

# ***CP* violation in the *B* system with the LHCb experiment \***

AURÉLIEN MARTENS, ON BEHALF LHCb COLLABORATION

LPNHE, Université Pierre et Marie Curie, Université Paris Diderot,  
CNRS/IN2P3, Paris, France.

During 2011, LHCb has collected an integrated luminosity of  $1.1 \text{ fb}^{-1}$ , giving rise to a large variety of measurements. Amongst these, measurements of *CP* violation in *B* decays play a central role. Three highlights are presented in this paper. An evidence for  $b \rightarrow u$  transitions in  $B^\pm \rightarrow DK^\pm$  is obtained, confirming recent BELLE results. A first evidence for direct *CP* violation in the  $B_s^0$  system is presented and *CP* violation is observed in the  $B^0$  system, using respectively  $B_s^0 \rightarrow K^-\pi^+$  and  $B^0 \rightarrow K^+\pi^-$  decays. An unambiguous world leading measurement of the mixing phase  $\phi_s$  of the  $B_s^0$  system is obtained by looking at  $b \rightarrow c\bar{c}s$  transitions.

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## **1. The LHCb detector**

The LHCb detector [1] is a single arm spectrometer designed to accurately measure decay products of *B* and *D* mesons for precision measurements at the LHC. In the following an overview of the variety of *CP* violation measurements in *B* decays provided by LHCb at the very beginning of 2012 is presented. Results not related to *CP* violation in the *B* decays can be found in other contributions [2, 3, 4]. The commissioning of the detector and the performance reached with the current data is summarized in [5]. Key ingredients for the analyses presented in the following are the ability to trigger on and to disentangle different modes owing to dedicated ring-imaging Cherenkov detectors. Some channels of interest additionally require good tagging capabilities and excellent proper time resolution, that are detailed elsewhere [6].

The data sample used for the analyses presented here ranges from  $36 \text{ pb}^{-1}$  to  $0.4 \text{ fb}^{-1}$ . Three different categories of analyses are distinguished with respect to the studied final states. Results from *B* decays to open charm

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are first detailed, followed by charmless  $B$  decays and finally  $B$  decays to charmonium.

## 2. $B$ decays to open charm

### 2.1. General strategy

$B$  decays to open charm final states allow a theoretically clean extraction of the Cabibbo-Kobayashi-Maskawa (CKM) angle  $\gamma = \phi_3$ , see for instance [7] for a recent review. At present this angle is constrained with a combined precision of  $10^\circ$  by direct measurements while the standard model prediction is accurate at few degrees [8, 9].

The strategy is to exploit the  $\gamma$ -sensitive interference between  $b \rightarrow u$  and  $b \rightarrow c$  transitions that occur in the  $B \rightarrow DX$  tree level decays<sup>1</sup>. Since there is no contribution from penguin diagrams, these measurements provide a standard model benchmark for further comparison with global CKM fits.

Two classes of such  $B$  decays can be distinguished depending on the need or not for a time dependent analysis. Self-tagged decays like  $B^\pm \rightarrow DK^\pm$  or  $B^0 \rightarrow DK^{*0}$ , where the flavour of the final state  $K^\pm$  or  $K^{*0}$  determines the flavour of the  $B$ , allow time independent extractions of  $\gamma$  while  $B_s^0 \rightarrow D_s^- K^+$  and  $B^0 \rightarrow D^- \pi^+$  require a time dependent analysis.

### 2.2. Evidence for $b \rightarrow u$ transitions in $B^\pm \rightarrow DK^\pm$ decays

One of the most promising channels is  $B^\pm \rightarrow DK^\pm$ , where the  $D$  can be reconstructed in many different decay modes, common to the  $D^0$  and the  $\bar{D}^0$ . As shown on Fig. 1, clear signals of  $147 \pm 15$  and  $48 \pm 11$  candidates are respectively obtained for the suppressed  $B^\pm \rightarrow (K^\mp \pi^\pm)_D \pi^\pm$  and  $B^\pm \rightarrow (K^\mp \pi^\pm)_D K^\pm$  modes with  $340 \text{ pb}^{-1}$ . These yields are simultaneously fitted together with the favoured modes to extract  $CP$ -violating observables [10]:

$$R_{ADS}^{B^\pm \rightarrow DK^\pm} = (1.66 \pm 0.39 \pm 0.24) \times 10^{-2} \quad (1a)$$

$$A_{ADS}^{B^\pm \rightarrow (K^\mp \pi^\pm)_D K^\pm} = -0.39 \pm 0.17 \pm 0.02 \quad (1b)$$

$$R_{ADS}^{B^\pm \rightarrow D\pi^\pm} = (4.13 \pm 0.41 \pm 0.40) \times 10^{-3} \quad (1c)$$

$$A_{ADS}^{B^\pm \rightarrow (K^\mp \pi^\pm)_D \pi^\pm} = 0.09 \pm 0.10 \pm 0.01, \quad (1d)$$

where  $R_{ADS}$  and  $A_{ADS}$  are respectively defined, in the case of  $B^\pm \rightarrow DK^\pm$ , as:

$$R_{ADS} = \frac{\mathcal{B}(B^- \rightarrow (K^\pm \pi^\mp)_D K^-) + \mathcal{B}(B^+ \rightarrow (K^\mp \pi^\pm)_D K^+)}{\mathcal{B}(B^- \rightarrow (K^\mp \pi^\pm)_D K^-) + \mathcal{B}(B^+ \rightarrow (K^\pm \pi^\mp)_D K^+)} \quad (2a)$$

<sup>1</sup>  $D$  represents either a  $D^0$  or a  $\bar{D}^0$  meson.

$$A_{ADS} = \frac{\mathcal{B}(B^- \rightarrow (K^\pm \pi^\mp)_D K^-) - \mathcal{B}(B^+ \rightarrow (K^\mp \pi^\pm)_D K^+)}{\mathcal{B}(B^- \rightarrow (K^\pm \pi^\mp)_D K^-) + \mathcal{B}(B^+ \rightarrow (K^\mp \pi^\pm)_D K^+)}. \quad (2b)$$

