PROCEEDINGS OF SCIENCE

# Flavour tagging and mixing at LHC$b$

**Stefania VECCHI**[*†]
*INFN, Sezione di Ferrara*
*E-mail:* stefania.vecchi@fe.infn.it

We report on the optimization and calibration of the flavour tagging algorithms using the decays $B^0 \to D^{*-}\mu^+\nu_\mu$ , $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$ and $\sim 36$ pb$^{-1}$ of data from the LHC$b$ 2010 physics run. After a data-driven optimization and calibration, the measured effective tagging efficiency $1.99 \pm 0.15\%$ for the opposite-side tagger combination and $2.64 \pm 0.22\%$ for the same-side pion and opposite-side tagger combination. The optimized flavour tagging was used to measure the $B^0_{d/s} - \bar{B}^0_{d/s}$ mixing frequencies using the decays $B^0_d \to D^-\pi^+$ and $B^0_s \to D^-_s(3)\pi^+$. The results are $\Delta m_d$ is $0.499 \pm 0.032 \pm 0.003$ ps$^{-1}$ and $\Delta m_s$ = $17.63 \pm 0.11 \pm 0.04$ ps$^{-1}$.

*The 13th International Conference on B-Physics at Hadron Machines - Beauty2011,*
*April 4-8 2011*
*Amsterdam, The Netherlands*

*Speaker.
†on behalf of the LHC$b$ collaboration

 

PoS(BEAUTY 2011)053

## 1. Introduction

The LHC*b* experiment was mainly designed to study "*B*-physics": in particular to perform precision measurement of *CP* violation in the *B* sector and to study rare *B* decays. With improved results from LHC*b* it will be possible to have a better knowledge of the Standard model (SM) or find indirect evidence of new physics (NP).

The main requirements to achieve these goals are to collect high statistics of $b-$hadron decays in specific channels with low background contamination. For the measurement of *CP* asymmetries in time dependent analysis it is also important to measure the *B* proper-time with good resolution and to be able to identify the initial flavour of the decaying meson (*flavour tagging*).

The LHC*b* experiment and its performances are described in [1] and [2]. The optimization and calibration of the flavour tagging algorithms performed analyzing data from the LHC*b* 2010 physics run and the measurement of the $B_d^0-\bar{B}_d^0$ and $B_s^0-\bar{B}_s^0$ mixing frequencies are presented in this report.

## 2. Flavour Tagging

The identification of the initial flavour of the reconstructed $B_d^0$ and $B_s^0$ meson is a key element for most of the measurements of flavour or *CP* asymmetries, to establish whether the meson contained a $b$ or a $\bar{b}$ quark. This procedure is performed at LHC*b* by means of different flavour tagging algorithms [3]: the Opposite-side (OS) tagger algorithms (muon, electron, and kaon) use the charge of the lepton from semileptonic *b*-hadron decays and the kaon from the $b\to c\to s$ decay chain to define the flavour of the signal *B* meson. Moreover they use the charge of the opposite *b*-decay vertex reconstructed inclusively. The Same-side (SS) tagger algorithms determine directly the flavour of the signal *B* mesons by exploiting the correlation of particles in the fragmentation chain. In $B_d^0$ /$B_s^0$ events, from the fragmentation of a $\bar{b}$ quark, an extra $\bar{d}$ /$\bar{s}$ is available to form a pion/kaon that in a fraction of the cases is charged and identifies the flavour of the signal *B* . Also pions can originate from the decays of excited *B* states. These particles are used in the so called pion/kaon same-side tagger.

For each tagger, the probability of the tag decision to be correct is estimated by means of a *neural network* trained on Monte Carlo events to identify the correct flavour of the signal *b*-meson. These probabilities are then calibrated on data using $B^+\to J/\psi K^+$ control channel.

When more than one tagger is available per event, the decisions of the different taggers are then combined using the mistag probabilities of the contributing taggers. Two possibilities are considered: the combination of OS taggers only, common to all the *b*-hadrons, and the combination of all taggers including SS, which are different for the $B_s^0$ , and $B_d^0$ and $B^+$ cases.

