Studies of charmless B decays at LHCb

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Why charmless B decays?

- Sensitive to suppressed CKM matrix elements and their phases
- Good probe for New Physics (NP) searches. Test the Standard Model (SM) and look for deviations in CKM structure:
  - $b \rightarrow u$ tree processes.
  - $b \rightarrow s, d$ loop transitions: NP may appear in the loop
- Direct CP violation in time-integrated measurements: arises from the interference between contributing amplitudes

$$A_{CP} = \frac{\Gamma_{\bar{B} \rightarrow f} - \Gamma_{B \rightarrow f}}{\Gamma_{\bar{B} \rightarrow f} + \Gamma_{B \rightarrow f}}$$
The LHCb detector
$\Lambda^0_b, \Xi^0_b \rightarrow \overline{K}^0_s ph^-$

(h = K, \pi)

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Motivation

• no b-baryon charmless three-body decays had yet been observed
• possibility of direct CP violation searches (no mixing)

Objectives

• search for $\Lambda^0_b$, $\Xi^0_b \rightarrow K^0_s \pi^- \pi^-$ decays
• measurement of branching fractions (or set upper limits)
• normalization channel $B^0 \rightarrow K^0_s \pi^+ \pi^-$
• CP violation measurement for the observed $\Lambda^0_b \rightarrow K^0_s p \pi^-$ decay
$\Lambda^0_b, \Xi^0_b \rightarrow K^0_s p \pi^-$

$$\mathcal{B}(\Lambda_b^0 \rightarrow \bar{K}^0 p \pi^-) = (1.26 \pm 0.19 \pm 0.09 \pm 0.34 \pm 0.05) \times 10^{-5}$$

First observation (8.6 $\sigma$)!

$$f_{\Xi_b^0} / f_d \times \mathcal{B}(\Xi_b^0 \rightarrow \bar{K}^0 p \pi^-) < 1.6(1.8) \times 10^{-6}$$

at 90% (95%) CL

$\Lambda^0_b, \Xi^0_b \rightarrow K^0_s p K^-$

$$\mathcal{B}(\Lambda_b^0 \rightarrow K^0 p K^-) < 3.5(4.0) \times 10^{-6}$$

$$f_{\Xi_b^0} / f_d \times \mathcal{B}(\Xi_b^0 \rightarrow \bar{K}^0 p K^-) < 1.1(1.2) \times 10^{-6}$$

at 90% (95%) CL

CP Asymmetry

$$A_{CP}(\Lambda_b^0 \rightarrow K^0 p \pi^-) = 0.22 \pm 0.13(stat) \pm 0.04(syst)$$

- phase space integrated measurement

structure at low $p\pi^-$ invariant mass
\[ B^0_{(s)} \rightarrow h^+h'^- \text{ lifetimes} \]

\[ (h = K, \pi) \]
Objectives

• $B^0_s \rightarrow K^+K^-$ decay: CP even final state (decay consists almost entirely of the light mass eigenstate).

• Small CP violation predicted in SM

\[ A_{\Delta \Gamma}(B_s^0 \rightarrow K^+K^-) = \frac{-2Re(\lambda)}{1 + |\lambda|^2} = -0.97^{+0.014}_{-0.009} \]

• Measure the $B^0_s \rightarrow K^+K^-$ effective lifetime: useful to constrain the $B_s$ mixing phase and the CP violation parameter $A_{\Delta \Gamma_s}$

\[ \tau_{K^+K^-} \approx \Gamma_s^{-1} \left(1 + \frac{A_{\Delta \Gamma_s} \Delta \Gamma_s}{2 \Gamma_s}\right) \]

where \( \Gamma_s = \frac{\Gamma_H + \Gamma_L}{2} \) and \( \Delta \Gamma_s = 2 |\Gamma_{12}| \cos \Phi_M / \Gamma \)

• Measure the $B^0 \rightarrow K^+\pi^-$ and $B^0_s \rightarrow K^-\pi^+$ lifetimes: contribute to the world average of $\tau(B^0)$ and $\tau(B^0_s)$.

