Measurements of B^0 and B_s^0 mixing frequencies at LHCb

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Abstract. This document describes the measurements of the B^0 and B_s^0 mixing frequencies performed at LHCb using the data sample corresponding to an integrated luminosity of 1 fb^{-1} collected during 2011. The knowledge of the mixing frequencies provides a constraint on the apex of the CKM unitarity triangle and is a key ingredient for several CP-violation measurements. Analyses of the flavour oscillations allow also to measure the B^0 and the B_s^0 production asymmetries.

1. Introduction

The $B^0_{(q)}$-$\bar{B}^0_{(q)}$ mixing (q=d,s), described in the SM by box Feynman diagrams, are due to the misalignment of the flavour eigenstates and the mass eigenstates. The latter, denoted as B_{H^q} and B_{L^q}, have a mass difference Δm_q = $m_{H^q} - m_{L^q}$, which corresponds to the mixing frequency. The theoretical predictions on Δm_q are affected by large uncertainties due to hadronic parameters entering the calculations, which partially cancel in the ratio $\frac{\Delta m_s}{\Delta m_d}$, allowing to constraint the apex of the CKM unitarity triangle. The mixing frequencies are measured through the time-dependent mixing asymmetry:

$$A(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) - N_{mix}(t)} \approx \cos(\Delta m t)$$

where $N_{unmix}(t)$ is the number of events for which the flavour at the decay time and the production time is the same, while $N_{mix}(t)$ is the number of events that have a different flavour at decay time and production time. The flavour of the B meson at the decay time is known from the charge of the final state particles in flavour specific decays; in LHCb, measurements of the mixing frequencies are performed with the following decay modes: $B_s^0 \to D_s^- \pi^+$, $B^0 \to D^- \pi^+$, $B^0 \to J/\psi K^{*0}$, and $B^0_{(s)} \to D^-_{(s)} \mu^+ \nu$. The knowledge of the flavour of the B meson at the production time is inferred by means of flavour tagging algorithms, which are classified in two categories: the Same Side (SS) and the Opposite Side (OS) taggers. The SS taggers exploit the charge of the fragmentation particles accompanying the B signal meson (SSK for B_s^0 and SSπ for B^0). The OS tagging algorithms use an inclusive reconstruction of the other b-hadron produced in the pp interaction (OSe, OSμ, OSK, OSVtxCharge) where the charge of the tagging particle is correlated with the flavour of the B meson. For each B candidate the tagging algorithms provide a decision on the flavour and a probability of such decision being wrong, namely mistag probability. If more than one tagger is available, it is possible to combine the tagging decisions and the mistag probabilities to obtain a final decision and a final mistag. In the following analyses the OS and the SS informations are combined in order to increase the tagging performance. The figure of merit of the tagging algorithms is called the effective tagging power ϵ_{eff} = $\epsilon_{tag}(1 - 2\omega)^2$, where ϵ_{tag} is the tagging efficiency and ω is the mistag probability. It gives the factor by which the statistical power

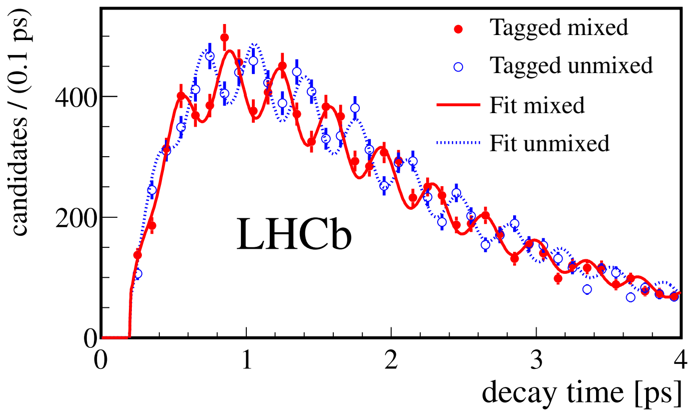

Figure 1. Fit to the decay time distribution for mixed and unmixed events in the $B_s^0 \to D_s^- \pi^+$ decay [2].

is reduced due to imperfect tagging decisions. The sensitivity to the mixing frequency is reduced by the mistag probability which dilutes the mixing frequency by O(60-80%), depending on the decay mode. Another source of dilution is due to the resolution of the decay time measurement; the good capabilities of the LHCb tracking system allow to achieve a decay time resolution of O(50) fs for fully reconstructed decay, to be compared with the fast oscillation of the B_s^0 mesons, which last a period of 350 fs.