The sensitivity of a measured *CP* asymmetry is directly related to the effective tagging efficiency $\varepsilon_{\rm eff}$ , or tagging power that is defined as: $\varepsilon_{\rm eff}=\varepsilon_{\rm tag}\,(1-2\omega)^2$ where $\varepsilon_{\rm tag}$ is the tagging efficiency, $\omega$ is the mistag fraction (the fraction of tagged events for which a wrong decision was taken). While the tagging efficiency can be measured in any channel from the fraction of events with a tagging decision available, the mistag fraction should be known to be able to measure a *CP* violation asymmetry in a neutral *B* decay. For example $\omega$ can be measured on data using flavour-specific decays, in which the final state uniquely defines the quark/antiquark content of the

| | OS combination | | | SS$\pi$+OS combination | | |
|---|---|---|---|---|---|---|
| channel | $\varepsilon_{\rm tag}$ (%) | $\omega$ (%) | $\varepsilon_{\rm eff}$ (%) | $\varepsilon_{\rm tag}$ (%) | $\omega$ (%) | $\varepsilon_{\rm eff}$ (%) |
| $B^0 \to D^{*-}\mu^+\nu_\mu$ | 18.3±0.2 | 33.6±0.8 | 1.97±0.18 | 28.9±0.2 | 34.2±0.8 | 2.87±0.32 |
| $B^+ \to J/\psi K^+$ | 15.4±0.3 | 32.2±1.2 | 1.97±0.31 | 23.0±0.5 | 33.9±1.1 | 2.38±0.33 |
| $B^0 \to J/\psi K^{*0}$ | 15.8±0.7 | 30.0±6.6 | 2.52±0.82 | 26.1±0.9 | 33.6±5.1 | 2.82±0.87 |

**Table 1:** The flavour tagging performance for the OS and SS$\pi$+OS measured in $B^0 \to D^{*-}\mu^+\nu_\mu$ , $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$ channels. The quoted uncertainties are statistical only.

decaying $b$-hadron. Alternatively the predicted mistag probability ($\eta$) can be used as a proxy of $\omega$ if it is calibrated on data.

The tagging performance was optimized using the data sample collected in 2010 that corresponds to an integrated luminosity of $\sim 36$ pb$^{-1}$. The aim of the optimization was to tune the tagging algorithms in order to maximize the tagging power of the single taggers and of the combination of taggers, to reach the best sensitivity to the $CP$ asymmetry measurements.

The tuning [3] was based on the analysis of the $B^0 \to D^{*-}\mu^+\nu_\mu$ and $B^+ \to J/\psi K^+$ channels, which are the self-tagging exclusive channels with the highest yield. In the first sample, which consists of $\sim 48\,000$ signal events, the mistag can be measured by fitting the time dependent $B^0_d - \bar{B}^0_d$ oscillations. In the $B^+ \to J/\psi K^+$ sample, which consists of $\sim 11\,000$ signal events, the mistag is computed comparing the tag decision with the charge of the final state and counting the number of events with correct or wrong tag that are identified as signal from the fit to the mass distribution.

To cross-check the results of the optimization the $B^0 \to J/\psi K^{*0}$ channel was used. Also in this case the mistag is measured from a fit to the time dependent $B^0_d$ oscillations.

The study of these channels allowed to optimize the performance of the OS and of the SS$\pi$ taggers. The optimization of the SS$K$ tagger could not be performed on 2010 data due to the limited statistics in the control channel $B^0_s \to D^-_s \pi^+$.

The optimized tagging performaces measured in the different control channels are summarized in Table 1. The tagging power, averaged on the three control channels considered, amount to $1.99 \pm 0.15\%$ and $2.64 \pm 0.22\%$ for the OS and SS$\pi$+OS combinations, respectively. The measured mistag fractions of the three channels agree within the statistical uncertainty. These results support the possibility to use the measured mistag fraction in a control channel as input for asymmetry measurements in the analysis of alternative channels. Possible asymmetries of the tagging performance of different $B$ flavour, for example related the different particle/antiparticle interaction with matter or to possible detector asymmetries were checked and found negligible within the present statistical uncertainty.

The tagging optimization procedure also includes the calibration of the mistag probability. For each individual tagger first and then for the OS combinations of taggers, the mistag probability ($\eta$), calculated event by event from the *neural network* output, is calibrated to the measured mistag fraction ($\omega$) using the self-tagged control channel $B^+ \to J/\psi K^+$ . A linear dependence between the measured and the calculated mistag probability for signal events is assumed:

$$\omega = p_0 + p_1 \cdot (\eta - < \eta >)\,, \tag{2.1}$$

where $p_0$ and $p_1$ are free parameters and $<\eta>$ is the mean mistag probability. Deviations from $p_0 =<\eta>$ and $p_1 = 1$ indicate that the calculated mistag probability should be corrected.

The resulting calibration parameters and estimated systematic uncertainties after the calibration are summarized in Table 2. The calibrated value is labelled with $\eta_c$. The mean values of $p_0-<\eta_c>$ and $p_1$ are consistent with 0 and 1 respectively as a result of the calibration performed on the same data sample. The systematic uncertainties are small and statistically limited.

| $B^+ \to J/\psi K^+$ | | | |
|---|---|---|---|
| | $p_0$ | $p_1$ | $<\eta_c>$ |
| OS | 0.338±0.012±0.004 | 1.01±0.12±0.01 | 0.339 |
| SS$\pi$+OS | 0.354±0.010±0.004 | 1.00±0.11±0.01 | 0.354 |

**Table 2:** Calibration parameters for the OS and SS$\pi$+OS taggers with $B^+ \to J/\psi K^+$ signal events after the calibration. The quoted uncertainties are statistical and systematic.