• Analysis performed with 1 fb$^{-1}$
- Data driven method to determine the decay time acceptance function
- Mass and lifetime assumed uncorrelated

\[ \tau_{B_s^0 \rightarrow K^+ K^-} = 1.407 \pm 0.016 \, (\text{stat}) \pm 0.007 \, (\text{syst}) \, \text{ps} \]

\[ \tau_{B^0 \rightarrow K^+ \pi^-} = 1.524 \pm 0.011 \, (\text{stat}) \pm 0.004 \, (\text{syst}) \, \text{ps} \]

\[ \tau_{B_s^0 \rightarrow \pi^+ K^-} = 1.56 \pm 0.06 \, (\text{stat}) \pm 0.01 \, (\text{syst}) \, \text{ps} \]

Constraints on \( \phi_s \) and \( \Gamma_s \)
$B^\pm \rightarrow \phi h^\pm$

Two possible sources of CP violation:
- interference between intermediate states (large strong phase differences)
- KK $\leftrightarrow \pi\pi$ rescattering: introduction of additional strong phases which could increase CP asymmetry

Local asymmetries observed at low $m_{KK}^2$ (just above the $\phi$ resonance).
No clear association with any resonance

$$m_{K^+K^-}^{high} < 15 GeV^2/c^4 \quad \text{and} \quad 1.2 < m_{K^+K^-}^{low} < 2.0 GeV^2/c^4$$

$$A_{CP}^{reg}(B^\pm \rightarrow K^\pm K^+K^-) = -0.226\pm0.020(stat)\pm0.004(syst)\pm0.007(J\psi K^\pm)$$

Similar results in other $B^\pm \rightarrow h^\pm h^+h^-$ modes
• Objective measurement of the CP asymmetry,
• Theoretical prediction from the SM: 1-2%


\[ \mathcal{A}_{CP}(B^\pm \rightarrow \phi K^\pm) = 0.022 \pm 0.021(\text{stat}) \pm 0.009(\text{syst}) \]

\[ B^\pm \rightarrow \phi K^\pm \]

\[ \mathcal{L} = 1.0 \text{ fb}^{-1} \text{ at 7 TeV} \]
• Two-dimensional fit of the B mass and \( \phi \) mass spectra
• Simultaneous fit of the \( B^+ \) and \( B^- \) candidates
• Control channel \( B^\pm \rightarrow J/\psi K^\pm \), to measure the production and detection asymmetry

• Objective: search for the decay
• Rare decay: dominated by $b \rightarrow d$ loop penguin transition and OZI suppressed
• SM prediction: $5 \times 10^{-9} - 7 \times 10^{-8}$ (arXiv:0804.1231v1, PRD 80(2009)014027)
• Useful to study the $\omega$-$\phi$ mixing

$B^\pm \rightarrow \phi \pi^\pm$

Two dimensional fit of the $B$ mass an the $\phi$ mass
Simultaneous fit of $B^\pm \rightarrow \phi K^\pm$ and $B^\pm \rightarrow \phi \pi^\pm$

$B^\pm \rightarrow \phi K^\pm$ sample used to improve sensitivity on $B^\pm \rightarrow \phi \pi^\pm$

$N(\phi \pi^\pm) = 19 \pm 19$

$\mathcal{B}(B^\pm \rightarrow \phi \pi^\pm) < 1.5 \times 10^{-7}$ at 90% CL

Previous upper limit: $\mathcal{B} < 2.4 \times 10^{-7}$ at 90% CL

(BABAR, PRD 74 (2006) 011102)

$B^0_s \rightarrow \phi K^{*0}$
- Objective: search for the $B^0_s \rightarrow \phi K^{*0}$ decay. New physics may appear in the loop
- Theoretical prediction:
  - QCD factorization: $(0.4^{+0.5}_{-0.3}) \times 10^{-6}$ (Nucl.Phys.B774(2007)64)
  - perturbative QCD: $(0.65^{+0.33}_{-0.23}) \times 10^{-6}$ (Phys.Rev.D76(2007)074018)
- Essential to understand QCD effects in channels related by $d \leftrightarrow s$ exchange symmetry
- Control channel $B^0 \rightarrow \phi K^{*0}$ (same final state, polarization fraction expected to be similar)

\[ N(B^0_s \rightarrow \phi K^{*0}) = 30 \pm 6 \]

\[ \mathcal{B}(B^0_s \rightarrow \phi K^{*0}) = (1.10 \pm 0.24(stat) \pm 0.14(syst) \pm 0.08(f_d/f_s)) \times 10^{-6} \]