2. Mixing Frequency Measurements

In what follows, I report the measurements of the mixing frequencies obtained in a data set corresponding to an integrated luminosity of 1 fb^{-1} collected by the LHCb detector in proton-proton collisions at 7 TeV center-of-mass energy.

2.1. Δm_s in $B_s^0 \to D_s^- \pi^+$

The measurement of Δm_s in the $B_s^0 \to D_s^- \pi^+$ decay mode is described in Ref.[2]. The measurement is obtained through a maximum likelihood fit to the B_s^0 invariant mass, decay time and tagging decision for subsamples corresponding to 5 D_s decay modes ($D_s \to \phi\pi$, $D_s \to K^* K$, $D_s \to K\pi\pi$ non resonant, $D_s \to KK\pi$, $D_s \to \pi\pi\pi$). The total probability density function (PDF) is $PDF(m)PDF(t, q|\sigma_t, \eta) \cdot P(\sigma_t)P(\eta)$, where q is the tagging decision and η the mistag probability for each event from the combination of the OS and SSK taggers. The time resolution, σ_t, is estimated event by event and calibrated on a large sample of D_s decays. The corresponding measured average effective time resolution $< \sigma_t >$ is 44 fs. Some of the selection requirements on variables correlated with the decay time introduce an efficiency as a function of the decay time (decay time acceptance), which is parametrized from simulations. The measured signal yield is 34 000 events. The effective tagging power ϵ_{eff} is 2.6% for the OS and 1.2% for the SSK. In figure 1 the fit to the decay time distribution for mixed and unmixed events is shown in the signal mass range ($5320 < m_{B_s} < 5550$). The B_s^0 fast oscillations are well resolved and allow to determine the value value of Δm_s = 17.768 $\pm$ 0.023 (stat.) $\pm$ 0.006 (syst.) ps^{-1}. The main systematic sources are due to the uncertainty on the detector alignment: the longitudinal scale (0.004 ps^{-1}) and the overall momentum scale (0.004 ps^{-1}). This is the best Δm_s measurement to date.

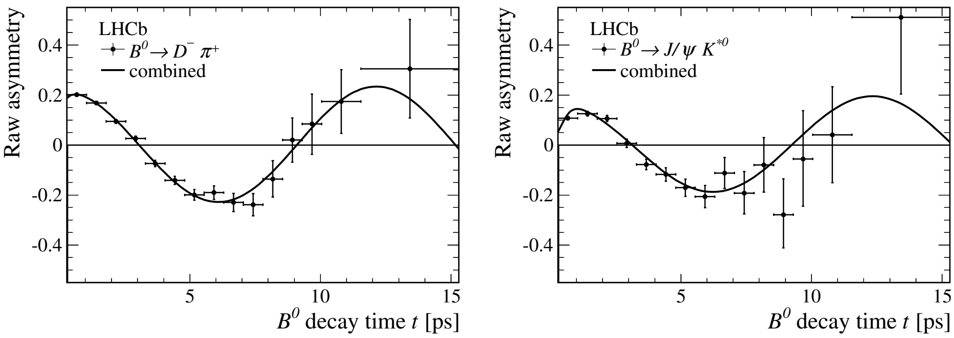

Figure 2. Fit to the mixing asymmetry in $B^0 \to D^-\pi^+$ on the left and in $B^0 \to J/\psi K^{*0}$ on the right [3].

