CP Violation
in Charmless 3-body B decays

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$B^\pm \rightarrow h^+ h^- h^\pm$ LHCb Brazilian Group
Outline

- Theory and Techniques
- The LHCb Detector
- $B^\pm \rightarrow h^+ h^- h^\pm$ decays. ($h = K, \pi$)
- $B^\pm \rightarrow p\bar{p}h^\pm$ decays.
Theory and Techniques
Introduction

- **CP Violation** (*Sakharov, Baryogenesys*)
- Discovered 1964 (*neutral kaons*)
- **Standard Model CPV** (*CKM matrix*)
- **SM CPV** (*insufficient, Universe*)
- **CKM matrix**: D (*small or null*), B (*measurable*)
- 3-body decays are interesting (*signatures in Dalitz Plot*)
Conditions for Direct CP Violation

- In charged B decays, we have multiple amplitudes:

\[ \mathcal{A}(B \rightarrow f) = |A_1|e^{i(\delta_1+\phi_1)} + |A_2|e^{i(\delta_2+\phi_2)} + |A_3|e^{i(\delta_3+\phi_3)} + ... \]

- Strong phases \((\delta_i)\) are invariant under CP Transformation: \(\delta_i \rightarrow \delta_i\)
- Weak phases \((\phi_i)\) change sign under CP Transformation: \(\phi_i \rightarrow -\phi_i\)

\[ \bar{\mathcal{A}}(\bar{B} \rightarrow \bar{f}) = |\bar{A}_1|e^{i(\delta_1-\phi_1)} + |\bar{A}_2|e^{i(\delta_2-\phi_2)} + |\bar{A}_3|e^{i(\delta_3-\phi_3)} + ... \]

- The Asymmetry can be calculated as:

\[ \mathcal{A}_{CP}(B \rightarrow f) = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} \propto \sum_{ij} \sin(\delta_i - \delta_j)\sin(\phi_i - \phi_j) \]

- Conditions for Direct CP Violation:

1) At least two amplitudes.
2) Non-zero weak phase difference, \(\phi_i - \phi_j \neq 0\)
3) Non-zero strong phase difference, \(\delta_i - \delta_j \neq 0\)
BSS Model for the $B^\pm \rightarrow \pi^+\pi^-\pi^\pm$ decay

1) At least two amplitudes. Tree x Penguin
   • In both diagrams: Initial State: B meson, Final State: $\pi\pi\pi$
   • BSS model: $b$ is considered as free. $\bar{u}$ is considered an spectator (quark level)

2) Non-zero week phase difference: CKM: $A^T \propto V_{ub}V_{ud}$, $A^P \propto V_{qb}V_{qd}$, $q = u, c, t$

3) Non-zero strong phase difference: (penguin: $q$ on its mass shell ($u, c$ for $b$ decays)).

Source of $\delta_i - \delta_j \neq 0$ are Short Distance Effects.!!!
Dalitz Plot

\[ B^\pm \rightarrow h^+ h^- h^{\pm} \]

\[ B^\pm \rightarrow p\bar{p} h^{\pm} \]

- **12 variables**
- **1 constraint**

\[ E_B = \sum_i E_i \]

- **12 variables**
- **3 constraints**

\[ \vec{p}_B = \sum_i \vec{p}_i \]

- **If p1, p2, p3 pseudoscalars**
- **3 constraints**

\[ E_i = \vec{p}_i^2 + m_i^2 \]

\[ 12 \text{ variables} - 10 \text{ constraints} = 2 \text{ variables:} \]

\[ s_{12} = (p_1 + p_2)^2, \quad s_{23} = (p_2 + p_3)^2 \]
Dalitz Plot

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

\[ A(s_{12}, s_{23}) = c_{nr} A_{NR}(s_{12}, s_{23}) + \sum_k c_k A_k(s_{12}, s_{23}) \]

Isobar Model: the decay amplitude is a coherent sum of a non-resonant amplitude plus resonant amplitudes.
Amplitude Analysis

\[ \mathcal{A}(s_{12}, s_{23}) = c_{nr} \mathcal{A}_{NR}(s_{12}, s_{23}) + \sum_{k} c_{k} \bar{\mathcal{A}}_{k}(s_{12}, s_{23}) \]

\[ \mathcal{F}^{B}(s_{12}, s_{23}) \mathcal{F}^{R}(s_{12}, s_{23}) \mathcal{B}W(s_{12}, s_{23}) \mathcal{M}(s_{12}, s_{23}) \]

Fitting the model to data (DP plane) we obtain the complex coefficients \( c_{nr}, c_{k} \) which tell us the contribution of resonances.

