

Flavour tagging performance in LHCb

Marc Grabalosa Gándara (*on behalf of the LHCb Collaboration*)

Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona,
Av. Diagonal 647, 08028 Barcelona, Spain

E-mail: marc.grabalosa.gandara@cern.ch

Abstract. To do precise CP violation measurements, the best possible determination of the flavour of the B-meson is necessary. This report summarizes the flavour tagging performances for the LHCb experiment. The flavour tagging is obtained through a combination of several methods, based on different signatures. The use of control channels, which are decays to flavour-specific final states, will allow to determine the wrong tag fraction ω (the probability of a tag to be wrong), which can be used as an input for the determination of CKM unitarity triangle angles.

1. Introduction

The LHCb is a second generation precision B physics experiment coming after B-Factories and Tevatron. It has been designed to study CP Violation and flavour oscillations in the B sector, as well as rare B decays. For these studies one needs to determine the flavour at the production of the reconstructed B mesons, in other words, it is necessary to establish whether the meson contained a b or a \bar{b} quark. This procedure is known as *flavour tagging*.

Tagging algorithms can be classified in two groups: same side (SS) and opposite side (OS) algorithms. SS algorithms exploit the correlation of the charge of mesons produced in the fragmentation chain with the original flavour of the signal B , *i.e.*, the B decay of interest. OS algorithms exploit the flavour anti-correlation between the B hadrons produced in the same event, by doing partial reconstruction of a flavour-specific final state of the accompanying b-hadron (the tagger B).

The LHCb has excellent tracking ($\delta p/p = 0.35\%$ to 0.55%) and vertexing ($\sim 10\mu m$ in transverse plane and $\sim 60\mu m$ in z) systems, as well as a good particle identification (PID) which is very important to distinguish between kaons and pions. It has by design a forward geometry, with a 0.3 rad polar angle acceptance, as $b\bar{b}$ pairs are basically produced in the beam direction. The LHCb will run at a lower luminosity than the other LHC experiments ($2 \cdot 10^{32} cm^{-2}s^{-1}$), in order to keep the number of primary interaction vertices close to one.

The statistical uncertainty on the measured CP asymmetries is directly related to the effective tagging efficiency [1], defined as

$$\varepsilon_{eff} = \varepsilon_{tag} D^2 = \varepsilon_{tag} (1 - 2\omega)^2 \quad (1)$$

where ε_{tag} is the tagging efficiency (probability that the tagging algorithm gives an answer), D the dilution term, and ω is the wrong tag fraction (the probability of the tagging assignment to be wrong), calculated as

$$\varepsilon_{tag} = \frac{N_R + N_W}{N_R + N_W + N_U} \quad \omega = \frac{N_W}{N_R + N_W} \quad (2)$$

with N_R , N_W and N_U being the number of correctly tagged, incorrectly tagged, and untagged events, respectively.

2. Flavour tagging algorithms in LHCb

The identification of the initial flavour of the reconstructed B meson, which is necessary for the CP asymmetry measurement, is performed at LHCb by means of different flavour tagging algorithms [2]. A brief description follows.

2.1. Opposite side tagging

Information from the tagger B meson in the event is obtained from the leptonic charge sign in semileptonic decays, from the charge of a kaon from the $b \rightarrow c \rightarrow s$ decay chain, or from the charge of the tracks from a secondary vertex reconstructed in the event.

The selection of tagging leptons and kaons is based on kinematical and topological cuts and particle identification, all tuned to maximize ϵ_{eff} . Transverse momentum (p_T) and momentum (p) cuts are applied. In the case of kaons, also cuts on impact parameter significance (IPS) are applied in order to reduce the large background from kaons from the primary vertex as seen in table 1. If several tagger candidate tracks exist of the same type, the one with highest p_T is selected.

Table 1. Cuts for the opposite side B tagging candidate.

	p_T (GeV/c)	p (GeV/c)	IP/ σ
μ^\pm	> 1.1		
e^\pm	> 1.1	> 4	
K^\pm	> 0.4	> 4	> 3.5

Particle identification algorithms provide an efficiency (purity) of 85% (75%), 75% (85%) and 80% (80%) for muons, electrons and kaons, respectively [3]. Typical performances for the opposite side taggers are shown in table 2 for two specific B mesons decay channels.

