Dalitz plot analyses of $B^0(s) \rightarrow K_S h^+ h'^-$ decays in $LHCb$ ($h^{(*)} = K / \pi$)

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On behalf of the $LHCb$ collaboration
Outline

- General introduction

- Update of $B^0_{(s)} \rightarrow K_S h^+ h^- \text{ branching fractions}$ [JHEP 11 (2017) 027]

- Amplitude analysis of $B^0 \rightarrow K_S \pi^+ \pi^- \text{ decays}$ and first observation of CP asymmetry in $B^0 \rightarrow K^*(892)^+ \pi^- [PRL. 120, 261801 (2018)]$

- Conclusions, status and plans for Dalitz plot analyses of other $B^0_{(s)} \rightarrow K^0 h^+ h^- \text{ decay modes}$
General introduction
In LHCb

- Large $b\bar{b}$ production cross section
- Simultaneous analysis of $B^0_s$ and $B^0_d$ decays to $K_S h^+ h^-' (h^' = K / \pi)$
- Transitions mediated by $b \to u$ (tree) and/or $b \to d,s$ (penguin) diagrams

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**Motivations (I)**

- Comparable amplitudes $\to$ interference that may result in large CP-violation effects
- In particular, these modes give access to the CKM angles $\beta$ ($K_S \pi^+ \pi^-$, $K_S K^+ K^-$), $\beta_s$ ($B^0_s$ decays), and $\gamma$ (e.g., see talks from E. Bertholet and B. Bhattacharya)
Motivations (II)

- New physics contributions may be present in loops and could significantly alter measured observables

Comparison of measurements with standard model (SM) predictions may indicate new physics (NP) contributions and in any case constrain the parameter space of NP models

- Challenge: small theoretical & experimental uncertainties for powerful comparison

- Dalitz-plot analyses allow to:
  - disentangle between intermediate (non) resonant contributions
  - measure their specific observables
  - measure phases between these contributions with no trigonometric ambiguities

Access to many observables!
General strategy

First, measure branching fractions to prepare, and provide input for, the Dalitz-plot analyses of all $B^0_{(s)} \rightarrow K_S h^+h'^-$ modes

- Time-integrated Dalitz-plot analyses, with no flavour tagging

- Full time-dependent Dalitz-plot analyses, giving access to CKM phases

Proceed in steps of increasing complexity, as allowed by the available dataset.

Larger data sample $\rightarrow$ more complete model giving access to more observables
\textbf{\(K_S\) reconstruction}

- \(K_S\) mesons are reconstructed via their decay to \(\pi^+\pi^-\), either two “Long” or two “Downstream” \(\pi\) tracks (2 \(K_S\) “categories”)

![Diagram of particle detector and track classification]
Updated branching fraction measurements of $B^0_{(s)} \to K_S h^+ h'^-$

(with 3 fb$^{-1}$)

[JHEP 11 (2017) 027]
Introduction of the analysis

$B_{d,s} \to K_S h^+ h^-$, with $h^{(*)} = K / \pi \to 8$ decays (6, considering $K_S K^{\pm} \pi^{\mp}$)

<table>
<thead>
<tr>
<th>$B_d$ → $K_S \pi^+ \pi^-$</th>
<th>$B_d$ → $K_S K^+ \pi^-$</th>
<th>$B_d$ → $K_S K^- \pi^+$</th>
<th>$B_d$ → $K_S K^+ K^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s$ → $K_S \pi^+ \pi^-$</td>
<td>$B_s$ → $K_S K^+ \pi^-$</td>
<td>$B_s$ → $K_S K^- \pi^+$</td>
<td>$B_s$ → $K_S K^+ K^-$</td>
</tr>
</tbody>
</table>

(in previous LHCb analysis (1fb$^{-1}$))

- Favorable
- Observed

Goals of the analysis using 3fb$^{-1}$:
- Update measurement of BFs
- Search for $B_s \to K_S K^+ K^-$

Dataset divided into:
- 4 final states
- 2 $K_S$ reconstruction categories
- 3 data-taking periods

→ 24 invariant-mass distributions
Analysis strategy

- Simultaneous fit of the 24 invariant mass spectra

### Diagram

- Shapes taken from Monte-Carlo, except for combinatorial background
- $B_d$ and $B_s$ masses and widths from fit to data
- Gaussian constraints on yields of misidentified signal and partially reconstructed background
- Fast Monte-Carlo developed for partially reconstructed background modelling
**Results**