On the high side of the theoretically expected range
• Objective: measurement of longitudinal polarization in \(B^0_s \rightarrow fK^{*0}\) decays

• Theoretical prediction: \(f_0 = 0.712^{+0.042}_{-0.048}\) (Phys.Rev.D76(2007)074018)

• Lower \(f_0\) compared to prediction measured in \(b \rightarrow s\) transition.

• \(f_0 = 0.80^{+0.12}_{-0.13}\) measured in \(B^0 \rightarrow K^{*0}K^{*0}\)

Acceptance corrected angular distribution:

\[
f_0 = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} = 0.51 \pm 0.15(stat) \pm 0.07(syst)
\]

\[
f_{\parallel} = \frac{|A_\parallel|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} = 0.21 \pm 0.11(stat) \pm 0.02(syst)
\]

\[
cos\delta_\parallel = -0.18 \pm 0.52(stat) \pm 0.29(syst) \text{ with } \delta_\parallel \text{ phase difference between } A_0, \text{ and } A_\parallel
\]
$B^0 \rightarrow \phi K^{*0}$
• FCNC process (b→s\bar{ss})
• gluonic penguin diagram: new physics may appear in the loop
• \( f_L \) predicted to be \(~0.8\). From measurement \( f_L \sim 0.5 \)
  (BaBar PRD 78(2008),092008; Belle PRD88(2013)072004)

What did we measure?
• direct CP asymmetry
• time-integrated polarization amplitude

- Analysis performed with 1 fb\(^{-1}\)
- 1655±42 \( B^0 \) signal candidates

Direct CP asymmetry:

\[ A_{CP}(B^0 \rightarrow \phi K^{*0}) = (1.5 \pm 3.2 \pm 0.5)\% \]

• reference channel \( B^0 \rightarrow J/\psi K^{*0} \)
• No CP violation observed

Best measurement!
Angular analysis:

Components included:
- P-wave contributions: $f_L, f_\perp, f_\parallel (f_\parallel = 1-f_L-f_\perp)$ + strong phases $\delta_\perp, \delta_\parallel$
- Two s-wave amplitudes taken in account ($A_s^{K\pi}, A_s^{KK}$) + two phases ($\delta_s^{K\pi}, \delta_s^{KK}$) from $B^0 \rightarrow \phi K\pi$ and $B^0 \rightarrow K^*KK$

\[
\begin{align*}
    f_L &= 0.497 \pm 0.019 \pm 0.015 \\
    f_\perp &= 0.221 \pm 0.016 \pm 0.013 \\
    f_S(K\pi) &= 0.143 \pm 0.013 \pm 0.012 \\
    f_S(KK) &= 0.122 \pm 0.013 \pm 0.008
\end{align*}
\]

- No dominant longitudinal component
- Results in agreement with BaBar (PRD 78(2008)092008) and Belle (PRD 88(2013)072004) measurements
Conclusions

- Charmless b-flavoured hadron decays are a good probe to search for new physics
- Several new results from LHCb in the charmless sector
  - new observations and improvements on branching fractions ($\Lambda^0_b, \Xi^0_b \rightarrow K^0_s p h^-$, $B^\pm \rightarrow \phi \pi^\pm$, $B^0_s \rightarrow \phi K^{*0}$)
  - lifetime measurements ($B^0_{(s)} \rightarrow h^+ h^-$)
  - measurements and improvements of global and local asymmetries ($B^\pm \rightarrow \phi K^\pm$, $B^\pm \rightarrow h^+ h^- h^\pm$)
  - angular analyses

A lot of work still to do...

- Combined amplitude analysis to extract the CKM angles
- Larger data samples (~9fb$^{-1}$ expected by 2018)
- Plenty of charmless channels still to explore