Table 2. Flavour tagging performance for two hadronic B decays.

Tagger	B^0 ($B^0 \rightarrow \pi^+\pi^-$)			B_s ($B_s \rightarrow D_s K$)		
	ϵ_{tag} (%)	ω (%)	ϵ_{eff} (%)	ϵ_{tag} (%)	ω (%)	ϵ_{eff} (%)
OS μ^\pm	8.7	32	1.14 ± 0.07	11.9	29.3	1.94 ± 0.09
OS e^\pm	3.6	33	0.39 ± 0.04	3.3	32.4	0.41 ± 0.04
OS K^\pm	28	36	2.09 ± 0.73	17.2	32.7	2.05 ± 0.10
OS vertex	22	39	1.01 ± 0.07	35.5	39.6	1.53 ± 0.09
SS π^\pm/K^\pm	15	39	0.73 ± 0.06	29.3	33.6	3.14 ± 0.12
Total	51	34	5.05 ± 0.22	62.6	31.2	8.83 ± 0.18

The opposite side B is also examined by reconstructing an additional secondary vertex. The algorithm finds a vertex in 45% of the triggered events. On average, 84% of the tracks in the vertex correspond to the decay of the tagger B.

This secondary vertex-finding algorithm uses charged tracks after kinematic and geometrical cuts, to build all possible double vertices. Then, the combination with best two-seed vertex likelihood value is selected. After this, other tracks are added to this seed vertex based on their kinematical properties (IPS, p_T). Finally a "weighted charge" of the vertex is computed by assigning to each track a normalized weight based on its p_T . Only if the summed weighted vertex charge is significantly different from zero, a flavour tag is assigned by assuming that the sign of the vertex charge corresponds to that of the b quark. The typical performance of the tagger are $\varepsilon_{tag} \simeq 35.5\%$, $\omega \simeq 39.6\%$ and $\varepsilon_{eff} \simeq 1.5\%$, as shown in table 2.

2.2. Same side tagging

The charges of the hadrons which are close in momentum space to the signal B provide information about the B flavour at production. In the fragmentation cascade, the accompanying quark in the B meson gives rise to a quark with opposite charge conjugation, which tends to form a pion (kaon) for B^0 (B_s^0) with a definite charge sign. For example, if a B_s^0 is produced in the fragmentation of a \bar{b} quark, an extra \bar{s} is available to form a hadron, which leads to a charged K in about 50% of the cases. In the case of B^0 , around 10% of the mesons are expected to be produced via the decay of a B^{**} state, accompanied by a decay pion which has the same charge sign as that of the B^{**} meson.

The selection of pion and kaon candidates requires a p_T (p) greater than 0.2 (2) and 0.6 (4) GeV/ c respectively. The IPS of the particle is required to be lower than 3 and 3.5 respectively, to avoid candidates from secondary interactions. In addition, rapidity and azimuthal angle cuts are applied in order to select pions or kaons which are produced close in momentum space to the signal B^0 hadron (see Table 3).

Table 3. Cuts for the kinematical properties of the signal B and SS taggers (pion and kaon). Here $\Delta\eta$ is the rapidity difference and $\Delta\phi$ is the difference in azimuthal angle between the candidates.

	$\Delta\eta$	$\Delta\phi$	$M(B\pi^\pm(K^\pm)) - M(B)$
π^\pm	$\Delta R < 1.2$		$< 1 \text{ GeV}/c^2$
K^\pm	< 1	< 1.1	$< 2.5 \text{ GeV}/c^2$

The performance of the same side taggers pions and kaons for the B_d and B_s channels respectively are indicated in table 2.

3. Combination of taggers and tagging performance in LHCb

The final tagging decision on the production flavour of the reconstructed B candidate can be taken following different strategies, combining all the taggers to obtain a final decision. The combination method reported in [2] allows to obtain an ω for each event from a neural net (NN) output. For each event, a wrong tag probability is computed for each of the tagger candidates present. The neural network has as input several properties of the tagger (for example its p_T and IPS) and it has been trained on independent MC samples. Each tagger gives an ω_i as a function of the NN output, comparing right and wrong tags as it is shown in figure 1.