$B^0 \rightarrow K^0_S \pi^+ \pi^-$

Candidates / (16.25 MeV/c$^2$)$^{-1}$

LHCb Downstream

$B^0 \rightarrow K^0_S K^+ K^-$

Candidates / (16.25 MeV/c$^2$)$^{-1}$

LHCb Downstream

$B^0_{(s)} \rightarrow K^0_S K^\pm \pi^\mp$

Candidates / (16.25 MeV/c$^2$)$^{-1}$

LHCb Downstream

Five BFs are measured relative to that of $B^0 \rightarrow K_S \pi^+ \pi^-$

All are compatible with previous results

Significance: 2.5$\sigma$

$B(B^0 \rightarrow K^0_S K^+ K^-) / B(B^0 \rightarrow K^0_S \pi^+ \pi^-) \in [0.008 - 0.051]$ at 90% confidence level

Eli Ben-Haim
CKM workshop, September 18th 2018
Amplitude analysis of $B^0 \to K_S \pi^+ \pi^-$ decays and first observation of CP asymmetry in $B^0 \to K^*(892)^+ \pi^-$ (using 3 fb$^{-1}$)

[PRL. 120, 261801 (2018)]
Intermediate resonances in $P \rightarrow 1\ 2\ 3$ appear as structures in the Dalitz plot, characterized by their mass, width and spin.

- Parameterization of amplitudes (isobar model):
  \[ A = \sum c_i F_i (m_{13}^2, m_{23}^2) \quad \text{B decays} \]
  \[ \bar{A} = \sum \bar{c}_i F_i (m_{23}^2, m_{13}^2) \quad \text{\bar{B} decays} \]

  Complex decay dynamics ($i = \text{intermediate state}$)
  Coefficients (e.g. Breit-Wigner)
  CP-violating CP-conserving

Directly extracted parameters: isobar coefficients $c_i$
Many observables ($A_{CP}, BF$s, …) are derived from these

\[ |c_i| \neq |\bar{c}_i| \quad \Rightarrow \text{CP violation in decay} \]

Overlapping resonant contributions
\[ \Rightarrow \text{interference} \]
\[ \Rightarrow \text{access to relative phases with no ambiguity such as} \]
\[ \sin2\beta_{\text{eff}} = \sin(180^\circ - 2\beta_{\text{eff}}) \]
(time dependent analysis)
Introduction of the analysis

- This mode contains intermediate states such as $\bar{B}^0 \rightarrow K^*\pi^+$, which could shed light on the “K\pi puzzle” (difference between $A_{CP}$ in $\bar{B}^0 \rightarrow K^-\pi^+$ and $B^- \rightarrow K^-\pi^0$)


- Current statistics do not allow to use flavour tagging (power $\sim$ 5% in LHCb)
  → analysis is time-integrated → involves incoherent sum of $B^0$ and $\bar{B}^0$ amplitudes

- CKM phases are thus not accessible, but direct CP asymmetries between flavour-specific (FS) states such as $\bar{B}^0 \rightarrow K^*\pi^+$ and $B^0 \rightarrow K^*\pi^-$ are measured

![Flavour-specific states](image)
Signal and background

- Signal region for the Dalitz-plot fit: ±3σ around nominal mass
- ~3.2K signal events
- Event selection allows to obtain purity of 85-95%
- Backgrounds due to combinatorial (3-13%) and cross-feed (2-3%)

Candidates / (16.25 MeV/c^2)

5000
5200 5400 5600 5800
m(K_S^0 \pi^+ \pi^-) [MeV/c^2]

LHCb

- B^0 \rightarrow K_S^0 \pi^+ \pi^-
- B_s^0 \rightarrow K_S^0 \pi^+ \pi^-
- Combinatorial
- B^0 \rightarrow K_S^0 K_S^{\pm} \pi^\mp
- B_s^0 \rightarrow K_S^0 K_S^{\pm} \pi^\mp
- B_{(s)} \rightarrow K_S^0 \pi^+ \pi^- (X)

[PRl. 120, 261801 (2018)]