**Asymmetry**

In order to consider asymmetry we define a contribution for the particle and the antiparticle:

\[ \mathcal{A}(s_{12}, s_{23}) = \sum_{j} c_{j} \mathcal{A}_{j}(s_{12}, s_{23}) + \sum_{j} \bar{c}_{j} \bar{\mathcal{A}}_{j}(s_{12}, s_{23}), \quad \mathcal{A}_{j}(s_{12}, s_{23}) = \bar{\mathcal{A}}_{j}(s_{12}, s_{23}) \]

\[ c_{j} \text{ and } \bar{c}_{j} \text{ contains weak and strong phases.} \]

\[ A_{CP} = \frac{|\bar{c}_{j}|^2 - |c_{j}|^2}{|\bar{c}_{j}|^2 + |c_{j}|^2} \]
Asymmetry Map from Mirandizing Method


- Histogram performed by an adaptive binning algorithm.
- Each bin contains the same number of events.
- The asymmetry was calculated from the events inside the bin.
- The vertical color scale tells us the asymmetry value.
LHCb Experiment
The LHCb Detector

- Single-arm forward spectrometer ($2 < \eta < 5$),
- Designed to study particles containing b and c quarks
- Includes a High precision tracking system
- Ring Imaging Cherenkov Detectors (charged hadrons)
- Calorimeter System (photons, electrons and hadrons)
- Muon System, interleaved layers of iron and MWPC (muons)

2011: $1 \text{ fb}^{-1}$, $\sqrt{s} = 7 \text{ TeV}$
2012: $2 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$
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LHCb MC
$\sqrt{s} = 8$ TeV

2011: $1$ $fb^{-1}$, $\sqrt{s} = 7$ TeV
2012: $2$ $fb^{-1}$, $\sqrt{s} = 8$ TeV
$B^\pm \to h^+ h^- h^\pm$ decays.
### Inclusive CP asymmetry [arXiv:1408.5373]

Measurement of the raw CP asymmetry from simultaneous mass fit to $B^+$ and $B^−$ candidates:

$$A_{raw} = \frac{N_{B^−} - N_{B^+}}{N_{B^−} + N_{B^+}}$$

- $B^− \rightarrow K^− \pi^+ \pi^−$  
  $N_{sig} = 181,074 \pm 556$

- $B^+ \rightarrow K^+ \pi^+ \pi^−$

- $B^− \rightarrow \pi^- \pi^+ \pi^−$  
  $N_{sig} = 24,907 \pm 222$

- $B^+ \rightarrow \pi^+ \pi^+ \pi^−$

- $B^− \rightarrow K^− K^+ K^−$  
  $N_{sig} = 109,240 \pm 354$

- $B^+ \rightarrow K^+ K^+ K^−$

- $B^− \rightarrow K^− K^+ \pi^−$  
  $N_{sig} = 6,161 \pm 172$

- $B^+ \rightarrow K^+ K^+ \pi^−$

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Inclusive CP asymmetry [arXiv:1408.5373]

- The raw asymmetry has to be corrected for the B-meson production asymmetry and the detector asymmetry:
  \[ A_{\text{raw}} \approx A_{\text{CP}} + A_P + A_{h'}_D \]

- Decays divided into two categories depending on the flavour of the unpaired hadron:
  \[
  B^\pm \to h^+ h^- K^\pm \quad A_{\text{CP}} = A_{\text{raw}} - A_P(B^\pm) - A_D(K^\pm)
  
  B^\pm \to h^+ h^- \pi^\pm \quad A_{\text{CP}} = A_{\text{raw}} - A_P(B^\pm) - A_D(\pi^\pm)
  \]

- \( A_P(B) \) from \( B \to J/\psi(\mu\mu)K \) studies and using \( A_D(K) = (−0.126 \pm 0.018)\% \) [PRL 108 (2012) 201601]
- \( A_D(\pi) = (0.00 \pm 0.25)\% \) from studies of prompt \( D^* \) decays [PLB 713 (2012) 186]

