td>( (K\pi)_0^- )</td>
<td>( \Re(\lambda_0) = 0.204 \pm 0.103 ) ( \Im(\lambda_0) = 0 ) ( \Re(\lambda_1) = 1 ) ( \Im(\lambda_1) = 0 )</td>
<td>EFKLLM</td>
</tr>
<tr>
<td>( K^*_2(1430)^- )</td>
<td>( m_0 = 1425.6 \pm 1.5 ) ( \Gamma_0 = 98.5 \pm 2.7 )</td>
<td>RBW</td>
</tr>
<tr>
<td>( K^*(1680)^- )</td>
<td>( m_0 = 1717 \pm 27 ) ( \Gamma_0 = 332 \pm 110 )</td>
<td>Flatté</td>
</tr>
<tr>
<td>( f_0(500) )</td>
<td>( m_0 = 513 \pm 32 ) ( \Gamma_0 = 335 \pm 67 )</td>
<td>RBW</td>
</tr>
<tr>
<td>( \rho(770)^0 )</td>
<td>( m_0 = 775.26 \pm 0.25 ) ( \Gamma_0 = 149.8 \pm 0.8 )</td>
<td>GS</td>
</tr>
<tr>
<td>( f_0(980) )</td>
<td>( g_\pi = 0.165 \pm 0.025 \text{ GeV} ) ( g_K = 0.695 \pm 0.119 \text{ GeV} )</td>
<td>Flatté</td>
</tr>
<tr>
<td>( f_0(1500) )</td>
<td>( m_0 = 1505 \pm 6 ) ( \Gamma_0 = 109 \pm 7 )</td>
<td>RBW</td>
</tr>
<tr>
<td>( \chi_{c0} )</td>
<td>( m_0 = 3414.75 \pm 0.31 ) ( \Gamma_0 = 10.5 \pm 0.6 )</td>
<td>RBW</td>
</tr>
</tbody>
</table>

Nonresonant (NR) \( \text{Phase space} \)

**EFKLLM**: \( (K\pi)^0 \) form factor from QCDf

First observation of $C P$ violation in $B^0 \rightarrow K^{*+}(892)\pi^-$ (6\sigma significance)
1. Types of $CP$ violation
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   - $B^0_s \rightarrow \phi\phi$, $K^*\bar{K}^*$
4-body Baryonic Decays

Rich underlying resonant structure

Probe $CP$ violation with integrated and scalar triple-product asymmetry measurements

$P$-odd triple products

$\Lambda_b^0$: $C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin \Phi$

$\bar{\Lambda}_b^0$: $\bar{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \propto \sin \bar{\Phi}$

$P$-odd asymmetries of $\hat{T}$ operator

$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$

$\bar{A}_{\hat{T}} = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$

Sensitive to interference between $P$-even and $P$-odd amplitudes
Λ^0_0 → pπ^−h^+h^−  Results

Based on 2011-12 data (3.0 fb\(^{-1}\))

Nature Physics 13 (2017) 391

No CP violation in integrated phase space

Divide into bins

Scheme A:

Based on dominant resonant structure

eg. Δ^{++}, N^*, \rho(770)

Scheme B:

Function of angle between decay planes

First evidence for CP violation (3.3σ)
\[ \Lambda^0_b \to pK^− \pi^+ \pi^− \]

New preliminary result based on 3.0 \(fb^{-1}\) \((p\pi^- h^+ h^-' \to pK^- h^+ h^-')\)

\[ \Lambda^0_b \to pK^− \pi^+ \pi^- \quad \text{Yield: } 19877 \pm 195 \]

\[ \Lambda^0_b \to pK^- K^+ K^- \quad \text{Yield: } 5297 \pm 83 \]

\[ \Xi^0_b \to pK^- \pi^+ K^- \quad \text{Yield: } 709 \pm 45 \]

Left: Scheme A, Right: Scheme B

Scheme A: Binned in dominant resonances

Scheme B: Binned in \(\Phi\)

Additional binned search in mass combinations

No significant asymmetries found

arXiv:1805.03941
$B_s^0 \rightarrow \phi\phi \,(b \rightarrow s\bar{s}s), \, K^*\bar{K}^* \,(b \rightarrow s\bar{d}d)$ penguin dominated final states

Highly sensitive to New Physics amplitudes in the mixing and decay processes

Final state is $CP$ admixture, time-dependent angular analysis to disentangle

Measure $CP$-violating mixing phase $\phi_{s\bar{s}s}^s, \phi_{s\bar{d}d}^s$

Theory: $|\phi_{s\bar{s}s}^s| < 0.02 \ \text{rad}$

Analysis based on Run 1 and 2015+16 data \((5 \text{ fb}^{-1})\), LHCb-CONF-2018-001

Effective tagging efficiency

\((5.74 \pm 0.43)\%\)

Red: \(CP\)-even \(VV\)

Green: \(CP\)-odd \(VV\)

Purple: \(SV + SS\)

\[
\phi_s^{\bar{s}s} = -0.07 \pm 0.13 \text{ (stat)} \pm 0.03 \text{ (syst)} \text{ rad}
\]

\[
|\lambda_{CP}| = 1.02 \pm 0.05 \text{ (stat)} \pm 0.03 \text{ (syst)}
\]

Additional search with triple product asymmetries shows no \(CP\) violation
Analysis based on 2011+12 data ($3 \, fb^{-1}$)

World’s first measurement

JHEP 03 (2018) 140

$K\pi$ mass distribution modelled

Effective tagging efficiency: $(5.17 \pm 0.17)\%$

Systematics dominated by multi-dimensional acceptance

No evidence for $CP$ violation

Results consistent with $B^0_s \rightarrow \phi\phi$

$$\phi^{sdd}_s = -0.10 \pm 0.13 \text{ (stat)} \pm 0.14 \text{ (syst)} \text{ rad}$$

$$|\lambda_{CP}| = 1.035 \pm 0.034 \text{ (stat)} \pm 0.089 \text{ (syst)}$$
LHCb provides a rich environment to search for various manifestations of $CP$ violation

Time-dependent measurement of $CP$ violation in $B \rightarrow h^+ h^-$
   Most precise single measurement

Amplitude analysis of $B^0 \rightarrow K_S^0 \pi^+ \pi^-$
   First observation of $CP$ violation in $B^0 \rightarrow K^*+ \pi^-$

Search for $CP$ violation in 4-body baryonic $b$ decays
   First evidence of $CP$ violation in $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$ with triple product constructs

Time-dependent measurements of $\phi_s$ with $B^0 \rightarrow VV$ channels
   $B_s^0 \rightarrow \phi\phi$ consistent with SM predictions
   First measurement with $B_s^0 \rightarrow K^* \bar{K}^*$