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Flavour tagging at LHCb and measurements of $B^0 - \bar{B}^0$ meson oscillations

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The identification of the flavour of reconstructed B_d^0 and B_s^0 mesons at production is necessary for the measurements of oscillations and time-dependent CP asymmetries. The opposite-side flavour tagging algorithms have been developed using simulated events and have been optimized and calibrated with different flavour specific B decays with 1 fb^{-1} of data collected in pp collisions at LHC with $\sqrt{s} = 7$ TeV during the 2011 physics run. Using flavour tagging LHCb has performed, among others, measurements of the $B_{d/s}^0 - \bar{B}_{d/s}^0$ mixing frequencies Δm_d and Δm_s, of the CP violating B_s^0 mixing phase ϕ_s, and of $\sin(2\beta)$.

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1. Introduction

The LHC*b* experiment is a forward spectrometer operating at the Large Hadron Collider, optimized for the study of B and D hadron decays. During the 2011 data taking, thanks to the excellent performances of the LHC machine and of the LHC*b* detector, the experiment collected 1.0 fb^{-1} of $\sqrt{s} = 7$ TeV pp collisions, which provided unprecedented large samples of heavy-flavoured hadrons. These data samples contributed to improve tests of the Standard Model and to search for indirect evidence of new physics.

In the following, a selection of the recent LHC*b* measurement of the B mixing and time dependent CP asymmetries is presented. For these measurements, the identification of the flavour of reconstructed B_d^0 and B_s^0 mesons at production (*flavour tagging*) is necessary. A description of the algorithms, of the methods used to optimize and calibrate their performances using data, and a summary of the results obtained are presented.

2. Flavour Tagging algorithms

The identification of the initial flavour of a reconstructed B meson is a fundamental ingredient for measurements of B^0 oscillations and time-dependent CP asymmetries. At LHC*b* it is performed in different ways:

- looking at the decay of the "other" $b-$hadron produced in the event (Opposite Side tagging, OS) by using either the charge of the lepton (μ, e) from semileptonic b decays, the charge of the kaon from the $b \to c \to s$ decay chain, or the charge of the inclusive secondary vertex reconstructed from b-hadron decay products;

- another possibility is to exploit the particle produced in the fragmentation chain of the b-quark that leads to the signal B (Same Side tagging, SS): a pion for B_d^0 or B^+ (also produced from B^{**} decays) and a kaon for B_s^0. When the associated meson is charged the initial flavour of the signal can be defined.

The tagging algorithms (taggers) have been developed using simulated events. In the case of single-tagger algorithms, they utilize the kinematic (momentum, p, and transverse momentum, p_{T}) and geometric properties (impact parameter or impact parameter significance with respect to the vertex that originated the signal B , PV, and with respect to possible additional vertices, PU) of the tagging particle, as well as information useful for particle identification. Moreover, SS tagging algorithms exploit the correlation between the tagging particle and the signal B by using additional kinematic quantities, such as the distance in pseudorapidity, the invariant mass of the combination, etc. In the case of the OS vertex tagging algorithm, a displaced secondary vertex is built combining tracks not originated from the PV or the PU vertices that have a common origin.

In addition to the tag decision, the tagging algorithms provide an estimate of the probability of mis-tagging the event (η) by means of a *neural network* that combines kinematical and geometrical information of the tagging particle, of the B signal and some general information on the reconstructed event (for example multiplicity of tracks and interactions in the event). The neural network is trained on Monte Carlo events to recognize the correct tag. Then the mistag probability is calibrated using data. In case more than one tagging algorithm gives a response, each of the decisions and mistag probabilities are combined to determine the final decision and probability. The combined probability can be exploited on an event-by-event basis to assign larger weights to the events with low mistag and thus to increase the overall significance of an asymmetry measurement.

3. Performance, optimization and calibration of the flavour tagging

The performance of the tagging algorithms are determined by the tagging efficiency, $\varepsilon_{\rm tag}$, which represents the fraction of events with a tagging decision available, and by the dilution, D, related to the mistag fraction, ω, ($D = 1-2\omega$). ω defines the fraction of events with a wrong tagging decision. The sensitivity to a measured CP asymmetry is directly related to the effective tagging efficiency, $\varepsilon_{\rm eff}$, or tagging power, that represents the effective statistical reduction of the sample size and is defined as: $\varepsilon_{\rm eff} = \varepsilon_{\rm tag}D^2 = \varepsilon_{\rm tag}(1-2\omega)^2$. Due to the possibility of using the wrong particle to tag the event, the tagging performance is not perfect. Moreover OS tagging algorithms have an intrinsic dilution, due to the possibility that the "other" B is neutral and oscillates.