- Acceptance correction to take into account nonuniformity of efficiencies and raw asymmetries in the phase space

\[
\begin{align*}
A_{\text{CP}}(B^\pm \to K^\pm \pi^+ \pi^-) &= +0.025 \pm 0.004(\text{stat}) \pm 0.004(\text{syst}) \pm 0.007(J/\psi K^\pm) \\
A_{\text{CP}}(B^\pm \to K^\pm K^+ K^-) &= -0.036 \pm 0.004(\text{stat}) \pm 0.002(\text{syst}) \pm 0.007(J/\psi K^\pm) \\
A_{\text{CP}}(B^\pm \to \pi^\pm \pi^+ \pi^-) &= +0.058 \pm 0.008(\text{stat}) \pm 0.009(\text{syst}) \pm 0.007(J/\psi K^\pm) \\
A_{\text{CP}}(B^\pm \to \pi^\pm K^+ K^-) &= -0.123 \pm 0.017(\text{stat}) \pm 0.012(\text{syst}) \pm 0.007(J/\psi K^\pm)
\end{align*}
\]

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Dalitz Plot \[\text{[arXiv:1408.5373]}\]

Dalitz plots in the signal region with bkg: $\pm 34 \text{ MeV}/c^2$ ($hhh$ and $hhK$), $\pm 17 \text{ MeV}/c^2$ ($\pi KK$)
Dalitz Plot [arXiv:1408.5373]

Dalitz plots in the signal region with bkg: ±34 MeV/c² (hhh and hhK), ±17 MeV/c² (πKK)
Dalitz Plot [arXiv:1408.5373]

Dalitz plots in the signal region with bkg: $\pm 34 \text{ MeV}/c^2$ ($hhh$ and $hhK$), $\pm 17 \text{ MeV}/c^2$ ($\pi KK$)
Dalitz Plot \[\text{[arXiv:1408.5373]}\]

Dalitz plots in the signal region with bkg: \(\pm 34\) MeV\(c^2\) \((hhh\) and \(hhK\)), \(\pm 17\) MeV\(c^2\) \((\pi KK)\)
Dalitz Plot [arXiv:1408.5373]

Dalitz plots in the signal region with bkg: $\pm 34 \, \text{MeV}/c^2$ ($hhh$ and $hhK$), $\pm 17 \, \text{MeV}/c^2$ ($\pi KK$)
CP asymmetries in the phase space [arXiv:1408.5373]

- Also background subtracted (SPlot) and efficiency corrected

\[ B^\pm \rightarrow h^+ h^- h^\pm \]
\[ B^\pm \rightarrow p\bar{p}h^\pm \]
CP asymmetries in the phase space \[\text{arXiv:1408.5373}\]

Large asymmetries at low \(m_{\pi\pi}^2\)

Large asymmetries at low \(m_{KK}^2\)
Interference

- Zoom at low mass region. Asymmetry is more evident.
Interference

- The behavior of all channels change at midle of the vertical range
Interference: \( B^\pm \rightarrow \pi^+\pi^-\pi^\pm \)
Interference: \( B^{\pm} \rightarrow \pi^+\pi^-\pi^{\pm} \)

\[
\begin{align*}
B^{\pm} & \rightarrow h^+h^-h^{\pm} \\
B^{\pm} & \rightarrow p\bar{p}h^{\pm}
\end{align*}
\]
Interference: $B^\pm \rightarrow \pi^+\pi^-\pi^\pm$
Interference: \( B^{\pm} \to \pi^+\pi^-\pi^\pm \)

\[ 0.47 < m_{\pi\pi_{low}} \text{ GeV/c}^2 < 0.77 \]

\[ 0.77 < m_{\pi\pi_{low}} \text{ GeV/c}^2 < 0.92 \]
Interference: \[ B^\pm \rightarrow \pi^+ \pi^- \pi^\pm \] (Simple Isobar Model)

\[ B^+: \quad \mathcal{A}_+ = A_+^\rho e^{i\Phi_+^\rho} F_{\rho}^{BW} \cos \theta + A_{nr}^\rho e^{i\Phi_{nr}^\rho} F_{nr} \]

\[ B^-: \quad \mathcal{A}_- = A_-^\rho e^{i\Phi_-^\rho} F_{\rho}^{BW} \cos \theta + A_{nr}^\rho e^{i\Phi_{nr}^\rho} F_{nr} \]

The phase \((\Phi)\) contains the weak \((\phi)\) and strong \((\delta)\) phases.

\[ F_{\rho}^{BW} = \frac{1}{m_\rho^2 - s - im_\rho \Gamma_\rho(s)} \quad F_{nr} = 1 \]
Interference: $B^\pm \rightarrow \pi^+\pi^-\pi^\pm$ (Simple Isobar Model)