2.2. Combined measurement of Δm_d in $B^0 \to D^-\pi^+$ and in $B^0 \to J/\psi K^{*0}$

The measurements of Δm_d in the $B^0 \to D^-\pi^+$ and in the $B^0 \to J/\psi K^{*0}$ decay modes are described in [3]. The two analyses exploit a maximum likelihood fit to the B^0 invariant mass, decay time and tagging decision (combining the OS and the SSπ taggers). A single gaussian with a width of 50 fs is used to model the time resolution effects. For the decay time acceptance the $B^0 \to D^-\pi^+$ analysis extracts the parametrization using simulated events while the $B^0 \to J/\psi K^{*0}$ uses a specific data sample of $B^0 \to J/\psi K^{*0}$ in which the events are collected without applying any of the decay time biasing selections. In the $B^0 \to D^-\pi^+$ analysis the D^- meson is reconstructed in $K^+\pi^-\pi^-$ and the measured signal yield is 87 724 $\pm$ 321 events in a mass window of 5200 $< m_B <$ 5450. On the left of figure 2 the fit to the mixing asymmetry is reported from which a mixing frequency of Δm_d = 0.5178 $\pm$ 0.0061 (stat.) $\pm$ 0.0037 (syst.) ps^{-1} is extracted. In the $B^0 \to J/\psi K^{*0}$ analysis the J/ψ is reconstructed in the di-muon final state and the K^{*0} in the $K^+\pi^-$. The corresponding statistics is 39 148 $\pm$ 316 signal events and the OS and SSπ tagging performances are a slightly worse ($\epsilon_{eff}(\%)$ in $B^0 \to J/\psi K^{*0}$ is 2.0 for OS and 0.6 for SSπ while in $B^0 \to D^-\pi^+$ is 3.0 for OS and 1.32 for SSπ); in addition the background fraction in the signal region is higher. The measured Δm_d value is Δm_d = 0.5096 $\pm$ 0.0114 (stat.)$\pm$ 0.0022 (syst.) ps^{-1}. The larger statistical error in $B^0 \to J/\psi K^{*0}$ is due to the lower statistics, the worse tagging performance and a higher background fraction in the signal region. On the right side of figure 2 the mixing asymmetry fit is shown. For both measurements the most relevant systematic effect is due to the fit model: 0.0037 ps^{-1} for $B^0 \to D^-\pi^+$ and 0.0022 ps^{-1} for $B^0 \to J/\psi K^{*0}$. The combined result is Δm_d = 0.5156 $\pm$ 0.0114 (stat.) $\pm$ 0.0022 (syst.) ps^{-1}. This is the most precise combination of Δm_d results from a single experiment.

2.3. Δm_d and Δm_s in semi-leptonic decays

An analysis of $B^0_{(s)} \to D^-_{(s)}\mu^+\nu_\mu X$ decays where $D^-_{(s)} \to KK\pi$ is presented in [4]. The measurements of Δm_d and Δm_s are closely related and represent the first observation of B^0_s mixing using only semi-leptonic decays. The analysis proceeds through a simultaneous fit to the D^-_s measured mass, the $B^0_{(s)}$ decay time and the tagging decision (only from OS for the B^0 while for B^0_s both the OS and SSK information is used). In semi-leptonic decays the reconstructed momentum is systematically low due to the escape of the neutrino which is not detected. Consequently the estimation of the decay time is biased. A correction based on simulation ("k-factor") is applied event by event. As a consequence the time resolution is worse compared to fully reconstructed modes and it depends on the decay time. For the $B^0_s \to D^-_s\mu^+X$ the measured yield is $\approx$ 201 200 events and the B^0_s mixing frequency is found to be Δm_s

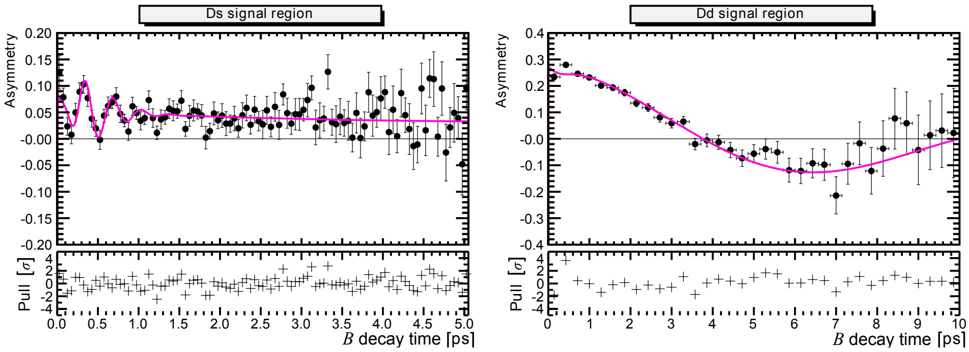

Figure 3. Fit to the mixing asymmetry for B_s^0 on the left and for B^0 on the right