The tagging performance can be measured in data using flavour-specific B decays as control channels, such as $B^+ \to J/\psi K^+$, $B^0 \to D^{*-}\mu^+\nu_\mu$ and $B^0 \to J/\psi K^{*0}$. For charged mesons, the mistag fraction is obtained by comparing the tagging decision with the flavour of the signal B, while for the neutral mesons it is determined by fitting the B^0 flavour oscillations as a function of the decay time. By analyzing the control channels it was possible to find the tagging selection cuts that maximize the tagging power on data [1] and to calibrate the predicted mistag η to the measured mistag fraction, ω. A linear dependence between ω and η is used, as suggested by the data distribution: $\omega = p_0 + p_1 \cdot (\eta - \langle\eta\rangle)$, where p_0 and p_1 are free parameters, and $\langle\eta\rangle$ is the mean predicted mistag. Deviations from $p_0 = \langle\eta\rangle$ and $p_1 = 1$ indicate that the predicted mistag should be corrected.

The optimization of the tagging performance and the calibration are applied to each tagger. In addition, due to the correlation among taggers, mainly between the OS vertex and the other OS taggers, the OS combined probability needs to be calibrated with data. For the OS, the reference control channel for optimization and calibration is $B^+ \to J/\psi K^+$, while the other channels are used as cross checks. Figure 1 shows the result of the calibration of the OS combined mistag probability, after the calibration procedure. The parameters corresponding to the linear fit are:

$$p_0 = 0.392 \pm 0.002(\text{stat.}) \pm 0.009(\text{syst.}) \quad p_1 = 1.035 \pm 0.021(\text{stat.}) \pm 0.012(\text{syst.}) \quad \langle\eta_c\rangle = 0.391,$$

consistent with a calibrated mistag probability η_c. The systematic uncertainties on the calibration parameters were evaluated by comparing the tagging performances of different decay channels (e.g. in $B^0 \to J/\psi K^{*0}$, as shown in Fig. 1, right), on B^+ and B^- samples separately and during different running periods. The performance of the OS tagging in different control channels with 0.37fb^{-1} are summarized in Table 1. Differences in the trigger and off-line selection are responsible for the different performances among channels.

4. Measurements relying on flavour tagging

The calibrated mistag probability was used in several time-dependent asymmetry measurements involving different B decay channels.

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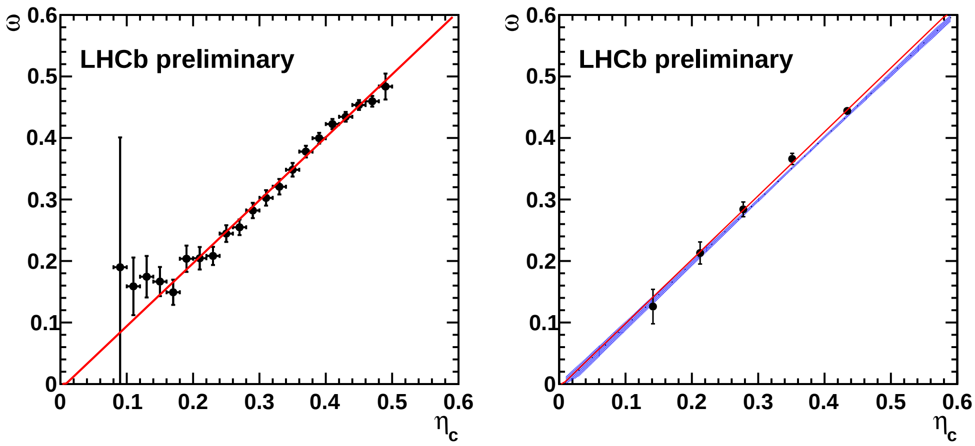

Figure 1: Measured mistag fraction (ω) versus predicted mistag probability after calibration (η_c) for signal $B^+ \to J/\psi K^+$ (left) and $B^0 \to J/\psi K^{*0}$ with 1fb^{-1} data sample. In each plot, the solid (red) line represents the result of a linear fit to the data set. In the right plot, the the shaded (blue) area represent the $\pm 1\sigma$ variation of the calibration from the $B^+ \to J/\psi K^+$ channel.

	$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K^{*0}$	$B^0 \to D^{*-}\mu^+\nu_\mu$
$\varepsilon_{\rm tag}D^2$ (%)	2.10±0.08±0.24	2.09±0.09±0.24	2.53±0.10±0.27

Table 1: Performance of the OS tagging in different control channels, determined using the event-by-event mistag probability calibrated using the $B^+ \to J/\psi K^+$ channel and a data sample corresponding to 0.37fb^{-1}.

