Charm rescattering in B decays: a new CP violation mechanism?

Patricia C. Magalhães#

I. Bediaga++ and T. Frederico*

# Technical University of Munich - TUM
++ CBPF - RJ - Brazil
* ITA - SP - Brazil

Implications of LHCb measurements and future prospects
17 - 19 October 2018 - CERN

patricia.magalhaes@tum.de
Context

- D and B three-body HADRONIC decays are dominated by resonances
  - spectroscopy
  - information of MM interactions $\rightarrow$ no $K\bar{K}$ data available
  - study of CP-Violation $\rightarrow$ can lead to new physics
- new high data sample from LHCb $\rightarrow$ more to come from LHCb and Belle II $\rightarrow$ requires better models

- B and D 3-body decay.....
  - $\neq$ scales!!! $\rightarrow$ similar FSI
  - B phase-space $\rightarrow$ + FSI possibilities
heavy meson decay

- dynamics

\[ \text{HM} \rightarrow W \rightarrow \text{FSI} \rightarrow \text{observed} \]

**to extract information from data we need an amplitude MODEL**

- weak primary vertex (W)

\[ W^\mu \quad \text{quark} \rightarrow \text{hadron} \]

\[ b, c \]

- QCD factorization approach
  - not precise for 3-body
  - not allow all kinds of FSI and 3-body NR

- Final State Interactions (FSI)

\[ M = \text{FSI} + \ldots \]

\[ (2+1) \]

\[ \text{3-body} \]

- 2-body is crucial

- full unitarity: Faddeev, Khury-Trieman, triangles
Amplitude analysis models

- **isobar model:**
  - violates two-body unitarity (2 res in the same channel);
  - do NOT include rescattering and coupled-channels;
  - non resonant as constant
  - free parameters are not connected with theory!

- **ππ S-wave**
  - fit could change this interference
  - more than 2 scalars

new LHCb amplitude analysis models

- $B^+ \rightarrow \pi^+\pi^-\pi^+$, $B^+ \rightarrow \pi^+K^-K^+$ ➔ $\pi\pi$ S-wave parametrisation, rescattering, … (2+1) Maria’s talk

- $\bar{B}^0 \rightarrow K_s\pi^-\pi^+$ ➔ $K\pi$ S-wave FF from DR (2+1) PRL 120 (2018)26, 261801

- $D^+ \rightarrow K^+K^+K^-$ ➔ theoretical model based on Chiral Lagrangian (2+1+3) soon!

PRD 98 056021 (2018) Aoude, Magalhaes, dos Reis & Robilotta

➔ prediction for KK scattering amplitude
massive localized Acp  
\( B^\pm \to hhh \)  

Charge Parity Violation:  
\[ A_M \to f = A_1 e^{i(\delta_1-\phi_1)} + A_2 e^{i(\delta_2-\phi_2)} \]  
\[ |A_M \to f|^2 - |A_M \to f|^2 = -4A_1A_2 \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \neq 0 \]  
\[ \rightarrow \text{two \neq weak and strong phases} \]

BSS model  
\[ c \pm \text{not enough!} \]

Bander Silverman & Soni PRL 43 (1979) 242  

hadronic interactions  
\[ \rightarrow \text{strong phase} \]
CPV on data

- **low-energy CPV** [1 - 2] GeV
  \[ \pi \pi \rightarrow KK \]

  Frederico, Bediaga & Lourenço
  PRD89(2014)094013

- **FSI** $\rightarrow$ strong phase
  Wolfenstein PRD43 (1991) 151

- **CPT:**
  \[
  \tau = 1 / \Gamma_{\text{total}} = 1 / \Gamma_{\text{total}} \\
  \Gamma_{\text{total}} = \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_4 + \Gamma_5 + \Gamma_6 + \ldots \\
  \Gamma_{\text{total}} = \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_4 + \Gamma_5 + \Gamma_6 + \ldots
  \]

  $\rightarrow$ CPV in one channel should be compensated by another one with opposite sign

- **high mass CPV?**

charm rescattering

LHCb Implications 2018

patricia.magalhaes@tum.de
CPV high energy

- CPV high mass?
  - $B^+ \rightarrow K^- K^+ K^+$
  - $B^\pm \rightarrow hhh$ high statistic 109k
  - nonresonant $\rightarrow$ all phase-space
  - dominated by penguin
  - presence of charm resonances: $\chi c 0$, $J/\psi$

- $D \bar{D}$ open channel
  - same opposite Acp observed in coupled-channels

- charm intermediate processes as source of strong phase

charm rescattering
Charm rescattering

- charm FSI: $B \rightarrow 3h$, $B_c \rightarrow 3h$, $B \rightarrow K^* \mu \mu$, ...

\[ B^\pm \rightarrow K^+ K^- K^+ \]

**charm contribution to $B^\pm \rightarrow K^+ K^- K^+$**

**PLB 780 (2018) 357**

other application

\[ B_c^+ \rightarrow K^- K^+ \pi^+ \]