Eli Ben-Haim

CKM workshop, September 18th 2018
Signal model and observables

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Parameters</th>
<th>Lineshape</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^-$</td>
<td>$m_0 = 891.66 \pm 0.26$</td>
<td>RBW</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 50.8 \pm 0.9$</td>
<td></td>
</tr>
<tr>
<td>$(K\pi)^-\pi$</td>
<td>$\Re(e(\lambda_0)) = 0.204 \pm 0.103$</td>
<td>EFKLMM</td>
</tr>
<tr>
<td></td>
<td>$\Im(e(\lambda_0)) = 0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Re(e(\lambda_1)) = 1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Im(e(\lambda_1)) = 0$</td>
<td></td>
</tr>
<tr>
<td>$K^*_2(1430)^-$</td>
<td>$m_0 = 1425.6 \pm 1.5$</td>
<td>RBW</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 98.5 \pm 2.7$</td>
<td></td>
</tr>
<tr>
<td>$K^*(1680)^-$</td>
<td>$m_0 = 1717 \pm 27$</td>
<td>Flatté</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 332 \pm 110$</td>
<td></td>
</tr>
<tr>
<td>$f_0(500)$</td>
<td>$m_0 = 513 \pm 32$</td>
<td>RBW (Bugg model)</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 335 \pm 67$</td>
<td></td>
</tr>
<tr>
<td>$\rho(770)^0$</td>
<td>$m_0 = 775.26 \pm 0.25$</td>
<td>GS</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 149.8 \pm 0.8$</td>
<td></td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>$m_0 = 965 \pm 10$</td>
<td>Flatté</td>
</tr>
<tr>
<td></td>
<td>$g_\pi = 0.165 \pm 0.025$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$g_K = 0.695 \pm 0.119$ GeV</td>
<td></td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>$m_0 = 1505 \pm 6$</td>
<td>RBW</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 109 \pm 7$</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>$m_0 = 3414.75 \pm 0.31$</td>
<td>RBW</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 10.5 \pm 0.6$</td>
<td></td>
</tr>
</tbody>
</table>

Nonresonant (NR) Phase space

**EFKLLM:** $F_j(m) = F(m) \left( \frac{\lambda_0}{m^2} + \lambda_1 \right)$

Baseline model inspired by analysis from B-factories


- Evaluated by add/remove algorithm
- Critical role of the $(K\pi)$ S-wave $\rightarrow$ EFKLMM model

From the raw asymmetry:

$$A_{raw} = \frac{|\bar{c}_j|^2 - |c_j|^2}{|\bar{c}_j|^2 + |c_j|^2}$$

is derived the CP asymmetry:

$$A_{CP} = A_{raw} - A_{\Delta}$$

$$A_{\Delta} = A_P(B^0) + A_D(\pi)$$

(-0.35 ± 0.81)% (0 ± 0.25)%

[D$_s^+$,PRL 110 (2013) 221601, PLB 713 (2012) 186]

- Fit fractions (CP averaged):

$$F_i = \frac{\iint_{DP} |c_i F_i(s_+, s_-)|^2 ds_+ ds_-}{\iint_{DP} \left| \sum_j c_j F_j(s_+, s_-) \right|^2 ds_+ ds_-}$$


Eli Ben-Haim

CKM workshop, September 18th 2018
Results: fit fractions

\[ \mathcal{F}(K^*(892)^-\pi^+) = 9.43 \pm 0.40 \pm 0.33 \pm 0.34 \% \]
\[ \mathcal{F}((K\pi)_0^-\pi^+) = 32.7 \pm 1.4 \pm 1.5 \pm 1.1 \% \]
\[ \mathcal{F}(K^*_2(1430)^-\pi^+) = 2.45 \pm 0.10 \pm 0.08 \pm 0.14 \pm 0.12 \% \]
\[ \mathcal{F}(K^*(1680)^-\pi^+) = 7.34 \pm 0.30 \pm 0.31 \pm 0.06 \% \]
\[ \mathcal{F}(f_0(980)K^0_S) = 18.6 \pm 0.8 \pm 0.7 \pm 1.2 \% \]
\[ \mathcal{F}(\rho(770)^0K^0_S) = 3.8 \pm 1.1 \pm 0.7 \pm 0.4 \% \]
\[ \mathcal{F}(f_0(500)K^0_S) = 0.32 \pm 0.40 \pm 0.08 \pm 0.19 \pm 0.23 \% \]
\[ \mathcal{F}(f_0(1500)K^0_S) = 2.60 \pm 0.54 \pm 1.28 \pm 0.60 \% \]
\[ \mathcal{F}(\chi_{c0}K^0_S) = 2.23 \pm 0.40 \pm 0.32 \pm 0.22 \pm 0.13 \% \]
\[ \mathcal{F}(K^0_S\pi^+\pi^-)^{NR} = 24.3 \pm 1.3 \pm 3.7 \pm 4.5 \% \]

\[ \uparrow \quad \uparrow \quad \uparrow \quad \text{stat.} \quad \text{syst.} \quad \text{model} \]