Figure 1 shows the dependency of the measured mistag fraction as a function of the calculated mistag probability after the calibration procedure for the signal events of the same sample used for the calibration. The linear fit superimposed corresponds to the parametrization of Eq.(2.1) and the parameters of Table 2.

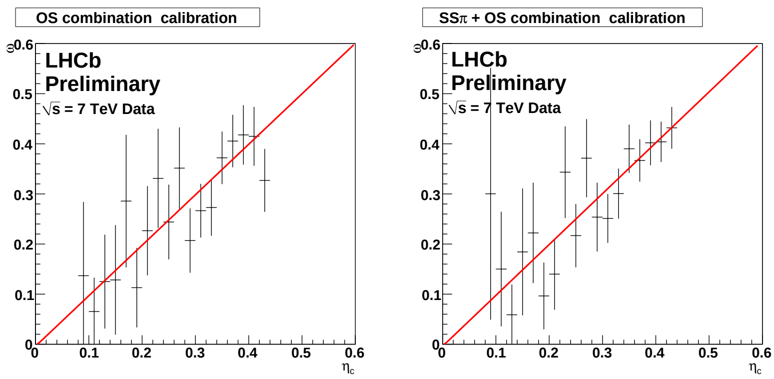


**Figure 1:** Measured mistag fraction ($\omega$) versus calculated mistag probability ($\eta_c$) calibrated on $B^+ \to J/\psi K^+$ signal events for the OS (left) and SS$\pi$+OS (right) combinations. Points with errors are data, the red curves represent the result of the mistag calibration for the signal, corresponding to parameters of Table 2. The data sample is the same used for the mistag calibration.

The calibrated mistag probability was checked on the $B^0 \to J/\psi K^{*0}$ channel [4], fitting the time dependent asymmetry with floating calibration parameters. The results confirm a proper calibration, albeit with very large uncertainties: $p_0 = 0.333 \pm 0.025 \pm 0.003$, $p_1 = 0.71 \pm 0.26 \pm 0.24$ and $<\eta_c>= 0.35$, compatible with expectations.

## 3. Measurement of the $B^0_{d/s} - \bar{B}^0_{d/s}$ mixing frequencies

The flavour tagging power was exploited in the measurement of the $B^0_{d/s} - \bar{B}^0_{d/s}$ mixing frequencies $\Delta m_d$ and $\Delta m_s$ in time dependent analysis of $B_d^0 \to D^- \pi^+$ and $B_s^0 \to D_s^-(3)\pi^+$ respectively [5], [6].

About 6000 events were selected in the $B_d^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ channel from a sample of data corresponding to an integrated luminosity of 36 pb$^{-1}$. The analysis was based on the fit of the reconstructed $B_d^0$ mass and proper time and of the tagging informations. Experimental effects like the proper-time acceptance, due to trigger and selection cuts, or the proper-time resolution were determined from Monte Carlo simulations. The flavour tagging decision and the per-event mistag probability were used in the fit. Since the trigger and the selection of this channel is completely different from the ones of the channel used to calibrate the mistag probability ($B^+ \to J/\psi K^+$ ) the calibration parameters were floated in the fit. The results confirm a proper calibration, albeit with very large uncertainties: $p_0 = 0.313 \pm 0.021 \pm 0.004$, $p_1 = 0.61 \pm 0.20 \pm 0.15$ and $<\eta_c>= 0.328$ for the OS combination, compatible with expectations.

The resulting value of $\Delta m_d$ is $0.499 \pm 0.032 \pm 0.003$ ps$^{-1}$ is consistent with the PDG [7] average value $\Delta m_d = 0.507 \pm 0.005$ ps$^{-1}$, though affected by a large statitical uncertainty.

For the $\Delta m_s$ measurement about 1350 events were selected in the $B_s^0 \to D_s^-(3)\pi^+$ channels, considering several $D_s^-$ decays modes: $D_s^- \to \phi\pi^-$, $K^*K^-$ and $K^+K^-\pi^-$. The simultaneous analysis of the events of the different samples used a per-event proper-time resolution model that was calibrated on data using events with a "prompt" $D_s$ and a random $\pi$ reconstructed. The correction for the proper-time acceptance was determined from Monte Carlo simulations. Like for the measurement of $\Delta m_d$ , the per-event mistag probability was used. In this case, given that the signal is a $B_s^0$ and that the SS$K$ tagging was not available, only the information corresponding to the combination of the OS taggers was considered. The values of the calibration parameters obtained from the $B_d^0 \to D^-\pi^+$ channel were used as input for the similar channel $B_s^0 \to D_s^-\pi^+$ and their uncertainties were propagated accordingly in the fit for the determination of $\Delta m_s$ . The measured mixing frequency $\Delta m_s$ = $17.63 \pm 0.11 \pm 0.04$ ps$^{-1}$ is in very good agreement with the CDF measurement [8] $17.77 \pm 0.10 \pm 0.07$ ps$^{-1}$ and has a similar precision. The likelihood scan and the oscillation plot, obtained folding the data modulo $2\pi/\Delta m_s$, are shown in Figure 2. The significance of the mixing signal is $4.6\sigma$.

