Final state interaction effect on CP asymmetry in charmless three-body B decays

Tobias Frederico
Instituto Tecnológico de Aeronáutica (tobias@ita.br)

Collaborators: O. Lourenço (UFSCar) and I. Bediaga (CBPF)


”Implications of LHCb measurements and future prospects”
CERN, Oct 14-16, 2013
Outline

- Experimental facts:
  \[ B^\pm \rightarrow K^\pm \pi^+ \pi^-, \quad B \rightarrow KKK, \quad B \rightarrow \pi\pi\pi, \quad B \rightarrow \pi KK, \quad K\pi \rightarrow K\pi, \quad \pi\pi \rightarrow \pi\pi \]

- CPT constraint and FSI

- Pattern of CP violation in \( B^\pm \rightarrow K^\pm \pi^+ \pi^- \) and \( B^\pm \rightarrow K^\pm K^+ K^- \)

- Why no CP violation in \( B^\pm \rightarrow K^\pm p\bar{p} \)?

- Conclusion and Outlook
Where are the events?
Low two-body mass region in $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$!
(Supports the 2+1 decay process dominance.)

Low two-body mass region dominance (except charmonium):
$B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$, $B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \rightarrow \pi^{\pm}K^{+}K^{-}$, $B^{\pm} \rightarrow K^{\mp}\bar{p}\bar{p}$ !!!!!
Asymmetry in the Dalitz Plot: $B^± \to K^± \pi^+ \pi^-$ and $B^± \to K^± K^+ K^-$

Aaij et al. LHCb Coll. PRL111,101801(2013)

$B^±$ three-body decay populates low-mass region of the meson pair!
Asymmetry in the Dalitz Plot: $B^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow \pi^\pm K^+ K^-$

- $B^\pm$ three-body decay populates low-mass region of the meson pair!
- $\pi\pi \rightarrow KK$ s-wave inelastic scattering appreciable for $M_{\pi\pi} < 1.6$ GeV (D. H. Cohen et al., Phys. Rev. D 22, 2595 (1980)).

From "Charmless three-body B decays" talk by Irina NASTEVA
$K^+ \pi^- \rightarrow K^+ \pi^-$ scattering

Inelasticity: $\eta = 1 \Rightarrow 100\%$ of $hh \rightarrow hh$
$\eta = 0 \Rightarrow 0\% \rightarrow hh$

Argand plot.


No deviation from the unitary circle ($\eta = 1$) up to 1.6 GeV.
$\pi^+\pi^- \rightarrow \pi^+\pi^-$ scattering

CERN-Munich collaboration $\pi^+\pi^- \rightarrow \pi^+\pi^-$ (1973)

Large deviation from the unitary circle ($\eta = 1$) in s-wave up to about 1.6GeV!

Strongly coupled channels:

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

Cohen, D et al PRD 22 (1980) 2595

Fig. 6. Argand diagrams (Im $T_1$ versus Re $T_1$) for the partial wave amplitudes from the energy-dependent fit. Numbers indicate the $\pi\pi$ energy.
CPT invariance constraint and decay


- \( \text{CPT} |h\rangle = \eta \langle \bar{h} \rangle \), (\( \bar{h} \) is the charge conjugate state and \( \eta \) is a phase)

- The weak and strong Hamiltonians conserve CPT:
  \( (\text{CPT})^{-1} H_w \text{CPT} = H_w \) and \( (\text{CPT})^{-1} H_s \text{CPT} = H_s \)

- Weak decay amplitude: \( \langle \lambda_{\text{out}}|H_w|h\rangle \), \( \lambda_{\text{out}} \) with FSI from the strong interaction.

- CPT constraint: \( \langle \lambda_{\text{out}}|H_w|h\rangle = \langle \lambda_{\text{out}}|(\text{CPT})^{-1} H_w \text{CPT}|h\rangle = \eta_h \eta_\lambda \langle \bar{\lambda}_{\text{in}}|H_w|\bar{h}\rangle^* \).

  \[ \langle \lambda_{\text{out}}|H_w|h\rangle = \eta_h \eta_\lambda \sum_{\bar{\lambda}_\prime} S_{\bar{\lambda}_\prime,\bar{\lambda}} \langle \bar{\lambda}'_{\text{out}}|H_w|\bar{h}\rangle^* \text{,} \quad S_{\bar{\lambda}',\bar{\lambda}} = \langle \bar{\lambda}'_{\text{out}}|\bar{\lambda}_{\text{in}} \rangle \]

- \( \Gamma_h = \Gamma_{\bar{h}} \): identical particle and antiparticle life-times.
CP violation

*CPT, Tree and Penguin amplitudes.*

- Decay amplitude can be written in two pieces as [Bander, Silverman, Soni, PRL 43, 242 (1979)] \( A^\pm = [a^T e^{i(\delta^T \pm \gamma)} + a^P e^{i\delta^P}] \),