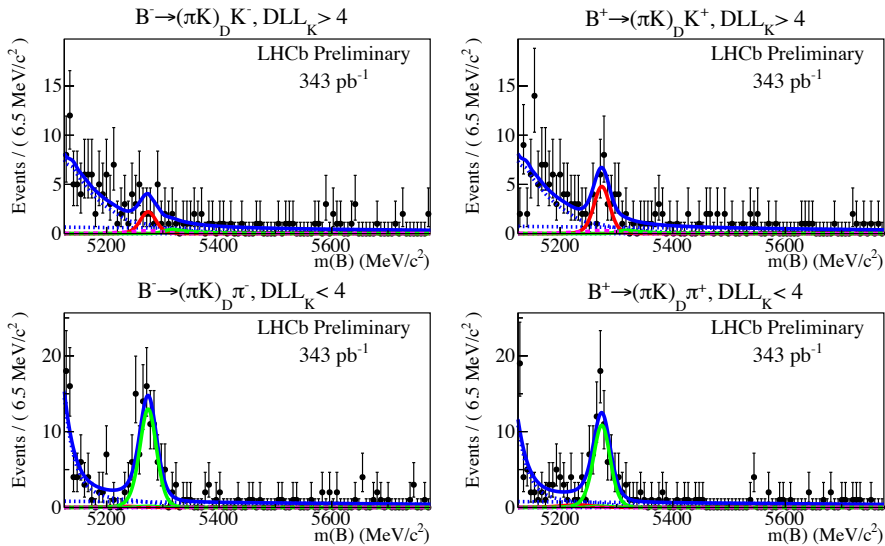


Fig. 1. Suppressed  $B^\pm \rightarrow (K^\mp \pi^\pm)_D K^\pm$  (top) and  $B^\pm \rightarrow (K^\mp \pi^\pm)_D \pi^\pm$  (bottom) candidates. The solid red (dark) curves correspond to  $B^\pm \rightarrow DK^\pm$  and the solid green (light) curve is  $B^\pm \rightarrow D\pi^\pm$ , see [10] for details.

This result is not only in good agreement but also compete with previous measurements performed at  $B$  factories, as summarized for instance in [11]. Including systematic uncertainties, a  $4\sigma$  evidence of a non vanishing  $R_{ADS}^{B^\pm \rightarrow DK^\pm}$  is obtained. Systematic uncertainties are dominated by the knowledge of particle identification efficiencies and the modeling of the low mass region, where typically partially reconstructed  $B \rightarrow DKX$  backgrounds lie. These uncertainties partially cancel in the extraction of the direct  $CP$  asymmetry  $A_{ADS}^{B^\pm \rightarrow (K^\mp \pi^\pm)_D K^\pm}$ . In addition to the previous systematic uncertainties, kaon interaction and charmless background asymmetries contribute at the sub-percent level in the total uncertainty. Further improvements are thus expected with statistically larger data samples, allowing a first observation of  $b \rightarrow u$  transitions in  $B^\pm \rightarrow DK^\pm$  using the whole 2011 dataset.

### 2.3. Complementarity of other $D$ decays

Since a similar analysis to the one already performed with  $D^0 \rightarrow K^\mp \pi^\pm$  can be realized with  $D^0 \rightarrow K^\mp \pi^\pm \pi^+ \pi^-$ , this mode is also looked for. The

number of observed favoured  $B^\pm \rightarrow (K^\pm \pi^\mp \pi^+ \pi^-)_D K^\pm$  candidates is found to be approximately two times less than for  $D^0 \rightarrow K^\mp \pi^\pm$  with  $36 \text{ pb}^{-1}$  of 2010 data [12].

A complementary constraint on the angle  $\gamma$  can be obtained with the  $CP$ -eigenstate  $D^0 \rightarrow K^+ K^-$  decay mode, for which approximately 40 events are observed in  $36 \text{ pb}^{-1}$ . A statistically limited extraction of  $R_{CP^+}^{B^\pm \rightarrow DK^\pm} = 1.48 \pm 0.31 \pm 0.12$  is thus performed with this data sample [12]. This result is in agreement with other measurements [11], but with larger uncertainties. However the integrated luminosity used for this analysis is approximately 30 times smaller than the full 2011 data sample, and will thus be competitive once updated.

Complementary constraints are obtained via Dalitz measurements of  $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ , also studied at LHCb. The  $B^\pm \rightarrow (K_s^0 \pi^+ \pi^-)_D \pi^\pm$  mode is clearly observed with  $95 \pm 14$  events using  $36 \text{ pb}^{-1}$  [12]. This represents approximately one eights of the statistics available for  $D^0 \rightarrow K^+ K^-$ , the yield reduction being mainly due to the loss of trigger and reconstruction efficiencies due to the  $K_s^0$  lifetime.

#### 2.4. Additional results with other $H_b^0$ decays

Other decays of  $b$  hadrons are also sensitive to  $\gamma$ .

With  $36 \text{ pb}^{-1}$ , the first observation of the  $B_s^0 \rightarrow \bar{D}^0 \bar{K}^{*0}$  decay mode is performed by reconstructing  $D^0 \rightarrow K^\mp \pi^\pm$  and  $K^{*0} \rightarrow K^+ \pi^-$ . Its branching fraction is measured relatively to  $\bar{B}^0 \rightarrow D^0 \rho^0$  to be  $\frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D^0 K^{*0})}{\mathcal{B}(\bar{B}^0 \rightarrow D^0 \rho^0)} = 1.48 \pm 0.34 \pm 0.15 \pm 0.12$  [13]. This mode has the same final state than the  $\gamma$ -sensitive  $B^0 \rightarrow DK^{*0}$  decay, and is thus a first step towards measurement of  $CP$ -violating observables in  $B^0 \rightarrow DK^{*0}$ . This mode contributes also as a partially reconstructed background in the  $B^\pm \rightarrow DK^\pm$  study, for which the low mass fit model enters as one of the dominant systematics. The knowledge of the size of this background contribution is thus impacting the  $B^\pm \rightarrow DK^\pm$  measurement.

The favoured  $B^\pm \rightarrow DK^\pm \pi^+ \pi^-$  mode is also observed for the first time with  $36 \text{ pb}^{-1}$  and found to represent approximately one fourth of the statistics in  $B^\pm \rightarrow DK^\pm$  [14].

Similarly the  $\Lambda_b \rightarrow D^0 p K^-$  is observed for the first time with approximately 100 candidates in  $330 \text{ pb}^{-1}$  [15].

#### 2.5. Prospects for time dependent measurements

$B_s^0 \rightarrow D_s^- K^+$  and  $B^0 \rightarrow D^- \pi^+$  decays can be used to further constrain the angle  $\gamma$  by measuring the angle  $\gamma + \phi_{mixing}$ , where  $\phi_{mixing}$  denotes the

mixing angle, either  $\phi_s$  or  $-2\beta$  respectively in  $B_s^0$  or  $B^0$  decays. Details on the technique and original references can be found in [16].