- Difference of magnitudes (Short Distance Effect)

$$\Delta |A_+|^2 = |A_+|^2 - |A_-|^2 = [(A_+^\rho)^2 - (A_-^\rho)^2] |F_{\rho}^{BW}|^2 \cos^2 \theta + [(A_+^{nr})^2 - (A_-^{nr})^2] |F_{nr}|^2 + 2 \cos \theta |F_{\rho}^{BW}|^2 |F_{nr}| \{ (m_\rho^2 - s) [A_+^\rho A_+^{nr} \cos(\Phi_+ - \Phi_+^{nr}) - A_-^\rho A_-^{nr} \cos(\Phi_- - \Phi_-^{nr})] - m_\rho \Gamma_\rho [A_+^\rho A_+^{nr} \sin(\Phi_+ - \Phi_+^{nr}) - A_-^\rho A_-^{nr} \sin(\Phi_- - \Phi_-^{nr})] \}$$

- Real part of the BW (Long Distance Effect)

- Imag part of the BW (Long Distance Effect)
Interference: \( B^\pm \to \pi^+ \pi^- \pi^\pm \) (Simple Isobar Model)

Monte Carlo simulation for the short distance term:

\[
A_{CP} \propto \left[ (A^\rho_+)^2 - (A^\rho_-)^2 \right] |F^{BW}_\rho|^2 \cos^2 \theta + \ldots
\]

\[
-2(m_\rho^2 - s) |F^{BW}_\rho|^2 |F_{nr}|^2 \cos \theta \ldots
\]

\[
+2m_\rho \Gamma_\rho |F^{BW}_\rho|^2 |F_{nr}|^2 \cos \theta \ldots
\]

- If it were the dominant term, we should see a peak at the \( \rho \) mass.
- The peak should have the same sign for \( \cos \theta > 0 \) and for \( \cos \theta < 0 \)
Interference: $B^\pm \to \pi^+\pi^-\pi^\pm$ (Simple Isobar Model)

Monte Carlo simulation for the long distance term (Re BW):

$$A_{CP} \propto [(A_+^\rho)^2 - (A_-^\rho)^2]|F_{\rho}^{BW}|^2 \cos^2 \theta + ...$$

$$-2(m_\rho^2 - s)|F_{\rho}^{BW}|^2 |F_{nr}|^2 \cos \theta...$$

$$+2m_\rho \Gamma_\rho |F_{\rho}^{BW}|^2 |F_{nr}|^2 \cos \theta...$$

- In this case, we should see an interferent pattern with asymmetry zero at the $\rho$ mass.
- For $\cos \theta > 0$ the asymmetry is (+) below the $\rho$ mass and (-) above.
- For $\cos \theta < 0$ the behaviour is opposite.
Interference: $B^\pm \rightarrow \pi^+\pi^-\pi^\pm$ (Simple Isobar Model)

Monte Carlo simulation for the long distance term ($\text{Im BW}$):

$$A_{CP} \propto [(A^\rho_+)^2 - (A^\rho_-)^2]|F^{BW}_\rho|^2 \cos^2 \theta + ...$$

$$-2(m^2_\rho - s)|F^{BW}_\rho|^2|F_{nr}|^2 \cos \theta...$$

$$+2m_\rho \Gamma_\rho |F^{BW}_\rho|^2|F_{nr}|^2 \cos \theta...$$

- In this case, also we should see a peak at the $\rho$ mass.
- But the peak has opposite sign for $\cos \theta > 0$ and $\cos \theta < 0$. 
Interference: \( B^\pm \rightarrow \pi^+ \pi^- \pi^\pm \) (Simple Isobar Model)

Long distance term (Re BW)
Interference: $B^\pm \rightarrow \pi^+ \pi^- \pi^\pm$ (Simple Isobar Model)

Long-distance effects play an important role generating strong phase.
Rescattering \( \pi\pi \rightarrow KK \)

Large asymmetries: \(1 < m_{\pi\pi} < 1.5\)

Large asymmetries: \(1 < m_{KK} < 1.5\)
Rescattering \( \pi \pi \rightarrow KK \)

Invariant masses with \( \pi \pi \) and \( KK \) in the "rescattering region": \((1.0 - 1.5)\text{GeV} / c^2\)

\[
A_{CP}(K \pi \pi) = +0.121 \pm 0.012 \pm 0.017 \pm 0.007
\]

\[
A_{CP}(KKK) = -0.211 \pm 0.011 \pm 0.004 \pm 0.007
\]

\[
A_{CP}(\pi \pi \pi) = +0.172 \pm 0.021 \pm 0.015 \pm 0.007
\]

\[
A_{CP}(\pi KK) = -0.328 \pm 0.028 \pm 0.029 \pm 0.007
\]

All the asymmetries have more than 5\(\sigma\) of significance

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Scattering and CPT constraint

High local asymmetries not obviously associated to resonances.