Then, the global tag of the event is obtained by the combination of the taggers using their individual right-tag probabilities given by $(1 - \omega_i)$. Finally, the overall ω of the event is computed by the combination of such probabilities. To calculate the final combined effective efficiency, events with similar ω , according to the NN output, are grouped together in 5 categories (which

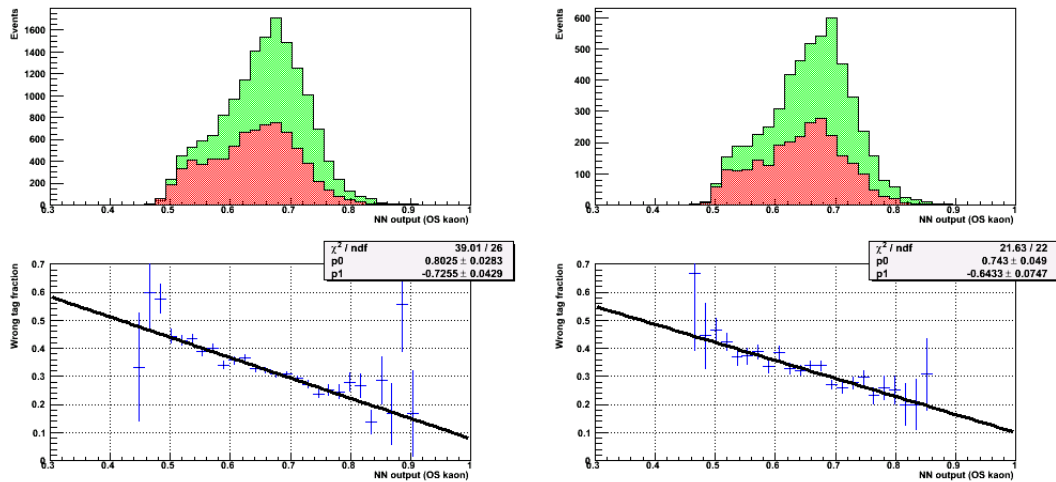


Figure 1. Mistag rate as a function of the NN output for the opposite side kaon tagger, for $B^+ \rightarrow J/\psi K^+$ (left) and $B_d \rightarrow J/\psi K_s$ (right).

will be treated separately in the CP fits), in order to improve the global performance of tagging, as shown in figure 2.

Another possibility is currently being investigated where the decision can be made by examining all possible particle identification combinations, obtaining an ω for each PID combination. In the combined particle identification method, we can obtain an ω for each event according to the taggers which are present in a given event (either OS or SS). Each combination will give an ω as an output, as the combinations had been sorted previously with MC studies in decreasing order of mistag rate. This method will be considered as a backup solution, as it gives a lower performance. The global ϵ_{eff} is about 20% lower than would be obtained through the combination based on the neural net method.

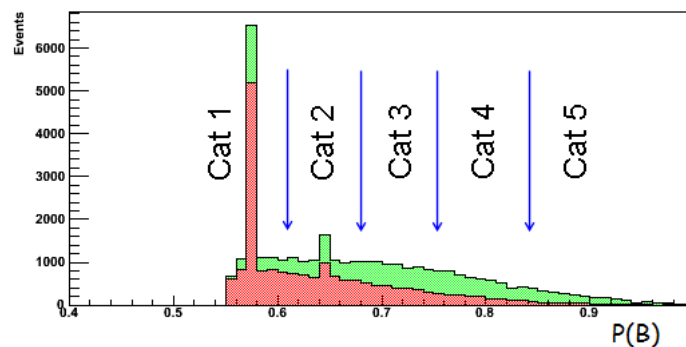


Figure 2. Probability of an event to contain a b quark. The light shaded histogram corresponds to right tagged events, in dark the wrong tagged events. Arrows indicate the binning into 5 tagging categories.