On the road to these measurements, a determination of  $f_s/f_d = 0.253 \pm 0.017 \pm 0.017 \pm 0.020$  has been performed with  $36 \text{ pb}^{-1}$ , using the similar decay modes  $B_s^0 \rightarrow D_s^- \pi^+$ ,  $B^0 \rightarrow D^- K^+$  and  $B^0 \rightarrow D^- \pi^+$  [17, 18]. The branching fractions of  $B_s^0 \rightarrow D_s^- K^+$  and  $B_s^0 \rightarrow D_s^- \pi^+$  are then measured with  $340 \text{ pb}^{-1}$  [19, 20].

$B_s^0 \rightarrow D_s^- \pi^+$  is also used, together with  $B_s^0 \rightarrow D_s^- \pi^+ \pi^+ \pi^-$ , to assert LHCb capabilities for tagged time dependent measurements. In particular a competitive measurement of  $\Delta m_s = 17.63 \pm 0.11 \pm 0.02 \text{ ps}^{-1}$  is performed with only  $36 \text{ pb}^{-1}$  [21].

Additional modes with higher multiplicities, like  $B_s^0 \rightarrow D_s^- K^+ \pi^+ \pi^-$  could also be used in the future to further increase the sensitivity to  $\gamma$ . As a first step,  $B^0 \rightarrow D^- K^+ \pi^+ \pi^-$  is observed for the first time with  $36 \text{ pb}^{-1}$  [14].

### 3. Hadronic charmless $B$ decays

#### 3.1. General strategy

A complementary way to extract  $\gamma$ , sensitive to new physics effects, consists in measuring  $CP$  violation in charmless  $B$  decays, where generally many contributions from different diagram topologies must be considered. Thus the extraction of the weak phases is more complicated than in the open charm case. On the other hand, the presence of dominant loop contributions makes this extraction sensitive to new physics, and can thus be compared with standard model benchmark measurements. For instance, the  $B \rightarrow hh'$  decays are key channels at LHCb to develop this strategy [16]. On a longer term, tagged time dependent analyses are targeted to maximally exploit the information contained in these decays.

#### 3.2. First evidence for $CP$ violation in the $B_s^0$ system

Searches for direct  $CP$  violation in the flavour specific  $B^0 \rightarrow K^+ \pi^-$  decays are performed with  $320 \text{ pb}^{-1}$ . Small corrections to the raw  $CP$  asymmetries, clearly visible by eye on Fig. 2, are introduced to account for detection and production asymmetries. Detection asymmetries, induced by different reconstruction efficiencies and by different cross sections in the interactions of oppositely charged particles with the detector material, are determined by means of large samples of two-body  $D$  meson decays. The former contribution amounts to about 0.2% and is further cancelled owing to the ability to flip the magnetic field in LHCb. The latter is dominated by the kaon detection asymmetry and amounts to 1%. The production asym-

metry of  $B^0$  mesons is estimated using  $B^0 \rightarrow J/\psi K^{*0}$  decays, assuming no  $CP$  violation. This asymmetry is further diluted by the mixing of the  $B^0$  mesons and the shape of the proper time acceptance. Owing to the fast  $B_s^0$  oscillations, the possible presence of a  $B_s^0$  production asymmetry plays no role. The total correction from these polluting asymmetries amounts to  $1.0 \pm 0.2\%$  and  $-0.7 \pm 0.6\%$  respectively in the  $B_s^0$  and  $B^0$  cases.

$B_s^0$  and  $B^0$   $CP$ -violating asymmetries are thus determined to be [22]:

$$A_{CP}^{B_s^0 \rightarrow K\pi} = \frac{\mathcal{B}(\bar{B}_s^0 \rightarrow K^+\pi^-) - \mathcal{B}(B_s^0 \rightarrow K^-\pi^+)}{\mathcal{B}(\bar{B}_s^0 \rightarrow K^+\pi^-) + \mathcal{B}(B_s^0 \rightarrow K^-\pi^+)} \quad (3a)$$

$$= 0.27 \pm 0.08 \pm 0.02$$

$$A_{CP}^{B^0 \rightarrow K\pi} = \frac{\mathcal{B}(\bar{B}^0 \rightarrow K^-\pi^+) - \mathcal{B}(B^0 \rightarrow K^+\pi^-)}{\mathcal{B}(\bar{B}^0 \rightarrow K^-\pi^+) + \mathcal{B}(B^0 \rightarrow K^+\pi^-)} \quad (3b)$$

$$= -0.088 \pm 0.011 \pm 0.008$$

For the first time, an evidence of  $CP$  violation in the  $B_s^0$  system is obtained and for the first time at an hadron collider a direct  $CP$  asymmetry is observed with more than  $5\sigma$ . The dominating systematics are linked to the modeling of the  $B$  invariant mass in the  $B_s^0$  case and to the polluting asymmetries in the  $B^0$  case and will be reduced with larger integrated luminosities. These results are in agreement and competitive with previous measurements made at  $B$  factories and by CDF, see for instance [23].

### 3.3. Additional LHCb results in $B \rightarrow hh'$ decays

With  $320 \text{ pb}^{-1}$   $B^0 \rightarrow K^+K^-$  and  $B_s^0 \rightarrow \pi^+\pi^-$  decay modes, dominated by exchange and penguin annihilation diagrams, are searched for. The first observation for  $B_s^0 \rightarrow \pi^+\pi^-$  is thus performed and its branching fraction measured to be  $\mathcal{B}(B_s^0 \rightarrow \pi^+\pi^-) = (0.98_{-0.19}^{+0.23} \pm 0.11) \times 10^{-6}$ , while the  $B^0 \rightarrow K^+K^-$  branching fraction is found equal to  $\mathcal{B}(B^0 \rightarrow K^+K^-) = (0.13_{-0.05}^{+0.06} \pm 0.07) \times 10^{-6}$ . These observations are in good agreement with previous results on these branching fractions. These measurements allow to assess the size of the pollution coming from these diagrams in the extraction of the  $CP$  violating observables.

An independent analysis of  $B_s^0 \rightarrow K^+K^-$  decays is also performed to measure its effective lifetime, that is sensitive to  $CP$  violation and potential new physics. It is performed both through an absolute lifetime measurement by estimating a per event acceptance function (see Fig. 3 left), and through a measurement relative to the  $B^0 \rightarrow K^+\pi^-$  lifetime<sup>2</sup> (see Fig. 3 right) that

<sup>2</sup> The effective lifetime in the  $B^0$  system equals the  $B^0$  lifetime thanks to the vanishing lifetime difference of  $CP$ -eigenstates in the  $B^0$  system.