- **positive** for $K^\pm \pi^+\pi^-$
- **negative** for $K^\pm K^+K^-$
- **positive** for $\pi^+\pi^- \pi^\pm$
- **negative** for $K^+K^-\pi^\pm$

\[ \sum_{f_{\alpha} \in F_i} \Gamma(P \rightarrow f_{\alpha}^{(i)}) = \sum_{\bar{f}_{\alpha} \in \bar{F}_i} \bar{\Gamma} (\bar{P} \rightarrow \bar{f}_{\alpha}^{(i)}) \]

(Bigi & Sanda 2nd edition pp 57)

all $f_{\alpha}$ in $F_i$ connected via strong interactions

for two modes $\pi\pi$ and $KK$:

\[ \Delta \Gamma_{\pi\pi} = - \Delta \Gamma_{KK} \]


\[ \Delta \Gamma_{KK} = (\sin \gamma) \sqrt{1 - \eta^2} \cos(\delta_{KK} + \delta_{\pi\pi} + \Phi) F(M^2_{KK}) \]

(Inelasticity and Unitarity)
$B^\pm \rightarrow p\bar{p}h^\pm$ decays.
$B^\pm \rightarrow p\bar{p}h^\pm$ decays

- Yields extracted with an unbinned maximum likelihood fit

- Background subtracted Dalitz distributions using sPlot technique

- At low $m_{pp}^2$ invariant mass the behaviour is differently distributed in the two modes

- Charmonium bands clearly visible: $J\psi$, $\psi(2S)$ and $\eta_c$

- At low $m_{pk}^2$ invariant mass we see $\Lambda(1520)$
$B^\pm \rightarrow p\bar{p}h^\pm$ decays

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$B^\pm \to p\bar{p}h^\pm$ decays

- Yields extracted with an unbinned maximum likelihood fit

\begin{align*}
\text{LHCb} & \quad B^+ \to p\bar{p}K^+ \\
N & = 18721 \pm 142
\end{align*}

\begin{align*}
\text{LHCb} & \quad B^+ \to p\bar{p}\pi^+ \\
N & = 1988 \pm 74
\end{align*}

- Background subtracted Dalitz distributions using sPlot technique

\begin{align*}
\text{LHCb} & \quad B^+ \to p\bar{p}K \\
\text{Signal yield} / (0.16 \text{ GeV}^2/c^4) & \quad \text{Candidates} / (0.01 \text{ GeV}/c^2)
\end{align*}

\begin{align*}
\text{LHCb} & \quad B^+ \to p\bar{p}\pi^+ \\
\text{Signal yield} / (0.20 \text{ GeV}^2/c^4) & \quad \text{Candidates} / (0.01 \text{ GeV}/c^2)
\end{align*}

- At low $m^2_{pp}$ invariant mass the behaviour is differently distributed in the two modes
- Charmonium bands clearly visible: $J\psi$, $\psi(2S)$ and $\eta_c$
- At low $m^2_{pk}$ invariant mass we see $\Lambda(1520)$
**B^± → p¯p h^±** decays: Dynamics

- Measurement of the forward-backward asymmetry

\[ A_{FB} = \frac{N(\cos \theta_p > 0) - N(\cos \theta_p < 0)}{N(\cos \theta_p > 0) + N(\cos \theta_p < 0)} \]

- Variation of the \( A_{FB} \) as a function of \( m_{p\bar{p}} \)

- Opposite behaviour for the two decay modes

\[ A_{FB}(p\bar{p}K^+, m_{p\bar{p}} < 2.85\text{GeV}/c^2) = 0.495 \pm 0.012(\text{stat}) \pm 0.007(\text{syst}) \]
\[ A_{FB}(p\bar{p}\pi^+, m_{p\bar{p}} < 2.85\text{GeV}/c^2) = -0.409 \pm 0.033(\text{stat}) \pm 0.006(\text{syst}) \]
$B^\pm \rightarrow p\bar{p}h^\pm$ decays: CP asymmetries