Analyzing the decays $B^0_d \to D^-\pi^+$ in a data sample corresponding to about 36 pb^{-1} taken in 2011, LHC*b* measured the B^0_d mixing frequency: $\Delta m_d = (0.499 \pm 0.032(\text{stat.}) \pm 0.003(\text{syst.}))$ ps^{-1} [2]. For this measurement a first version of the optimization and calibration of the flavour tagging was used [3]. It was obtained on the corresponding statistics available at that time and also included the contribution of the SS pion tagger of about 0.7%, for a total tagging power of $\varepsilon_{\rm tag}D^2 = (4.3 \pm 1.0)\%$. Figure 2 (left) shows the mixing asymmetry as a function of the B^0_d decay time. The oscillation pattern is clearly visible; its amplitude is determined mainly by the dilution due to tagging. With a similar sample of $B^0_d \to J/\psi K^0_s$ decays LHC*b* measured $\sin(2\beta) = 0.53^{+0.28}_{-0.29}(\text{stat.}) \pm 0.05(\text{syst.})$ [6]. In this case the total tagging power was $\varepsilon_{\rm tag}D^2 = (2.82 \pm 0.87)\%$. These results are consistent with the world averages, though they have limited statistical precisions. Since the date of the conference, these two measurements have been updated using the whole data sample collected in 2011, corresponding to an integrated luminosity of about 1 fb^{-1}. The new results confirm the previous ones with a much better accuracy [7], [8].

The B^0_s mixing frequency was also measured using a sample 0.34 fb^{-1} and the $B^0_s \to D^-_s\pi^+$ decays. For this measurement a first optimization of the SS kaon tagger using prompt D^-_s decays was also used, contributing to about 1.3% to the total tagging power $\varepsilon_{\rm tag}D^2 = (4.3 \pm 1.0)\%$. This result is in agreement with the previous result from CDF [5] and supersedes it in precision: $\Delta m_s = (17.725 \pm 0.041(\text{stat.}) \pm 0.026(\text{syst.}))$ ps^{-1} [4]. Figure 2 shows the mixing asymmetry as a function of the B^0_s decay time modulo $2\pi/\Delta m_s$, so that the oscillation pattern becomes more clear.

In this case the oscillation amplitude is determined both by the dilution due to tagging and the dilution due to the decay time resolution.

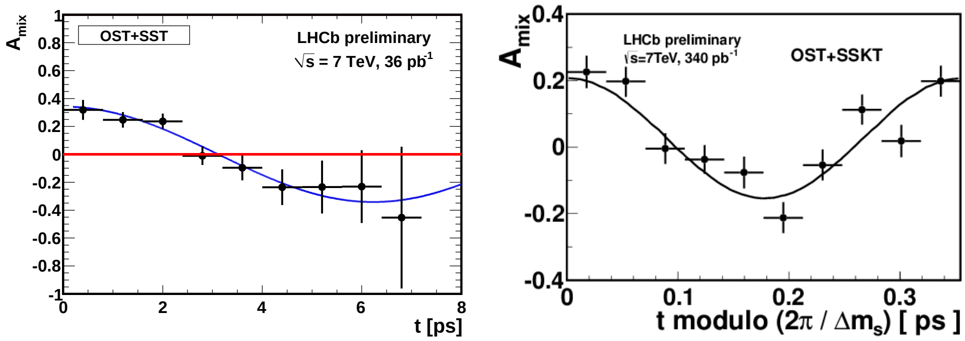

Figure 2: Mixing asymmetry for $B_d^0 \to D^-\pi^+$(left) and $B_s^0 \to D_s^-\pi^+$(right) candidates as a function of the decay time (modulo $2\pi/\Delta m_s$ in the right plot). Both the results correspond to an early optimization of OS and SS taggers.

One of the most remarkable contributions of flavour tagging to a *CP* measurement by LHC*b* is the determination of the B_s^0 mixing phase ϕ_s in the analyses of the $B_s^0 \to J/\psi\phi$ and the $B_s^0 \to J/\psi\pi^+\pi^-$ decay channels with a data sample of 1 fb^{-1}. Thanks to the large yield of signal events, the low background contamination, the excellent decay time resolution and the flavour tagging, LHC*b* has measured ϕ_s and $\Delta\Gamma_s$ with the best precision: $\phi_s = -0.001 \pm 0.101(\text{stat.}) \pm 0.027(\text{syst.})$, $\Delta\Gamma_s = (0.116 \pm 0.018(\text{stat.}) \pm 0.006(\text{syst.}))$ ps^{-1} [9], [10], [11]. These results are in good agreement with the predictions of the Standard Model. For these measurements only the OS tagging combination was considered. It correspond to a tagging power of about 2.1%.

5. Conclusions

The identification of the initial flavour of a reconstructed signal B^0 meson is a fundamental ingredient for measurements of B^0 oscillations and time-dependent *CP* asymmetries that was successfully employed in several measurements by LHC*b*. Using flavour-specific decay channels it was possible to measure, optimize and calibrate the performance of flavour tagging algorithms on data. The measured tagging power for the combination of the opposite side taggers is 2.1–3.5%, depending on the decay channel. Same side taggers were also used in some analyses: the additional tagging power given by the SS pion tagger is about 0.7%, while for the SS kaon tagger is about 1.3%, after a preliminary optimization using prompt D_s decays.

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