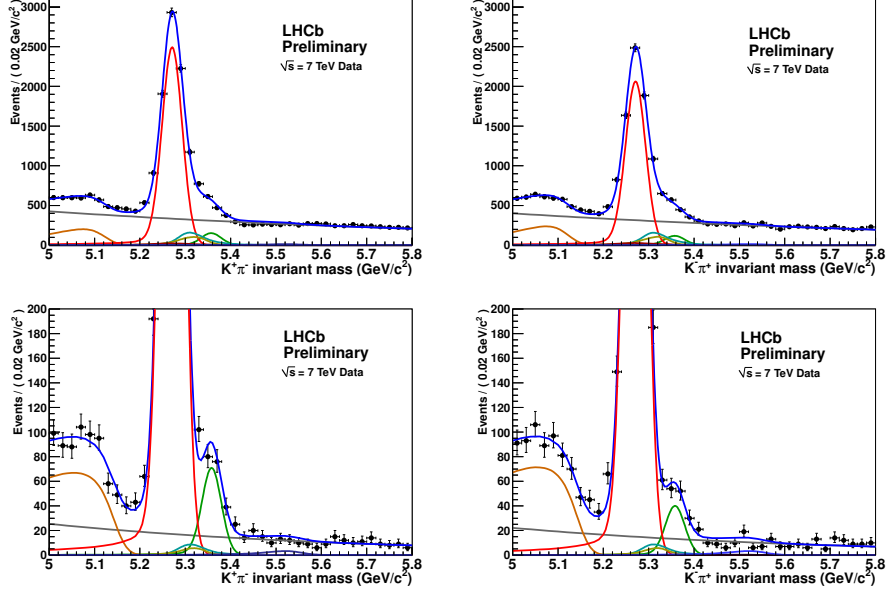


Fig. 2. The  $K^+\pi^-$  (left) and  $K^-\pi^+$  (right) invariant mass spectra optimized for the  $B^0$  asymmetry measurement (top), and for the  $B_s^0$  asymmetry measurement (bottom). The main components of the fit model are  $B^0 \rightarrow K^+\pi^-$  (red),  $B^0 \rightarrow \pi^+\pi^-$  (light blue),  $B_s^0 \rightarrow K^+K^-$  (dark yellow),  $B_s^0 \rightarrow K^-\pi^+$  (green), combinatorial background (grey), 3-body partially reconstructed decays (orange) [22].

assumes similar acceptance functions for both modes. The result  $\tau_{KK} = 1.440 \pm 0.096 \pm 0.008 \pm 0.003$  ps [24], obtained with  $36 \text{ pb}^{-1}$ , is in good agreement with the standard model prediction  $\tau_{KK} = 1.390 \pm 0.032$  [25].

### 3.4. LHCb prospects for three body decays

With  $36 \text{ pb}^{-1}$ , LHCb performs competitive measurements of ratio of branching fractions for charged  $B$  decays in three charmless charged hadrons [26]:

$$\frac{\mathcal{B}(B^\pm \rightarrow K^\pm K^+ K^-)}{\mathcal{B}(B^\pm \rightarrow K^\pm \pi^+ \pi^-)} = 0.52 \pm 0.03 \pm 0.01 \quad (4a)$$

$$\frac{\mathcal{B}(B^\pm \rightarrow K^\pm p \bar{p})}{\mathcal{B}(B^\pm \rightarrow K^\pm \pi^+ \pi^-)} = 0.19 \pm 0.02 \pm 0.02. \quad (4b)$$

The  $B^\pm \rightarrow K^\pm p \bar{p}$  mode is reconstructed without any veto on charmonium resonances. An independent analysis performs, with the same data sample,

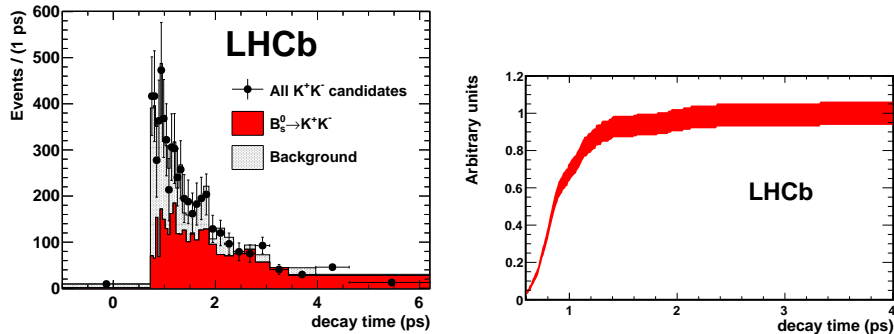


Fig. 3. Proper time distribution of the  $B_s^0 \rightarrow K^+ K^-$  candidates used in the relative lifetime measurement (left) and average decay-time acceptance function for signal events used for the absolute lifetime measurement, where the error band is an estimate of the statistical uncertainty (right) [24].

the measurement of the branching fraction for this decay mode relative to charmonium intermediate resonance and gives [27]:

$$\frac{\mathcal{B}(B^\pm \rightarrow K^\pm p\bar{p})}{\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm) \mathcal{B}(J/\psi \rightarrow p\bar{p})} = 4.6 \pm 0.6 \pm 0.5. \quad (5)$$

These results are in fair agreement with the existing world averages. The next step will consist in a measurement of time-integrated  $CP$  asymmetries, sensitivity to time dependent  $CP$  asymmetries will come with even larger integrated luminosities.

### 3.5. LHCb results and prospects for decays in four body final states

Four charged body decays can be reconstructed in quasi-two body approaches that allow to have additional lever arms against the larger combinatorial background. In particular, the first observation of  $B_s^0 \rightarrow K^{*0} \bar{K}^{*0}$  is performed with  $36 \text{ pb}^{-1}$ . This allows not only to extract the branching fraction for this decay mode,  $\mathcal{B}(B_s^0 \rightarrow K^{*0} \bar{K}^{*0}) = (2.81 \pm 0.46 \pm 0.45 \pm 0.34) \times 10^{-5}$ , but also to measure the longitudinal polarization,  $f_L = 0.31 \pm 0.12 \pm 0.04$  [28]. This latter measurement is quite different from the one performed with  $B^0 \rightarrow K^{*0} \bar{K}^{*0}$  despite these two decays are U-spin related. However the former is consistent with expectations.