- Variation of $A_{CP}$ as a function of the Dalitz-plot variables only for $B^\pm \rightarrow p\bar{p}K^\pm$
- Adaptive binning analysis
B\(^{\pm} \rightarrow p\bar{p}h^{\pm}\) decays: CP asymmetries

- Variation of \(A_{CP}\) as a function of the Dalitz-plot variables only for \(B^{\pm} \rightarrow p\bar{p}K^{\pm}\)
- Adaptive binning analysis

\[m_{Kp}^2 > 10 \text{ GeV}^2/c^4\]

\[m_{Kp}^2 < 10 \text{ GeV}^2/c^4\]
\( B^\pm \rightarrow p\bar{p}h^\pm \) decays: CP asymmetries

- The raw CP is corrected for production and detection asymmetries as in \( B^\pm \rightarrow h^+ h^- h^\pm \) decays.

\[
\begin{align*}
B^\pm \rightarrow p\bar{p}K^\pm & \quad A_{CP} = A_{raw} - A_P(B^\pm) - A_D(K^\pm) \\
B^\pm \rightarrow p\bar{p}\pi^\pm & \quad A_{CP} = A_{raw} - A_P(B^\pm) - A_D(\pi^\pm)
\end{align*}
\]

First evidence of CPV in baryonic B decays

<table>
<thead>
<tr>
<th>Mode/region</th>
<th>( A_{CP} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_c(\rightarrow p\bar{p})K^\pm )</td>
<td>( 0.040 \pm 0.034 ) (stat) ( \pm 0.004 ) (syst)</td>
</tr>
<tr>
<td>( \psi(2S)(\rightarrow p\bar{p})K^\pm )</td>
<td>( 0.092 \pm 0.058 ) (stat) ( \pm 0.004 ) (syst)</td>
</tr>
<tr>
<td>( p\bar{p}K^\pm, \ m_{p\bar{p}} &lt; 2.85 \text{ GeV}/c^2 )</td>
<td>( 0.021 \pm 0.020 ) (stat) ( \pm 0.004 ) (syst)</td>
</tr>
<tr>
<td>( p\bar{p}K^\pm, \ m_{p\bar{p}} &lt; 2.85 \text{ GeV}/c^2, \ m_{K_p}^2 &lt; 10 \text{ GeV}^2/c^4 )</td>
<td>( -0.036 \pm 0.023 ) (stat) ( \pm 0.004 ) (syst)</td>
</tr>
<tr>
<td>( p\bar{p}K^\pm, \ m_{p\bar{p}} &lt; 2.85 \text{ GeV}/c^2, \ m_{K_p}^2 &gt; 10 \text{ GeV}^2/c^4 )</td>
<td>( 0.096 \pm 0.024 ) (stat) ( \pm 0.004 ) (syst)</td>
</tr>
<tr>
<td>( p\bar{p}K^\pm, \ m_{p\bar{p}}^2 &lt; 6 \text{ GeV}^2/c^4, \ m_{K_p}^2 &lt; 10 \text{ GeV}^2/c^4 )</td>
<td>( -0.066 \pm 0.026 ) (stat) ( \pm 0.004 ) (syst)</td>
</tr>
<tr>
<td>( p\bar{p}K^\pm, \ m_{p\bar{p}}^2 &lt; 6 \text{ GeV}^2/c^4, \ m_{K_p}^2 &gt; 10 \text{ GeV}^2/c^4 )</td>
<td>( 0.087 \pm 0.026 ) (stat) ( \pm 0.004 ) (syst)</td>
</tr>
<tr>
<td>( p\bar{p}\pi^\pm, \ m_{p\bar{p}} &lt; 2.85 \text{ GeV}/c^2 )</td>
<td>( -0.041 \pm 0.039 ) (stat) ( \pm 0.005 ) (syst)</td>
</tr>
</tbody>
</table>

- Systematics uncertainties dominated by the uncertainty on the \( A_{CP}(J/\psi K) \) measurement

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$B^\pm \rightarrow p\bar{p}h^\pm$ decays: B.F. measurements

• Branching fraction of $B^+ \rightarrow \bar{\Lambda}(1520)(K^+\bar{p})p$ relative to $B^+ \rightarrow J/\psi(p\bar{p})K^+$

$$\frac{\mathcal{B}(B^+ \rightarrow \bar{\Lambda}(1520)(K^+\bar{p})p)}{\mathcal{B}(B^+ \rightarrow J/\psi(p\bar{p})K^+)} = \frac{N_{\Lambda \rightarrow Kp}}{N_{J/\psi \rightarrow p\bar{p}}} \times \frac{\epsilon_{J/\psi \rightarrow p\bar{p}}^{gen}}{\epsilon_{\Lambda \rightarrow Kp}^{gen}} \times \frac{\epsilon_{J/\psi \rightarrow p\bar{p}}^{sel}}{\epsilon_{\Lambda \rightarrow Kp}^{sel}}$$