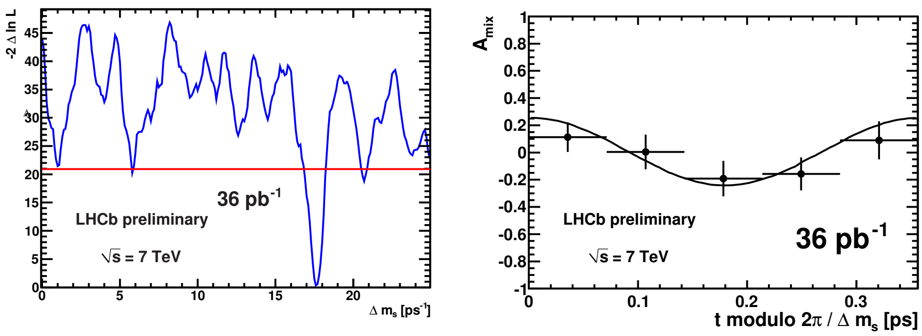


**Figure 2:** Left: likelihood scan for $\Delta m_s$ in the range $[0.0, 25.0]$ ps$^{-1}$. The line at 20.94 indicates the likelihood value evaluated in the limit of infinite mixing frequency. Right: Mixing asymmetry for signal $B_s^0$ candidates as function of proper time modulo $\frac{2\pi}{\Delta m_s}$.

The current systematic uncertainty is dominated by the not yet optimal detector alignment and magnetic field calibration and by the statistically limited precision of the parametrization used to describe the mistag probability and of the proper-time error distributions. Therefore there are good prospects for LHC*b* to improve the precision of $\Delta m_s$ in the near future.

## 4. Conclusions

The LHC*b* experiment collected about 36 $\mathrm{pb}^{-1}$ of data in the 2010 LHC run. Using this data sample it was possible to optimize the performance of the $B$ flavour tagging algorithms and calibrate the predicted mistag probability. The measured tagging power is $1.99 \pm 0.15\%$ for the opposite-side tagger combination and $2.64 \pm 0.22\%$ for the same-side pion and opposite-side tagger combination. The optimized flavour tagging was used in the analysis of $B_d^0 \to D^-\pi^+$ and $B_s^0 \to D_s^-(3)\pi^+$ for the measurement of the $B_{d/s}^0 - \bar{B}_{d/s}^0$ mixing frequencies. The measurement of $\Delta m_d$ is in agreement with the best world average, though with limited statistical precision. The measured value of $\Delta m_s$ $17.63 \pm 0.11 \pm 0.04\ \mathrm{ps}^{-1}$ is in very good agreement with the CDF measurement and a has similar accuracy. These measurements demonstrate that LHC*b* is able to perform flavour tagged time dependent analysis of $CP$ violating $B_{d/s}^0$ decays and perform the world's best measurements in several prominent decay modes by the end of 2011.



## References

[1] LHC*b* collaboration, "The LHCb detector at LHC", Journal of Instrumentation (JINST) 3 (2008) S08005.

[2] N. Harnew, "LHC*b* detector and performance", these proceedings.

[3] LHC*b* collaboration, "Optimization and calibration of the LHC*b* SSavour tagging performance using 2010 data", LHCb-CONF-2011-003

[4] LHC*b* collaboration, "Measurement of $CP$ violation in the time-dependent analysis of $B^0 \to J/\psi K_S^0$ decays with the 2010 data", LHCb-CONF-2011-004.
M. Grabalosa Gandara, "First measurements of sin $2\beta$ at LHC*b* with $B^0 \to J/\psi K_s^0$, these proceedings.

[5] LHC*b* collaboration,"Measurement of $\Delta m_d$ in $B_d^0 \to D^-\pi^+$", LHCb-CONF-2011-010

[6] LHC*b* collaboration, "Measurement of $\Delta m_s$ in the decay $B_s^0 \to D_s^-(K^+K^-\pi^-)(3)\pi$", LHCb-CONF-2011-005.

[7] K. Nakamura *et al.* (Particle Data Group), "Review of particle physics", J. Phys. G 37, 075021 (2010).

[8] A.Abulencia, et al. (CDF collaboration) Phys. Rev. Lett. **97**, 242003 (2006)