Triple product asymmetries are also measured in the  $B_s^0 \rightarrow \phi\phi$  decay. These asymmetries, sensitive to  $CP$ -violation under the assumption that



$CPT$  is conserved, are measured with  $340 \text{ pb}^{-1}$ , see Fig. 4, [29]:

$$A_U = \frac{N(U < 0) - N(U > 0)}{N(U < 0) + N(U > 0)} = -0.064 \pm 0.057 \pm 0.014 \quad (6a)$$

$$A_V = \frac{N(V < 0) - N(V > 0)}{N(V < 0) + N(V > 0)} = -0.070 \pm 0.057 \pm 0.014, \quad (6b)$$

where  $U = \frac{1}{2} \sin(2\Phi)$ ,  $V = \sin(\varepsilon\Phi)$  and  $\varepsilon = \text{sign}(\cos\theta_1 \cos\theta_2)$ ,  $\Phi$  being the angle between the decay planes of the two  $\phi$  mesons and  $\cos\theta_{1,2}$  the helicity angles in the two  $\phi$  meson decays. This result is in agreement with a previous existing CDF measurement. On the longer term, this channel may also be used for the determination of the mixing phase in the  $B_s^0$  system  $\phi_s$ .

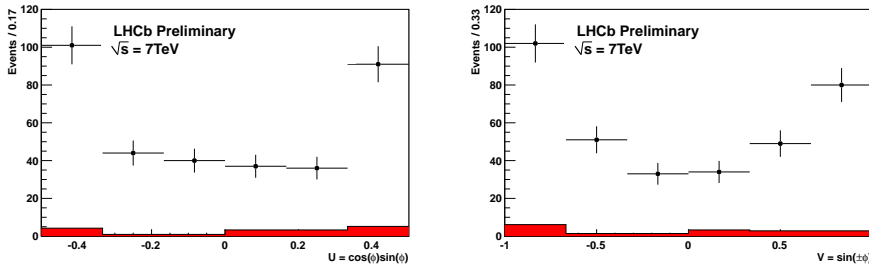


Fig. 4. Distributions of the  $U$  (left) and  $V$  (right) observables for the  $B_s^0 \rightarrow \phi\phi$  data in the mass range  $5286.6 < m(B_s^0) < 5446 \text{ MeV}$ . The distribution for the background is taken from the mass sidebands and shown in red. [29].

## 4. $B$ decays to final state with charmonium

### 4.1. General strategy

$CP$ -violation in the interference between the mixing and the decay is precisely predicted to be  $\phi_s^{SM} = -2\beta_s = -0.0363 \pm 0.0017 \text{ rad}$  within the standard model. This quantity can be experimentally measured via tree-level dominated  $b \rightarrow c\bar{c}s$  transitions, for which the vanishing phase is robust against new physics contributions. Measuring the phase of the interference of these diagrams with the diagram involved in the mixing allows to extract the weak mixing phase. This method is similar to the one developed at  $B$  factories to precisely determine the mixing phase  $\beta$  in the  $B^0$  system.

### 4.2. Measurement of $\phi_s$ in $B_s^0 \rightarrow J/\psi\phi$

A clean  $B_s^0 \rightarrow J/\psi\phi$  sample of about 8500 events is obtained with  $370 \text{ pb}^{-1}$ , allowing the extraction of the mixing phase  $\phi_s$ , the average  $B_s^0$

decay width  $\Gamma_s$  and the decay width difference of mass eigenstates  $\Delta\Gamma_s$ . Involving two vector mesons as intermediate resonances an angular analysis is required in addition to the proper time measurement. Background and three signal components, that correspond to the two P-wave amplitudes and an S-wave amplitude, are simultaneously fitted, see Fig. 5. One of the two ambiguous solutions [30] related by the transformation  $(\phi_s, \Delta\Gamma_s) \rightarrow (\pi - \phi_s, -\Delta\Gamma_s)$ :

$$\phi_s = 0.15 \pm 0.18 \pm 0.06 \text{ rad} \quad (7a)$$

$$\Gamma_s = 0.657 \pm 0.009 \pm 0.008 \text{ ps}^{-1} \quad (7b)$$

$$\Delta\Gamma_s = 0.123 \pm 0.029 \pm 0.011 \text{ ps}^{-1}, \quad (7c)$$

is in good agreement with the standard model prediction, see Fig. 6. This result shows for the first time an evidence for a non vanishing decay width difference of the two  $B_s^0$  mass eigenstates, in good agreement with the standard model prediction  $\Delta\Gamma_s^{SM} = 0.082 \pm 0.021 \text{ ps}^{-1}$ .

#### 4.3. Resolving the ambiguity in $\phi_s$

Taking advantage of the fact that the strong phase difference of the S-wave relative to the P-wave is expected to decrease with an increasing  $K^+K^-$  invariant mass<sup>3</sup>, the two previous ambiguities can be resolved. Indeed, the sign of this strong phase difference changes depending on the choice of the one or the other ambiguity. It is found with  $370 \text{ pb}^{-1}$  that the decreasing strong phase difference is the solution with  $\phi_s$  close to zero rather than  $\pi$ , see Fig. 7 [31].

#### 4.4. Additional constraints and prospects on $\phi_s$

Additional charmonium decay modes can be used to further constrain measurements of the mixing phase. Since  $f_0(980)$  is a spin-0 resonance, an angular analysis of the  $B_s^0 \rightarrow J/\psi f_0(980)$  decay mode is not required to extract the mixing phase. However, this mode is potentially polluted by other  $\pi^+\pi^-$  contributions. In particular, pollution of spin-2 resonances is found to be negligible as shown on Fig. 8. Using the previous measurement for  $\Gamma_s$  and  $\Delta\Gamma_s$ ,  $\phi_s = -0.44 \pm 0.44 \pm 0.02 \text{ rad}$  is obtained with  $410 \text{ pb}^{-1}$  [32]. The combination of the two measurements,  $\phi_s = 0.03 \pm 0.16 \pm 0.07 \text{ rad}$ , is performed by fitting simultaneously  $B_s^0 \rightarrow J/\psi f_0(980)$  and  $B_s^0 \rightarrow J/\psi \phi$  [33].

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<sup>3</sup> The P-wave, Breit-Wigner, phase increases rapidly with  $m_{K^+K^-}$  while the S-wave, Flatté, phase varies slowly with  $m_{K^+K^-}$ .