The resonances $K^*(1680)$ and $f_0(1500)$ were not included in this mode by B-factories

On the other hand, we see no significant sign of $f_2(1270)$

Alternative LASS modelling for the S-wave has been examined and resulted in:

\[-2\Delta \ln \mathcal{L} = 85\]

No systematic uncertainty is assigned to the choice of the $K\pi$ S-wave model

Dominant model uncertainty is related to the $\pi\pi$ S-wave model

Results in agreement with the measurements from the B factories (for components that can be compared)
Results: CP asymmetries

![Graphs showing CP asymmetries](image)

First observation of CP violation in $B^0 \rightarrow K^*(892)\pi$ with $\sim 6\sigma$

Consistent with SM predictions* and previous world average:

$A(K^*(892)\pi) = -0.23 \pm 0.06$

* [JHEP09 (2008) 038; PRD78 034011 (2008), PRD91, 014011 (2015)]
Summary, status and prospects

- An updated measurement of the $B^0_{(s)} \rightarrow K_S h^+ h'^-$ BFs with 3 fb$^{-1}$ is available
  → Only mode that is not yet observed: $B_s \rightarrow K_S K^+ K^-$ (significance: 2.5 $\sigma$)

- **First amplitude analysis of** $B^0 \rightarrow K_S \pi^+ \pi^-$ decays in a hadron collider
  → First observation (6 $\sigma$) of direct CP violation in $B^0 \rightarrow K^*(892)\pi^-$

- Upcoming Dalitz-plot analyses
  - About to be published with Run-I (3 fb$^{-1}$):
    - $B_s \rightarrow K_S K^\pm \pi^\mp$ time-integrated, untagged
  - Analyses under way using Run-II data
    - $B^0 \rightarrow K_S K^+ K^-$ time-dependent (+ search for $B_S \rightarrow K_S K^+ K^-$ decays)
    - $B^0 \rightarrow K_S \pi^+ \pi^-$ time-dependent
    - $B_s \rightarrow K_S \pi^+ \pi^-$ time-integrated, untagged

Run-II dataset (and beyond) will provide unprecedented insights for these modes
Measured branching fractions

\[ \frac{\mathcal{B} (B^0 \rightarrow K^0_{s} K^{\pm}\pi^{\mp})}{\mathcal{B} (B^0 \rightarrow K^0_{s} \pi^{+}\pi^{-})} = 0.128 \pm 0.017 \text{ (stat.)} \pm 0.009 \text{ (syst.)}, \]

\[ \frac{\mathcal{B} (B^0 \rightarrow K^0_{s} K^+ K^-)}{\mathcal{B} (B^0 \rightarrow K^0_{s} \pi^{+}\pi^{-})} = 0.385 \pm 0.031 \text{ (stat.)} \pm 0.023 \text{ (syst.)}, \]

\[ \frac{\mathcal{B} (B^0_s \rightarrow K^0_{s} \pi^{+}\pi^{-})}{\mathcal{B} (B^0 \rightarrow K^0_{s} \pi^{+}\pi^{-})} = 0.29 \pm 0.06 \text{ (stat.)} \pm 0.03 \text{ (syst.)} \pm 0.02 \left( \frac{f_s}{f_d} \right), \]

\[ \frac{\mathcal{B} (B^0_s \rightarrow K^0_{s} K^{\pm}\pi^{\mp})}{\mathcal{B} (B^0 \rightarrow K^0_{s} \pi^{+}\pi^{-})} = 1.48 \pm 0.12 \text{ (stat.)} \pm 0.08 \text{ (syst.)} \pm 0.12 \left( \frac{f_s}{f_d} \right), \]

\[ \frac{\mathcal{B} (B^0_s \rightarrow K^0_{s} K^+ K^-)}{\mathcal{B} (B^0 \rightarrow K^0_{s} \pi^{+}\pi^{-})} \in [0.004; 0.068] \text{ at } 90\% \text{ CL}. \]