= 17.93 ± 0.22 (stat.) ± 0.15 (syst.) ps^{-1}. The left of figure 3 shows the fit to the mixing asymmetry for the B_s^0 events. The oscillations are visible at small time while at larger time they are dumped by the time resolution effect. For this reason even if the yield is larger than the previous $B_s^0 \to D_s^- \pi^+$ analysis, the statistical precision is worse. For the $B^0 \to D^- \mu^+ X$ the yield is ≈ 50 700 events and the B^0 mixing frequency is equal to: Δm_d = 0.503 ± 0.011 (stat.) ± 0.014 (syst.) ps^{-1}. On the right of figure 3 the fit to the B^0 mixing asymmetry is shown. Several systematic effects are studied for both the measurements. The most relevant ones for Δm_s are connected to the time resolution model (0.09 ps^{-1}), the k-factor correction (0.09 ps^{-1}) and the simulation input for the k-factor evaluation (0.06 ps^{-1}). The Δm_d measurement is mostly affected by the parametrization of the background (0.008 ps^{-1}), the time resolution model (0.007 ps^{-1}) and the k-factor correction (0.0055 ps^{-1}).

3. B^0 and B_s^0 Production Asymmetries

The $B^0_{(s)}$-$\bar{B}^0_{(s)}$ production asymmetry in proton-proton collisions represents an important ingredient for CP violation analyses since CP asymmetries must be disentangled from other sources. The measurements of the B^0 and B_s^0 production asymmetry, A_P, are reported in [5]. LHCb has measured these quantities by using data collected at 7 TeV during the 2011 run and by analyzing the flavour specific decays: $B^0 \to D^- \pi^+$ and $B^0 \to J/\psi K^{*0}$ for $A_P(B^0)$ and $B_s^0 \to D_s^- \pi^+$ for $A_P(B_s^0)$. No flavour tagging is necessary. The analysis is based on a simultaneous fit to the B invariant mass and decay time in which the decay rates depend on the production asymmetry:

$$\Gamma_{B^0_{(s)}}(t) \approx (1 - f(A_{CP} + A_{det}))e^{-\Gamma_{(s)}t} \cdot [\cosh(\frac{\Delta\Gamma_{(s)}t}{2}) - f \cdot A_P \cos(\Delta m_{(s)}t)]$$

where A_{CP} is the CP asymmetry and it is assumed to be zero in these specific decays. A_{det} is the detection asymmetry and is a free parameter of the fit. The mixing frequencies are constrained: for Δm_d the world average value Δm_d = 0.510 ± 0.004 ps^{-1} [6] is used and for Δm_s the LHCb measurement Δm_s = 17.768 ± 0.024 ps^{-1} [2] is used. The production asymmetries are measured in bins of transverse momentum of the B meson and pseudorapidity; no dependence is observed. An integrated measurement of A_P is performed in the ranges $4 < p_T < 30$ GeV/c, $2.5 < \eta < 4.5$. The measured production asymmetries are $A_P(B^0)$ = -0.35 ± 0.76 (stat.) ± 0.28 (syst.) % and $A_P(B_s^0)$ = 1.09 ± 2.61 (stat.) ± 0.61 (syst.)%. Both the measurements are compatible with zero.

[1] LHCb Collaboration, *Performance of flavour tagging algorithms optimised for the analysis of $B_s^0 \to J/\psi\phi$.*, Eur. Phys. J. C 72 (2012) 2022
[2] LHCb Collaboration, *Precision measurement of the B_s^0-$\bar{B}_s^0$ oscillation frequency with the decay $B_s^0 \to D_s^- \pi^+$.*, New J. Phys. 15 (2013) 053021.

[3] LHCb Collaboration, *Measurement of the B^0-$\bar{B}^0$ oscillation frequency Δm_d with the decays $B^0 \rightarrow D^-\pi^+$ and $B^0 \rightarrow J/\psi K^{*0}$.*, Phys. Lett. B 719 (2013) 318-325.

[4] LHCb Collaboration, *Observation of B_s^0-$\bar{B}_s^0$ mixing and measurement of mixing frequencies using semileptonic B decays*, Eur. Phys. J. C 73 (2013) 2655.

[5] LHCb Collaboration, *Measurement of the B^0-$\bar{B}^0$ and B_s^0-$\bar{B}_s^0$ production asymmetries in 7 TeV pp collisions. arXiv:1408.0275* Submitted to Phys. Lett. B

[6] Heavy Flavour Averaging Group, Y. Amhis et al., *Averages of b-hadron, c-hadron and τ lepton properties as of early 2012*, *arXiv:1207.1158, update available online at http://www.slac.stanford.edu/xorg/hfag*