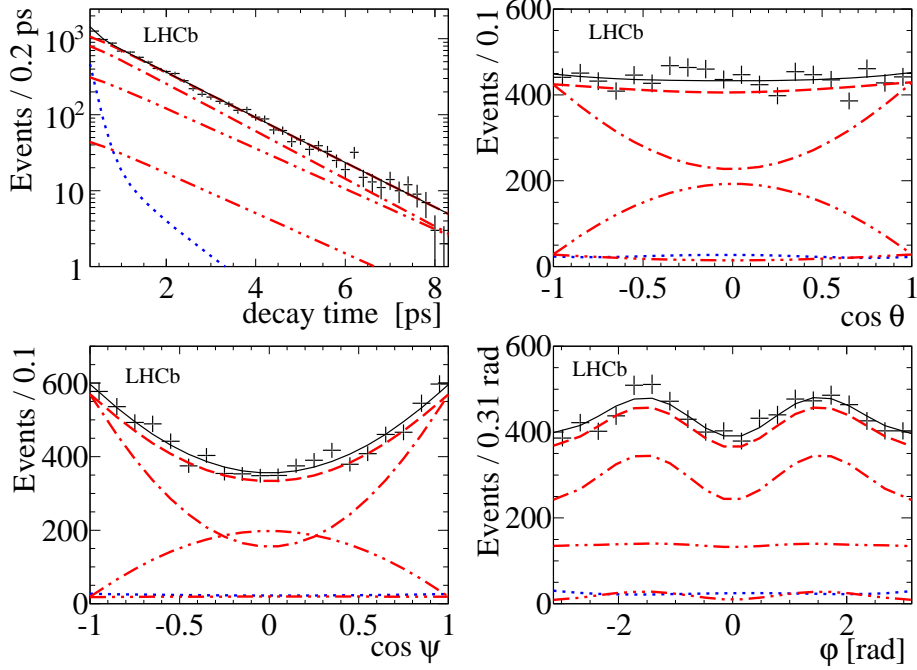


Fig. 5. Projections for the decay time and transversity angle distributions. The dashed (red), dotted (blue) and solid (black) lines represent the fitted contributions from signal, background and their sum. The remaining curves correspond to the  $CP$ -even P-wave (red dashed with single dot), the  $CP$ -odd P-wave (red dashed with double dot) and the S-wave (red dashed with triple dot) signal components [30].

The first observation of  $B_s^0 \rightarrow J/\psi f_2'(1525)$  (in  $K^+K^-$  final state), and the measurement of its branching fraction relative to  $B_s^0 \rightarrow J/\psi \phi$  :

$$\frac{\mathcal{B}(B_s^0 \rightarrow J/\psi f_2'(1525))}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)} = (26.4 \pm 2.7 \pm 2.4)\% \quad (8)$$

is obtained with  $160 \text{ pb}^{-1}$  [34]. It is however a more complicated channel for the extraction of  $\phi_s$  since involving a spin-2 resonance instead of a spin-1.

A measurement of the  $B_s^0 \rightarrow \psi(2S)\phi$  branching fraction relative to  $B_s^0 \rightarrow J/\psi \phi$  is also performed with  $36 \text{ pb}^{-1}$  [35]. The obtained result,  $\frac{\mathcal{B}(B_s^0 \rightarrow \psi(2S)\phi)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)} = 0.68 \pm 0.10 \pm 0.09 \pm 0.07$ , shows that it could substantially contribute in further improvements in the determination of  $\phi_s$ .

Finally the  $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$  branching fraction  $\mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) = (3.5_{-1.0}^{+1.1} \pm 0.9) \times 10^{-5}$  is measured with  $36 \text{ pb}^{-1}$  [36]. This will give, with

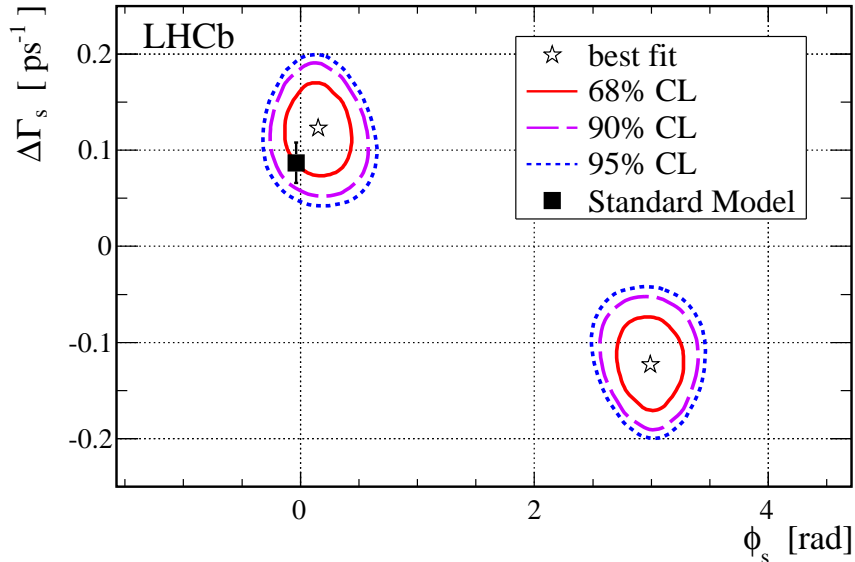


Fig. 6. Likelihood confidence regions in the  $\Delta\Gamma_s - \phi_s$  plane. The black square and error bar correspond to the Standard Model prediction [30].

larger statistics, insights to control the size of polluting penguin contributions in  $B_s^0 \rightarrow J/\psi \phi$ .

#### 4.5. Prospects for the decay mode $B_{d,s}^0 \rightarrow J/\psi K_S^0$

$CP$ -violation in  $B^0 \rightarrow J/\psi K_S^0$  is already extremely well determined by  $B$  factories, see for instance [37]. With  $36 \text{ pb}^{-1}$ , LHCb measured  $S_{J/\psi K_S^0} = 0.53_{-0.29}^{+0.28} \pm 0.05$  [38]. With 100 times more statistics (three times more than what collected by LHCb in 2011), it may well allow to have a measurement competitive with present world leading determinations.

To go further it will be necessary to constrain both the amplitude and the phase of the penguin contribution in  $B^0 \rightarrow J/\psi K_S^0$ . This can be done thanks to the study of  $B_s^0 \rightarrow J/\psi K_S^0$ , under  $SU(3)$  assumption. Its branching fraction is measured with  $380 \text{ pb}^{-1}$  relatively to  $B^0 \rightarrow J/\psi K_S^0$ :  $\frac{\mathcal{B}(B_s^0 \rightarrow J/\psi K_S^0)}{\mathcal{B}(B^0 \rightarrow J/\psi K_S^0)} = 0.0378 \pm 0.0058 \pm 0.0020 \pm 0.0030$  [39].