Using world average for $B^0 \rightarrow K^0_{s} \pi^{+}\pi^-$

\[ \mathcal{B} (B^0 \rightarrow K^0 K^{\pm}\pi^{\mp}) = (6.4 \pm 0.9 \pm 0.4 \pm 0.3) \times 10^{-6}, \]

\[ \mathcal{B} (B^0 \rightarrow K^0 K^+ K^-) = (19.1 \pm 1.5 \pm 1.1 \pm 0.8) \times 10^{-6}, \]

\[ \mathcal{B} (B^0_s \rightarrow K^0 \pi^{+}\pi^{-}) = (14.3 \pm 2.8 \pm 1.8 \pm 0.6) \times 10^{-6}, \]

\[ \mathcal{B} (B^0_s \rightarrow K^0 K^{\pm}\pi^{\mp}) = (73.6 \pm 5.7 \pm 6.9 \pm 3.0) \times 10^{-6}, \]

\[ \mathcal{B} (B^0_s \rightarrow K^0 K^+ K^-) \in [0.2; 3.4] \times 10^{-6} \text{ at } 90\% \text{ CL}, \]
# BABAR signal model

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Parameters</th>
<th>Line shape</th>
<th>Ref. for Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(980)$</td>
<td>$m_0 = 965 \pm 10$</td>
<td>Flatté</td>
<td>[31]</td>
</tr>
<tr>
<td></td>
<td>$g_\pi = 165 \pm 18$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$g_\rho = 695 \pm 93$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho^0(770)$</td>
<td>$m_0 = 775.5 \pm 0.4$</td>
<td>GS</td>
<td>[32]</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 146.4 \pm 1.0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$r = 5.3^{+0.9}_{-0.7} (\text{GeV}/c)^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^{*+}(892)$</td>
<td>$m_0 = 891.66 \pm 0.26$</td>
<td>RBW</td>
<td>[32]</td>
</tr>
<tr>
<td>$K^{*-}(892)$</td>
<td>$\Gamma_0 = 50.8 \pm 0.9$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$r = 3.6 \pm 0.6 (\text{GeV}/c)^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(K\pi)^{0+}$</td>
<td>$m_0 = 1415 \pm 3$</td>
<td>LASS</td>
<td>[27]</td>
</tr>
<tr>
<td>$(K\pi)^{0-}$</td>
<td>$\Gamma_0 = 300 \pm 6$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$m_{K\pi}^{\text{cut off}} = 1800$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$a = 2.07 \pm 0.10 (\text{GeV}/c)^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$r = 3.32 \pm 0.34 (\text{GeV}/c)^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>$m_0 = 1275.4 \pm 1.1$</td>
<td>RBW</td>
<td>[32]</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 185.2^{+3.1}_{-2.5}$</td>
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<tr>
<td></td>
<td>$r = 3.0 (\text{GeV}/c)^{-1}$</td>
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</tr>
<tr>
<td>$f_x(1300)$</td>
<td>$m_0 = 1471 \pm 7$</td>
<td>RBW</td>
<td>[27,28]</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 97 \pm 15$</td>
<td></td>
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</tr>
<tr>
<td>NR decays</td>
<td>$m_0 = 3414.75 \pm 0.35$</td>
<td>flat phase space</td>
<td>[32]</td>
</tr>
<tr>
<td>$\chi_{\epsilon\omega}$</td>
<td>$\Gamma_0 = 10.4 \pm 0.7$</td>
<td>RBW</td>
<td></td>
</tr>
</tbody>
</table>
$m^2(\pi\pi)$

$LHCb$

$[PRL. 120, 261801 (2018)]$
Analysis strategy

- Define a signal window around $B^0$ signal peak (3 standard deviations of the resolution model) in the invariant mass spectrum of $K_S\pi\pi$ candidates.
- Determine from the mass fit the signal fraction and build the distribution of combinatorial backgrounds in the DP of $B^0 \rightarrow K_S\pi\pi$, from the RHSB.
- Determine, in addition, from the invariant mass distribution fits, the empirical data-driven $B_s \rightarrow K_SK\pi$ DP distribution to model the cross-feed background component in the $B^0 \rightarrow KS\pi\pi$ DP.
- Obtain the histogram of the whole selection efficiency variation across the DP, evaluated from simulated events.
- Fit simultaneously the six category data samples and educate the final model by adding relevant new contributions to the baseline and decide on the basis of a tentatively objective algorithm to keep the resonance or not.
Systematic uncertainties

- Quantified effects from:
  - biases related to the Dalitz fit to the data,
  - the fraction of signal/background extracted from the mass fit,
  - uncertainties on the selection and tracking efficiency across the SDP,
    ➔ dominant (MC statistics)
  - uncertainty on the combinatorial background across the SDP.

- Signal model uncertainties
  - Fixed parameters of the line shapes
  - Addition/removal of marginal components to the nominal model
  - alternative models for the $\pi\pi$ S-wave
    ➔ dominant