- General way [PDG - 12. CP Violation in Meson Decays]:
  \[
  \mathcal{A}^\pm = A + e^{\pm i\gamma} B ,
  \]
  where A and B are complex amplitudes invariant for CP, carrying strong FSI

- CP transformation changes the sign of the weak phase \( \gamma \).
Coupled-Channel decay, CPT, FSI and CP asymmetry

\[ A^− = \langle \lambda_{out} | H_w | h \rangle = A_\lambda + e^{-i\gamma} B_\lambda, \quad A^+ = \langle \bar{\lambda}_{out} | H_w | \bar{h} \rangle = A_\lambda + e^{i\gamma} B_\lambda \]

- **CPT and FSI:**
  \[ A^\pm = A_\lambda + e^{\pm i\gamma} B_\lambda = \eta_\eta_\lambda \sum_{\lambda'} S_{\lambda',\lambda} (A_{\lambda'} + e^{\mp i\gamma} B_{\lambda'})^* \]

- **S-matrix and strong scattering amplitude:**
  \[ S_{\lambda',\lambda} = \delta_{\lambda',\lambda} + i t_{\lambda',\lambda}, \quad (\lambda = \alpha, \beta) \]

- **Perturbative treatment of FSI:**
  \[ A_\lambda = A_{0\lambda} + \delta A_\lambda \quad \text{and} \quad B_\lambda = B_{0\lambda} + \delta B_\lambda \]


Coupled-Channel decay, CPT, FSI and CP asymmetry: LO in strong interaction

- **Leading order in** $t_{\lambda',\lambda}$:
  
  $$A_{\lambda}^{\pm} = A_{0\lambda} + e^{\pm i\gamma}B_{0\lambda} + i \sum_{\lambda'} t_{\lambda',\lambda} (A_{0\lambda'} + e^{\pm i\gamma}B_{0\lambda'})$$

  $$A_{0\lambda} = \eta_h \eta_{\lambda} A_{0\lambda}^* \quad \text{and} \quad B_{0\lambda} = \eta_h \eta_{\lambda} B_{0\lambda}^*.$$ 

- **The CPT constraint for two-channels**:
  
  $$\Gamma(A_{\alpha}^+) + \Gamma(A_{\beta}^+) = \Gamma(A_{\alpha}^-) + \Gamma(A_{\beta}^-)$$  is still valid in LO!

  if $\text{Imag} \left[ B_{0\alpha} A_{0\alpha}^* \right] = -\text{Imag} \left[ B_{0\beta} A_{0\beta}^* \right]$ 

- **CP asymmetry**: $\Delta \Gamma_{\lambda} = \Gamma(h \to \lambda) - \Gamma(\bar{h} \to \bar{\lambda})$

- **Two-channels** $\alpha$ and $\beta$ coupled by the strong interaction: $\Delta \Gamma_{\alpha} = -\Delta \Gamma_{\beta}$. 
Inelasticity and CP violation

- Unitarity and symmetry of the S-matrix \((S_{\alpha,\beta} = S_{\beta,\alpha})\)

\[
S = \begin{bmatrix}
\eta e^{2i\delta_\alpha} & i\sqrt{1 - \eta^2} e^{i(\delta_\alpha + \delta_\beta)} \\
i\sqrt{1 - \eta^2} e^{i(\delta_\alpha + \delta_\beta)} & \eta e^{2i\delta_\beta}
\end{bmatrix}
\]

- Asymmetry: \(\Delta \Gamma_\alpha = 4(\sin \gamma) \left(\zeta_0 + \sqrt{1 - \eta^2} \zeta_1\right)\)

\[
\zeta_0 = \text{Imag} \left[ B_{0\alpha}^* A_{0\alpha} (1 + i(t_\alpha - t_{\alpha}^*)) \right]
\]

\[
\zeta_1 = \text{Real} \left[ B_{0\alpha}^* A_{0\beta} e^{i(\delta_\alpha + \delta_\beta)} - B_{0\beta}^* A_{0\alpha} e^{-i(\delta_\alpha + \delta_\beta)} \right]
\]

Born terms = partonic level [Bander, Silverman, Soni, PRL 43, 242 (1979)]

"Compound ” CP asymmetry [Cheng, Chua, and Soni, PRD71, 014030 (2005)]

- If the phases of \(B_{0\alpha}\) and \(A_{0\alpha}\) are equal \(\Rightarrow \zeta_0 = 0!\)
Estimate of \( \Delta \Gamma_{KK(\pi\pi)} \) in \( B^\pm \to K^\pm K^+ K^- \) (\( B^\pm \to K^\pm \pi^+ \pi^- \)).