## 5. Conclusion

During 2011 LHCb has collected an integrated luminosity of  $1.1 \text{ fb}^{-1}$ , clearing the way to the measurements of several decay modes of charm

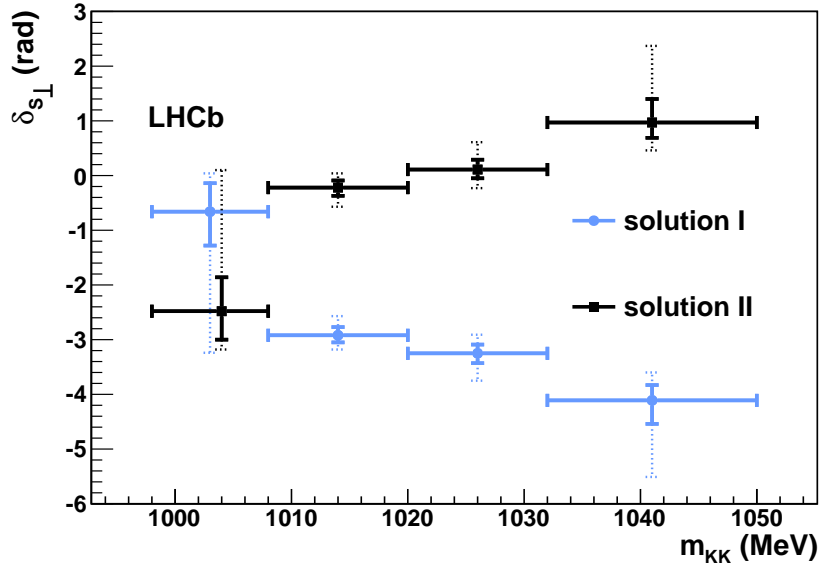


Fig. 7. Measured phase differences between S-wave and perpendicular P-wave amplitudes for the two solutions (in light blue the solution with  $\phi_s$  close to zero). The asymmetric error bars correspond to  $\Delta \ln \mathcal{L} = -0.5$  (solid) and  $\Delta \ln \mathcal{L} = -2$  (dotted) [31].

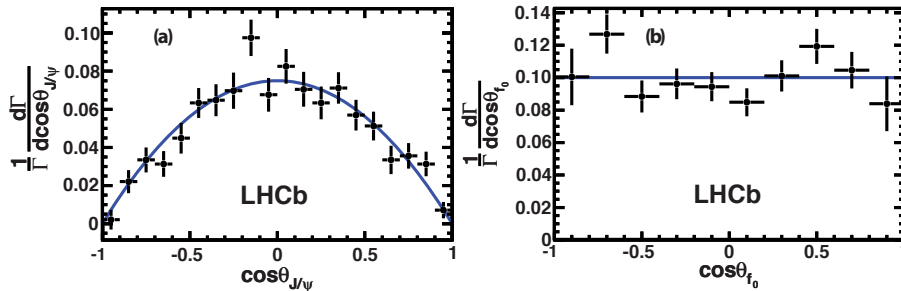


Fig. 8. Efficiency corrected, background subtracted helicity angle distributions in the  $\pi^+\pi^-$  mass region within  $\pm 90$  MeV of the  $f_0(980)$  mass of 980 MeV and within  $\pm 20$  MeV of the  $B_s^0$  mass for  $J/\psi$  (left) and  $f_0(980)$  (right). The solid lines show the expectations for a spin-0 object [32].

and beauty hadrons. Among the large variety of measurements performed by the collaboration,  $CP$  violation measurements in the  $B$  system are key observables. Three different categories of measurements have been presented here.

An evidence for  $b \rightarrow u$  transitions in  $B^\pm \rightarrow DK^\pm$  is obtained, confirming beginning of 2011 results from BELLE. This analysis is performed by reconstructing the final state  $D^0 \rightarrow K^\mp \pi^\pm$ , while other  $D$  decay modes are also under study at LHCb and will increase the sensitivity on tree-level determinations of the CKM angle  $\gamma$ . Additional similar  $B$  decay modes are also scrutinized at LHCb, and will potentially add significant information in the extraction of  $\gamma$ . Time dependent  $\gamma$  measurements are studied as well, and first intermediate physics results are obtained.

Charmless  $B$  decays also allow for the determination of weak phases, but with contributions from loop diagrams, so that the measurement is sensitive to new physics effects. First evidence for direct  $CP$  violation in the  $B_s^0$  system is obtained and  $CP$  violation is observed in the  $B^0$  system, using respectively  $B_s^0 \rightarrow K^- \pi^+$  and  $B^0 \rightarrow K^+ \pi^-$  decays. Other measurements involving two body decay modes are performed to complete the picture of  $B \rightarrow hh'$  decays. First intermediate measurements are performed with three body charged  $B$  decays and studies devoted to measurement of triple product asymmetries or longitudinal polarization measurements are performed with four body decays modes.

LHCb performs a world leading measurement of the mixing phase in the  $B_s^0$  system, by looking at  $b \rightarrow c\bar{c}s$  transitions. Both  $B_s^0 \rightarrow J/\psi \phi$  and  $B_s^0 \rightarrow J/\psi f_0(980)$  decay modes provide an interesting constraint on  $\phi_s$  and allow, for the first time, to determine the sign of the decay width difference in the  $B_s^0$  system. These measurements may be enriched in the future by additional  $\phi_s$ -sensitive decay modes, and the pollution from penguin diagrams may be well under control thanks to decay modes already seen at LHCb. Given the excellent results of  $B$  factories on the  $B^0$  mixing phase, a competitive measurement at LHCb would require larger integrated luminosities than the one collected in 2011.

All these results are very promising for the 2012 data taking and show that the knowledge of the  $CP$  violation in the  $B$  system is already improving thanks to measurements performed at LHCb.