The tagging performances for each individual tagger, as well as for the combination, are shown in table 2 for two typical hadronic decays of B^0 and B_s^0 mesons. Note that the overall ϵ_{eff} is significantly higher for B_s channels, as a consequence of the fact that the SS kaon selection

is purer than that of SS pions. On the other hand, there are also some significant differences between the performance of individual OS taggers for B^0 and B_s^0 due to the decay topology and trigger effects.

4. Control channels

The wrong tag fraction ω enters as a first order correction in the measurement of CP asymmetries [1], so its uncertainty on ω has to be kept as small as possible. MC simulation is not considered fully reliable due to large uncertainties on parameters such as the relative contribution of $b\bar{b}$ production mechanisms and the average event multiplicity, which strongly affect the tagging performance. The calibration of ω has therefore to be performed by studying real data on control channels.

In the case of control channels with B^+/B^- decays, ω can be directly extracted by comparison of the tagging algorithm with self-tagging control channels, where the flavour is uniquely determined from the charge sign of the decay products. For the case of B^0 and B_s^0 decays, ω must be extracted by fitting the known oscillation pattern.

Table 4. Performance expected from a selection of control channels in LHCb, for $2fb^{-1}$ of data, corresponding to one year of data taking.

Channel	Yield / $2fb^{-1}$	B/S	$\delta\omega/\omega(2fb^{-1})$
$B^0 \rightarrow J/\psi(\mu\mu)K^{*0}(K^+\pi^-)$	0.7 M	0.2	0.2%
$B_s^0 \rightarrow D_s^+\pi^-$	0.12 M	0.4	1.2%
$B^+ \rightarrow J/\psi(\mu\mu)K^+$	1.7 M	0.4	0.15%
$B^+ \rightarrow D^0\pi^+$	1.0 M	0.1	0.20%
$B^+ \rightarrow D^{0(*)}\mu^+\nu$	2.4 M	0.7	0.12%
$B_s^0 \rightarrow D_s^{(*)}\mu^+\nu$	2.0 M	0.6	1%

Table 4 shows the annual yield, the background to signal ratio (B/S), and the expected relative statistical uncertainty on ω for a number of control channels that have been considered in LHCb. The reachable statistical accuracy on the determination of ω from this list of control channels is estimated to be sufficient for the CP fits requirements.

In the case of the $B^+ \rightarrow J/\psi K^+$ channel, the measurement of ω_i for all opposite taggers can be obtained directly from data, and those ω_i can be then used in other channels, such as $B_d \rightarrow J/\psi K_s$. Figure 1 illustrates the dependence of ω on the NN output for the above-mentioned channels, which appears to be compatible within available statistics.

4.1. Mistag extraction in $\sin(2\beta)$ measurement

One of the first measurements requiring flavour tagging in B mesons will be $\sin 2\beta$ from $B^0 \rightarrow J/\psi(\mu\mu)K_s$ as a benchmark to demonstrate LHCb capability in CP asymmetry measurements.

For the evaluation of the mistag rate, the following strategy, using $B^+ \rightarrow J/\psi(\mu\mu)K^+$ and $B^0 \rightarrow J/\psi(\mu\mu)K^{*0}$ as control channels, is foreseen.

- With $B^+ \rightarrow J/\psi(\mu\mu)K^+$ events, for each tagger, the dependence of the mistag rate on the kinematical properties of the tagger will be determined, and combined into a single probability function per event.
- This function will be used to subdivide $B^0 \rightarrow J/\psi(\mu\mu)K^{*0}$ and $B^0 \rightarrow J/\psi(\mu\mu)K_s$ events into 5 samples of decreasing mistag rate (tagging categories).

- Flavour oscillations in the $B^0 \rightarrow J/\psi K^{*0}$ channel will be fitted as function of proper time, in each of the 5 categories mentioned above, in order to measure the mistag rate in each of them. These categories will then be used in the CP-violation fit for the $B^0 \rightarrow J/\psi K_s$ channel.