• Similar equation for the ratio $B^+ \rightarrow p\bar{p}\pi^+$ to $B^+ \rightarrow J/\psi(p\bar{p})\pi^+$

• Resonant modes extracted with a 2D fit to $p\bar{p}h^+$ and $p\bar{p}/K^+\bar{p}$

$$\frac{\mathcal{B}(B^+ \rightarrow \bar{\Lambda}(1520)(K^+\bar{p})p)}{\mathcal{B}(B^+ \rightarrow J/\psi(p\bar{p})K^+)} = 0.033 \pm 0.005(stat) \pm 0.007(syst)$$

$$\frac{\mathcal{B}(B^+ \rightarrow p\bar{p}\pi^+), m_{p\bar{p}} < 2.85 \text{GeV}/c^2}{\mathcal{B}(B^+ \rightarrow J/\psi(p\bar{p})\pi^+)} = 12.0 \pm 1.2(stat) \pm 0.3(syst)$$

• Using

  • $B(B^+ \rightarrow J/\psi K^+) = (1.016 \pm 0.033) \times 10^{-3}$ [PDG]
  • $B(J/\psi \rightarrow p\bar{p}) = (2.17 \pm 0.07) \times 10^{-3}$ [PDG]
  • $B(\Lambda(1520) \rightarrow K^+\bar{p}) = 0.234 \pm 0.016$ [Eur.Phys.J. A47(2011)133]

$$\mathcal{B}(B^+ \rightarrow \bar{\Lambda}(1520)(K^+\bar{p})p) = (3.15 \pm 0.48(stat) \pm 0.07(syst) \pm 0.26(BF)) \times 10^{-7}$$

$$\mathcal{B}(B^+ \rightarrow p\bar{p}\pi^+, m_{p\bar{p}} < 2.85 \text{GeV}/c^2) = (1.07 \pm 0.11(stat) \pm 0.03(syst) \pm 0.11(BF)) \times 10^{-6}$$
Summary

- New results with the full LHCb data set (3 fb$^{-1}$)

- $B^\pm \to h^+ h^- h^\pm$ decays
  - Evidence of global direct CP violation
  - High localised CP asymmetries across the Dalitz plot
  - Long-distance effects play an important role in generating a strong phase difference:
    - Interference between resonances.
    - Rescattering.

- $B^\pm \to p\bar{p}h^\pm$ decays
  - Large forward-backward asymmetries
  - First evidence CP violation in decays involving baryons
  - Sign-flip of CP asymmetry probably generated by interference of long-distance $p\bar{p}$ waves

- Next Step: Amplitude Analyses.
BackUp Slides
**BSS Model for the $B^\pm \rightarrow \pi^+\pi^-\pi^\pm$ decay**

- Strangeness = 0
- Penguin: $q = u, c, t$
- Tree Dominant.
- Different week phase (CKM mechanism).
- Different strong phase (for $u$ and $c$ in the penguin).

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]  

(1)

\[
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A[\lambda^3(1 - \rho - i\eta)] & -A\lambda^2 & 1
\end{pmatrix}
\]  

(2)
BSS Model for $B^\pm \to K^\pm \pi^+ \pi^-$ & $B^\pm \to K^\pm K^+ K^-$ decays

$B^-$

$\bar{u} \to s u \bar{u}$

$B^-$

$\bar{u} \to s u \bar{u}$

Strangeness = 1

Penguin: $q = u, c, t$

Penguin Dominant.

CPV expected from interference between tree and penguin diagrams
Amplitude Analysis

Problems in the usual Isobar Model:

- **Many** broad states (scalars) squeezed in a **narrow mass window**
- For D mesons the **Non-Resonant amplitude** $A_{0}^{NR}$ is assumed to be **constant** (due to the small phase space), but this is not the case for B meson decays.
- High Non-Resonant contribution in B meson decays.
- In Isobar Model, hard to disentangle the Non-Resonant and broad structures in the S-Wave.