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### REFERENCES

- [1] LHCb, A. Alves et al., *The LHCb Detector at the LHC*, *JINST* **3** (2008) S08005.
- [2] A. Ukleja, *Results on charm physics from LHCb experiment*, *Acta Phys.Polon.* **B43** (2012).
- [3] F. Soomro, *Search for rare decays in LHCb Experiment*, *Acta Phys.Polon.* **B43** (2012).
- [4] A. Alves, *Heavy flavour spectroscopy in LHCb Experiment*, *Acta Phys.Polon.* **B43** (2012).
- [5] F. Alessio, *Overview of the LHCb Experiment*, *Acta Phys.Polon.* **B43** (2012).
- [6] LHCb Collaboration, R. Aaij et al., *Opposite-side flavour tagging of B mesons at the LHCb experiment*, LHCb-PAPER-2011-027.
- [7] J. Zupan, *The case for measuring gamma precisely*, [arXiv:1101.0134](#).
- [8] M. Bona, *Standard Model updates and new physics analysis with the Unitarity Triangle fit*, *PoS EPS-HEP2011* (2011) 185.
- [9] V. Niess, *Global fit to CKM data*, *PoS EPS-HEP2011* (2011) 184.
- [10] LHCb Collaboration, *Evidence for the suppressed decay  $B^\pm \rightarrow (K^\mp \pi^\pm)_D K^\pm$* , LHCb-CONF-2011-044.
- [11] Y. Horii,  *$\phi_3$  measurements at B factories*, *Acta Phys.Polon.* **B43** (2012).
- [12] LHCb Collaboration, *A measurement of the ratio of branching fractions:  $\frac{\mathcal{B}(B^\pm \rightarrow DK^\pm)}{\mathcal{B}(B^\pm \rightarrow D\pi^\pm)}$  for  $D \rightarrow K\pi, KK, K\pi\pi\pi$  and  $K_S^0\pi\pi$* , LHCb-CONF-2011-031.
- [13] LHCb Collaboration, R. Aaij et al., *First observation of the decay  $\bar{B}_s^0 \rightarrow D^0 K^{*0}$  and a measurement of the ratio of branching fractions  $\frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D^0 K^{*0})}{\mathcal{B}(B^0 \rightarrow D^0 \rho^0)}$* , *Phys.Lett.* **B706** (2011) 32–39, [[arXiv:1110.3676](#)].
- [14] LHCb Collaboration, *First observations of the Cabibbo-suppressed decays  $\bar{B}^0 \rightarrow D^+ K^- \pi^+ \pi^-$  and  $B^- \rightarrow D^0 K^- \pi^+ \pi^-$* , LHCb-CONF-2011-024.
- [15] LHCb Collaboration, *Studies of beauty baryons decaying to  $D^0 p \pi^-$  and  $D^0 p K^-$* , LHCb-CONF-2011-036.
- [16] The LHCb Collaboration, B. Adeva et al., *Roadmap for selected key measurements of LHCb*, [arXiv:0912.4179](#).
- [17] P. Morawski, *The measurement of  $f_s/f_d$  from hadronic modes in LHCb experiment*, *Acta Phys.Polon.* **B43** (2012).
- [18] LHCb Collaboration, R. Aaij et al., *Determination of  $f_s/f_d$  for 7 TeV pp collisions and a measurement of the branching fraction of the decay  $B_d \rightarrow D^- K^+$* , *Phys.Rev.Lett.* **107** (2011) 211801, [[arXiv:1106.4435](#)].
- [19] A. Dziurda, *The measurement of branching ratio of  $B_s^0 \rightarrow D_s^- K^+$  and  $B_s^0 \rightarrow D_s^- \pi^+$  in the LHCb experiment*, *Acta Phys.Polon.* **B43** (2012).
- [20] LHCb Collaboration, *Measurements of the relative and absolute branching fractions of the decays  $B_s^0 \rightarrow D_s^\mp K^\pm$  and  $B_s^0 \rightarrow D_s^- \pi^+$* , LHCb-CONF-2011-057.
- [21] LHCb Collaboration, R. Aaij et al., *Measurement of the  $B_s^0$ - $\bar{B}_s^0$  oscillation frequency  $\Delta m_s$  in  $B_s^0 \rightarrow D_s^-(3)\pi$  decays*, [arXiv:1112.4311](#).

- [22] LHCb Collaboration, *Charmless charged two-body B decays at LHCb with 2011 data*, LHCb-CONF-2011-042.
- [23] X. Prudent, *Hadronic and rare B decays*, *Acta Phys.Polon.* **B43** (2012).
- [24] LHCb Collaboration, R. Aaij et al., *Measurement of the effective  $B_s^0 \rightarrow K^+ K^-$  lifetime*, *Phys.Lett.* **B707** (2012) 349–356, [arXiv:1111.0521].
- [25] R. Fleischer and R. Knegjens, *In Pursuit of New Physics with  $B_s^0 \rightarrow K^+ K^-$* , *Eur.Phys.J.* **C71** (2011) 1532, [arXiv:1011.1096].
- [26] LHCb Collaboration, *Relative branching ratio measurements of charmless  $B^\pm$  decays to three hadrons*, LHCb-CONF-2011-059.
- [27] LHCb Collaboration, *Measurements of the relative branching fractions of the  $B^\pm \rightarrow p\bar{p}K^\pm$  decay channel including charmonium contributions*, LHCb-CONF-2011-058.
- [28] LHCb Collaboration, R. Aaij et al., *First observation of the decay  $B_s^0 \rightarrow K^{*0}\bar{K}^{*0}$* , *Phys.Lett.* **B709** (2012) 50–58, [arXiv:1111.4183].
- [29] LHCb Collaboration, *Study of Triple Product Asymmetries in  $B_s \rightarrow \phi\phi$  decays*, LHCb-CONF-2011-052.
- [30] LHCb Collaboration, R. Aaij et al., *Measurement of the CP-violating phase  $\phi_s$  in the decay  $B_s^0 \rightarrow J/\psi\phi$* , arXiv:1112.3183.
- [31] LHCb Collaboration, R. Aaij et al., *Determination of the sign of the decay width difference in the  $B_s^0$  system*, arXiv:1202.4717.
- [32] LHCb Collaboration, R. Aaij et al., *Measurement of the CP violating phase  $\phi_s$  in  $B_s^0 \rightarrow J/\psi f_0(980)$* , *Phys.Lett.* **B707** (2012) 497–505, [arXiv:1112.3056].
- [33] LHCb Collaboration, *Combination of  $\phi_s$  measurements from  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow J/\psi f_0(980)$* , LHCb-CONF-2011-056.
- [34] LHCb Collaboration, R. Aaij et al., *Observation of  $B_s^0 \rightarrow J/\psi f_2'(1525)$  in  $J/\psi \rightarrow K^+ K^-$  final states*, arXiv:1112.4695.
- [35] LHCb Collaboration,  $\mathcal{B}(B_s^0 \rightarrow \psi(2S)\phi)/\mathcal{B}(B_s^0 \rightarrow J/\psi\phi)$ , LHCb-CONF-2011-014.
- [36] LHCb Collaboration, *Evidence for the decay  $B_s^0 \rightarrow J/\psi\bar{K}^{*0}$* , LHCb-CONF-2011-025.
- [37] K. Miyabayashi, *Time-dependent CPV and mixing at B-factories*, *Acta Phys.Polon.* **B43** (2012).
- [38] LHCb Collaboration, *Search for CP violation in  $B^0 \rightarrow J/\psi K_S^0$  decays with first LHCb data*, LHCb-CONF-2011-004.
- [39] LHCb Collaboration, *Measurement of the  $B_s^0 \rightarrow J/\psi K_S^0$  branching fraction*, LHCb-CONF-2011-048.