- \( s\)-wave scattering \( \pi\pi \to \pi\pi \) and \( KK \) (I=0)

- Channels \( \alpha \equiv K^+ K^- \) and \( \beta \equiv \pi^+ \pi^- \)

\[ \Delta \Gamma_{KK} = \int dM_{KK}^2 \left( \frac{\partial^2}{\partial M_{KK}^2 \partial M_{KK}^2} \Gamma_{B^- \to K^- K^+ K^-} - \frac{\partial^2}{\partial M_{KK}^2 \partial M_{KK}^2} \Gamma_{B^+ \to K^+ K^+ K^-} \right) \]

- 2+1 decay mechanism (\( K^\pm = \) spectator)

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

- Phase-space factor: \( F(M_{KK}^2) = (M_{K^+ K^-}^2)_{max} - (M_{K^+ K^-}^2)_{min} \)
Theo. vs. Exp. for $\Delta \Gamma_{\pi\pi}(KK)$ in $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$

- $\Phi < \delta_{KK} + \delta_{\pi\pi}$ and $\delta_{KK} \approx \delta_{\pi\pi}$
- $s$–wave $l=0 \ \delta_{\pi\pi}$ and $\eta$ from Pelaez and Yndurain PRD71,074016(05)
- Fit the absolute normalization

Figure: Theo. estimate (grey band) as a function of the subsystem mass compared to experimental data of (a) the asymmetry of $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$ decay (circles), and of (b) the asymmetry of $B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$ decay (squares). Exp. data from R. Aaij et al. (LHCb Coll.) PRL111,101801(2013).
No CP violation in $B^{\pm} \rightarrow K^{\pm} p \bar{p}$

R. Aaij et al. (LHCb Collaboration) PRD88, 052015 (2013)

STUDIES OF THE DECAYS $B^{+} \rightarrow \rho \bar{p} h^{+}$...

FIG. 7. Distribution of $A_{CP}$ for the Dalitz-plot projections on $m_{\rho p}$ and $m_{Kp}^{2}$ for $B^{\pm} \rightarrow \rho \bar{p} K^{\pm}$ events. In the $m_{\rho p}$ projection (left), the bin $[2.85, 3.15]$ GeV/c$^2$ contains only the value of the charless $p \bar{p} K^{\pm}$ after subtraction of the $\eta_c - J/\psi$ contribution. The $m_{Kp}^{2}$ projection (right) has been obtained after removing the charmonia bands.

▶ Why? FSI?
No CP violation in $B^\pm \rightarrow K^\pm p\bar{p}$: competing decay channels

Branching ratios for $pp$ annihilation at rest into three narrow mesons.

Claude Amsler  Reviews of Modern Physics, Vol. 70, No. 4, October 1998

<table>
<thead>
<tr>
<th>Two body final states</th>
<th>Three body final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \pi^-$</td>
<td>$\pi^+ \pi^- \pi^0$</td>
</tr>
<tr>
<td>$\pi^+ \pi^-$</td>
<td>$\pi^0 \eta \eta$</td>
</tr>
<tr>
<td>$\omega \pi$</td>
<td>$\pi^0 \pi^0 \omega$</td>
</tr>
<tr>
<td>$\omega \pi$</td>
<td>$\omega \pi^0 \omega$</td>
</tr>
<tr>
<td>$\omega \eta$</td>
<td>$\omega \pi^0 \eta$</td>
</tr>
<tr>
<td>$\omega \eta$</td>
<td>$\omega \pi^0 \eta$</td>
</tr>
<tr>
<td>$K^+ K^-$</td>
<td>$K^+ K^- \pi^+ \pi^- \pi^0$</td>
</tr>
</tbody>
</table>

Many channels with similar magnitude!
No CP violation in $B^\pm \rightarrow K^\pm p\bar{p}$

- many channels for $p\bar{p}$ at rest with similar branching ratios

- CPT constraint and FSI:

  $\Delta \Gamma_\lambda \sim 4(\sin \gamma) \text{Imag} \left[ i \sum_{\lambda' \neq \lambda} B^*_0 t_{\lambda',\lambda} A_{0\lambda} - i \sum_{\lambda' \neq \lambda} B^*_{0\lambda'} t^*_{\lambda',\lambda} A_{0\lambda} \right] \sim 0$

- Coherent sum of similar amplitudes with varying phases: vanishing result!
Conclusion and Outlook

Conclusion

- Constraint of CPT invariance + FSI
- Assumption that CP violation is due to the interference of two CP-conserving amplitudes separated by a CP-noninvariant weak phase.
- CP violation in three-body charmless $B^\pm$ decays is driven by the relevance of the $\pi\pi \rightarrow KK$ scattering!
- No CP violation in $B^\pm \rightarrow p\bar{p} h^\pm$ resulting from the coherent sum of several terms!

Outlook

- Normalization of the asymmetries (partonic amplitudes);
- Higher partial waves and isospins;
- Three-body rescattering? ($D \rightarrow KK\pi$)

$\dagger \ D^\pm \rightarrow K^{\mp}\pi^\pm\pi^\pm$

Magalhães, Robilotta, Guimarães, TF, de Paula, Bediaga, dos Reis, Maekawa, Zarnauskas, PRD84 (2011) 094001.