**charm rescattering to $B_c^+ \rightarrow K^- K^+ \pi^+$**

**PLB 785 (2018) 581**
hadronic loop

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

\[ D^+ \rightarrow \pi^+K^-\pi^+ \]

\[ B^+ \rightarrow W^+D^0 \rightarrow C_0 \times \text{form factor to regulate} \]

\[ Br [B \rightarrow DD_s^*] \sim 1\% \rightarrow 1000 \times Br [B \rightarrow KKKK] \]

\[ D^0 \bar{D}^0 \rightarrow K^+K^- \]

\[ \text{scattering amplitude} \]

\[ \text{phenomenological: S- matrix unitarity + Regge theory} \]

\[ \text{hadronic loop} \rightarrow \text{three-body FSI - introduce new complex structures} \]

\[ \text{Practical applications:} \]

- PCM & I Bediaga
  - arXiv:1512.09284

- PCM & M Robilotta
  - PCM et al
    - PRD 84 094001 (2011) [arXiv:1105.5120]
$D^0 \bar{D}^0 \rightarrow K^+ K^-$ scattering amplitude

- not well understand on literature
- important as FSI in B two-body decays
- phenomenological amplitude

- unitarity of the $S$-matrix

$S = \begin{pmatrix} \eta e^{2i\alpha} & \sqrt{1 - \eta^2} e^{i(\alpha+\beta)} \\ -\sqrt{1 - \eta^2} e^{i(\alpha+\beta)} & \eta e^{2i\beta} \end{pmatrix}$

- inspired in the damping factor of the $S$ matrix i.e. $\pi \pi \rightarrow K K$

$\eta = \mathcal{N} \sqrt{s/s_{th} - 1/(s/s_{th})^{2.5}}$

$KK: e^{2i\alpha} = 1 - \frac{2ik_1}{c(1 - k_1/k_0) + ik_1}, \quad DD: e^{2i\beta} = 1 - \frac{2ik}{\frac{1}{a} + ik}$

$k = \sqrt{\frac{s-s_{th}}{4}}, \quad k_1 = \sqrt{\frac{s-s_{th}}{4}}$ and $k_0 = \sqrt{\frac{s_0-s_{th}}{4}}$

$S_{\beta,\alpha} = \delta_{\beta,\alpha} + it_{\beta,\alpha}$

$t_{\beta,\alpha} = \sqrt{1 - \eta^2} e^{i(\alpha+\beta)}$

$D^0 \bar{D}^0 \rightarrow K^+ K^-$ scattering amplitude

\[ T_{\bar{D}^0 D^0 \rightarrow KK}(s) = \frac{s^\alpha}{s_{th \bar{D}D}^\alpha} \frac{2 \kappa_2}{\sqrt{s_{th \bar{D}D}}} \left( \frac{s_{th \bar{D}D}}{s + s_{QCD}} \right)^{\xi + \alpha} \left[ \frac{c + bk_1^2 - ik_1}{c + bk_1^2 + ik_1} \right] \left( \frac{1}{a + \kappa_2} \right)^{\frac{1}{2}}, \quad s < s_{th \bar{D}D} \]

\[ = -i \frac{2 \kappa_2}{\sqrt{s_{th \bar{D}D}}} \left( \frac{s_{th \bar{D}D}}{s + s_{QCD}} \right)^{\xi} \left( \frac{m_0}{s - m_0} \right)^{\beta} \left[ \frac{c + bk_1^2 - ik_1}{c + bk_1^2 + ik_1} \right] \left( \frac{1}{a - ik_2} \right)^{\frac{1}{2}}, \quad s \geq s_{th \bar{D}D} \]

- Parameters fix by data!
- Zero at threshold
- Discontinuity at threshold
hadronic loop

\[ A = i C \ m_a^2 \int \frac{d^4 \ell}{(2\pi)^4} \ \frac{T_{\bar{D}^0 D^0 \rightarrow K K} (s_{23}) \ [-2 \ p'_3 \ \cdot \ (p'_2 - p_1)]}{\Delta_{D^*} \ \Delta_{D^0} \ \Delta_{\bar{D}^0} \ \Delta_a}, \]

\[ \text{amplitude} \]

\[ \text{Re} \]

\[ \text{Im} \]

\[ \text{Mod} \]

\[ m(KK) \ \text{GeV} \]

\[ 1 \ 1.5 \ 2 \ 2.5 \ 3 \ 3.5 \ 4 \ 4.5 \]

\[ 0 \ 0.05 \ 0.1 \ 0.15 \]

\[ -0.1 \ -0.05 \ 0 \]

zero in between two bumps

rescattering \[ D^0 \bar{D}^0 \rightarrow K^+ K^- \]

play a major role
hadronic loop

\[ A = iC \, m_a^2 \int \frac{d^4 \ell}{(2\pi)^4} \frac{T_{D^0D^0 \rightarrow KK}(s_{23}) \left[-2 \, p_3' \cdot (p_2' - p_1)\right]}{\Delta_{D^+} \Delta_{D^0} \Delta_{\bar{D}_0} \Delta_a}, \]

\[ m(KK) \text{ GeV} \]

phase

\[ \text{can explain change CPV signal in DP!!!} \]

\[ B^+ \]

\[ D^*^0 \]

\[ D^0 \]

\[ \bar{D}_0 \]

\[ K^+ \]

\[ \bar{K}^+ \]

\[ K^- \]

change signal in the same region as Acp data

charm rescattering

LHCb Implications 2018

patricia.magalhaes@tum.de
remarks on $B^+ \rightarrow K^- K^+ K^+$ charm rescattering

- Triangle hadronic loop with FSI

- amplitude: two narrow peaks in between a zero (threshold)
  - superposition of triangles

- phase: change sign in a region close where data shows a CP asymmetry change in sign!