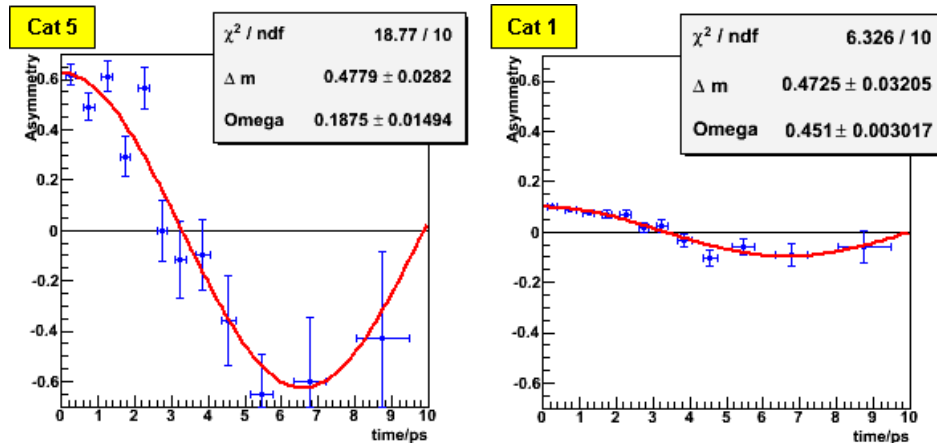


Figure 3. Fit to flavour oscillation asymmetry of $B^0 \rightarrow J/\psi K_0^*$ for best and worst mistag fraction categories. Only signal events are considered.

Figure 3 shows the flavour oscillations of $B^0 \rightarrow J/\psi K^{*0}$ in two of the 5 categories. The two plots correspond to the best and the worse tagging category with a fitted omega value of 18.8% and 45.5% respectively. One can crosscheck the result of the fit using the MC truth information, obtaining the mistag rates which are shown in table 5, which are also compatible with the corresponding numbers obtained for the $B^0 \rightarrow J/\psi K_s$ channel.

The expected precision in the measurement of $\sin(2\beta)$ at LHCb is 0.02 for $2fb^{-1}$ of data, assuming an uncertainty on ω of $\delta\omega/\omega \leq 1\%$ [4].

Table 5. Expected ω for the 5 categories in $B^0 \rightarrow J/\psi K_s$ and in its control channel ($B^0 \rightarrow J/\psi K^{*0}$). Results from proper time fit are compatible to MC results.

Category	MC		Proper time
	$B^0 \rightarrow J/\psi K_s$	$B^0 \rightarrow J/\psi K^{*0}$	$B^0 \rightarrow J/\psi K^{*0}$
$\omega_1(\%)$	45.4 ± 0.3	44.8 ± 0.2	45.1 ± 0.3
$\omega_2(\%)$	35.7 ± 0.7	36.8 ± 0.5	36.8 ± 0.7
$\omega_3(\%)$	28.3 ± 0.9	29.7 ± 0.7	29.8 ± 0.9
$\omega_4(\%)$	23.5 ± 1.3	23.7 ± 0.9	24.0 ± 1.3
$\omega_5(\%)$	17.3 ± 1.5	18.8 ± 1.1	18.8 ± 1.5

5. Conclusions

Flavour tagging is a fundamental ingredient for B physics measurements in LHCb. We briefly described here the different algorithms and methods used in LHCb for flavour tagging, as well as the strategy to measure ω directly from data without MC simulation, with the required statistical accuracy, taking into account many possible effects. The algorithms developed for

flavour tagging in LHCb give an effective tagging efficiency which ranges from 6% to 9.5% and from 4% to 5% for B_s^0 and B^0 decay channels respectively.

References

- [1] H. G. Moser, A. Roussarie, Mathematical methods for B0 anti-B0 oscillation analyses, Nucl. Instr. Meth. **A384** (1997) 491.
- [2] M. Calvi, O. Leroy and M. Musy, Flavour Tagging Algorithms and Performance in LHCb, CERN-LHCb-2007-058.
- [3] LHCb Collaboration, LHCb reoptimized detector design and performance, CERN-LHCC-2003-030.
- [4] S. Amato, J. R. T. de Mello Neto, C. Nunes, The LHCb sensitivity to $\sin 2\beta$ from $B^0 \rightarrow J/\psi(\mu\mu)K_s^0$ asymmetry, CERN-LHCb-2003-107.