The Partial Wave Analysis:

- This method was developed by **E791 collaboration**. PRD 73, 032004 (2006)

$$\mathcal{A} = \underbrace{S - \text{Wave}}_{a_{0}(s_i)e^{i\phi_{0}(s_i)}} + \underbrace{P - \text{Wave}}_{\text{Isobar Model}} + \underbrace{D - \text{Wave}}_{\text{Isobar Model}}$$

- The real functions $a_{0}(s_i)$ and $\phi_{0}(s_i)$ are **extracted directly from data**.
- **The measurement is inclusive**: convolution of elastic, inelastic scattering, mixed isospin, FSI, etc...
- **Accuracy** depends on the features of P-(or D-waves) - an interferometry analysis.
Interference: $B^\pm \rightarrow K^\pm \pi^+ \pi^-$
Interference: $B^\pm \rightarrow K^\pm \pi^+ \pi^-$
Interference: \( B^\pm \rightarrow K^\pm \pi^+ \pi^- \) (Simple Isobar Model)

\[
\begin{align*}
\mathcal{M}_+ &= a_+^\rho e^{i\delta^\rho} F_\rho^{\text{BW}} \cos \theta + a_+^f e^{i\delta^f} F_f^{\text{BW}} \\
\mathcal{M}_- &= a_-^\rho e^{i\delta^\rho} F_\rho^{\text{BW}} \cos \theta + a_-^f e^{i\delta^f} F_f^{\text{BW}} \\
F_R^{\text{BW}}(s) &= \frac{1}{m_R^2 - s - im_R \Gamma_R(s)} \quad R = \rho, f
\end{align*}
\]
Interference: $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ (Simple Isobar Model)

$$|\Delta M|^2 = |M_+|^2 - |M_-|^2$$

$$= \left( (a_+^0)^2 - (a_-^0)^2 \right) |F_{\rho}^{BW}|^2 \cos^2 \theta + \left( (a_+^f)^2 - (a_-^f)^2 \right) |F_{f}^{BW}|^2 + 2 \cos \theta |F_{\rho}^{BW}|^2 |F_{f}^{BW}|^2 \times$$

$$\{ [(m_\rho^2 - s)(m_f^2 - s) - m_\rho \Gamma_\rho m_f \Gamma_f][a_+^0 a_+^f \cos(\delta_+^0 - \delta_+^f) - a_-^0 a_-^f \cos(\delta_-^0 - \delta_-^f)]$$

$$- [m_\rho \Gamma_\rho (m_f^2 - s) - m_f \Gamma_f (m_\rho^2 - s)][a_+^0 a_+^f \sin(\delta_+^0 - \delta_+^f) - a_-^0 a_-^f \sin(\delta_-^0 - \delta_-^f)] \}$$

$$\left. \left( (m_\rho^2 - s)(m_f^2 - s) - m_\rho \Gamma_\rho m_f \Gamma_f \right) \right\}$$

$$2 \cos \theta |F_{\rho}^{BW}|^2 |F_{NR}|^2$$

Long distance interference: Real part of Dalitz CP asymmetry

Long distance interference: Imaginary part of Dalitz CP asymmetry
Interference: $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ (Simple Isobar Model)
Interference: $B^{\pm} \rightarrow K^{\pm} K^+ K^-$
Scattering and CPT constraint

- **Scattering:**
  CERN-Munich collab: $\pi^+\pi^- \rightarrow \pi^+\pi^-$ scattering Nuclear Physics B64 (1973) 134-162
  Strongly coupled channels: $\pi^+\pi^- \rightarrow K^+K^-$ PRD 22 (1980) 2595

**S-wave**

- **CPT constraint:**
  High local asymmetries not obviously associated to resonances.
  - positive for $K^\pm \pi^+\pi^-$
  - negative for $K^\pm K^+K^-$
  - positive for $\pi^+\pi^- \pi^\pm$
  - negative for $K^+K^-\pi^\pm$

\[ \sum_{f_\alpha \in F_i} \Gamma(P \rightarrow f_\alpha^{(i)}) = \sum_{\bar{f}_\alpha \in \bar{F}_i} \Gamma(\bar{P} \rightarrow \bar{f}_\alpha^{(i)}) \] (Bigi & Sanda 2nd edition pp 57)

all $f_\alpha$ in $F_i$ connected via strong interactions

for two channels $\alpha$ and $\beta$: $\Gamma(A^+_\alpha) + \Gamma(A^+_\beta) = \Gamma(A^-_\alpha) + \Gamma(A^-_\beta)$, then: $\Delta \Gamma_\alpha = -\Delta \Gamma_\beta$

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