- FSI mechanism to produce CP asymmetry at high mass

- interference between: ≠ triangles & NR sources & resonances
  - can shift the position of the CP asymmetry sign change

  → should be tested in data ANA!
We considered the charm penguins contributions as represented in the diagram of Fig. 2. However, it is very hard to precisely identify which are the charm mass propagating inside the loop and how does hadronization affect this picture. To guide our calculation, one follows the structure (recipe) proposed by Mannel et al. to describe the center region of the Dalitz plot for $B_c^+ \to K^- K^+ \pi^+$. The authors propose a functional form of this form factor to be:

$$A_p(s) = T(s) M_{B_s}^2 (f(s) + s/M_{B_s}^2)$$

where $f(s)$ is the vector form factor, which can assume the single-pole parametrization:

$$f(s) = \frac{1}{s/M_{B_s}^2}$$

for $M_{B_s}$ the mass of a vector meson $B^*_s$. One identifies the kernel $T$ as the charm bubble loop contribution. This amplitude was also calculated by Gerard and Hu (1991) and gave a simple amplitude, with a real and imaginary part given by:

$$\text{Re} \, \hat{s}(x) = \frac{1}{6} <\frac{5}{3} + 4x^2>$$

$$\text{Im} \, \hat{s}(x) = \pi \frac{6}{x}$$

for $x = q^2/4m_{B_s}^2$. This is exactly the bubble loop function we know very well, but considering a double charm propagation. The real and imaginary distribution are shown in the Figure below for the case of $m_{B_s} = 1.864$ which is the $D_0$ mass: $\text{Re} \, \hat{s}(x) = \frac{1}{6} <\frac{5}{3} + 4x^2>$ and $\text{Im} \, \hat{s}(x) = \pi \frac{6}{x}$. This is exactly the bubble loop function we know very well, but considering a double charm propagation. The real and imaginary distribution are shown in the Figure below for the case of $m_{B_s} = 1.864$ which is the $D_0$ mass.
Charm rescattering

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

- very suppressed direct production (annihilation)
- charm rescattering can be the dominant mechanism

![Diagram of charm rescattering](image)

**Phys. Rev. D94 (2016) no. 9, 091102**
Charm rescattering $B^+_c \rightarrow K^- K^+ \pi^+$

- toy Monte Carlo generator

Toy MC Dalitz plot $B^+_c \rightarrow K^+ K^- \pi^+$

20% of $K\pi$

change side bands but not the minimum position (thresholds)

leave a signature in the middle of the Dalitz plot
Charm rescattering $B_c^+ \rightarrow K^- K^+ \pi^+$

**Amplitudes projections**

- $\pi^+(p_1)$
- $K^+(p_2)$
- $K^-(p_3)$

→ *minima in different positions (≠ thresholds)*

→ *≠ mass parameters inside triangle and rescattering amplitudes are relevant*
**final remarks**

Triangle hadronic loop with charm FSI play an important role!

- $B^\pm \rightarrow K^+ K^- K^+$
  - mechanism to produce CP asymmetry at high mass

- $B_c^+ \rightarrow K^- K^+ \pi^+$
  - main mechanism to produce this final state

- If direct production (annihilation) $\rightarrow$ expect resonances in $KK$ and $K\pi\pi$ channels
  - not observed

- real data: interference between $\neq$ triangles & NR sources & resonances
  - cannot change the signature of a minima between the bumps and phases!
  - LHCb run 2 to confirm
FSI are important and play a major role in hadronic 3-body decays!

→ superposition of resonant and non-resonant at low and high energy

- different weak vertices topologies for same FS → how to add them?
  - need to merge the short and long distance descriptions!

- to improve ANA and learn from data we need:
  - good analytic and unitary 2-body coupled-channels up to high energy;
  - B-decays must include diff allowed dynamics at high-energy
    → charm rescattering!!

Thank you very much!
Backup slides
FSI in three-body decay:


PC Magalhães and I Bediaga  arXiv:1512.09284;


Falk et al. Phys. Rev. D 57,4290(1998);  
Figure 28: Dalitz plot of $B^\pm \to K^\pm \pi^+ \pi^+$ (top) and $B^\pm \to K^\pm K^+ K^+$ (bottom).

Figure 29: Dalitz plot of $B^\pm \to \pi^\pm \pi^+ \pi^+$ (top) and $B^\pm \to \pi^\pm K^+ K^+$ (bottom).