Measurements of $\Delta m_d$, $\Delta m_s$, and $\sin 2\beta$
with LHCb

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1 Introduction

The LHCb experiment [1] at the Large Hadron Collider (LHC) at CERN is dedicated to the study of $b$ and $c$ flavour physics. It exploits the large production cross-section of $b$ and $c$ hadrons in LHC’s $pp$ collisions. The measurement of time-dependent decay rates in decays of neutral $b$ mesons, i.e. $B^0$ and the $B^0_s$ mesons, gives access to a variety of observables that are linked to the Cabibbo-Kobayashi-Maskawa quark mixing matrix [2, 3]. The LHCb detector provides good decay time and impact parameter resolution, and an excellent particle identification system to efficiently reconstruct exclusive $B$ decay final states.

Precision measurements of the oscillation frequencies $\Delta m_d$ of $B^0-\bar{B}^0$ and $\Delta m_s$ of $B^0_s-\bar{B}^0_s$ meson mixing allow to constrain the apex of the CKM triangle while a measurement of the time-dependent $CP$-asymmetry in decays of $B^0 \rightarrow J/\psi K^0_S$ gives access to the CKM angle $\beta$. Hence, these measurements give valuable input to tests of the unitarity of the CKM matrix.

2 Flavour tagging in LHCb

Measurements of time-dependent asymmetries in decays of neutral $B$ mesons require flavour tagging, i.e. the knowledge on the production flavour of the reconstructed decay. As $b$ quarks are predominantly produced as $b\bar{b}$ pairs at LHCb, two classes of flavour tagging algorithms are utilised in LHCb [4, 5]. The same-side taggers reconstruct the charge of the hadronisation remnant of the signal $B$ meson, i.e. a $K^\pm$ from the $B^0_s$ hadronisation or a $\pi^\pm$ for the $B^0/B^\pm$. The opposite-side taggers reconstruct the flavour of the non-signal $b$ hadron by identifying the charge of its decay products, like leptons from semileptonic decays or kaons from $b \rightarrow c \rightarrow s$ decays.
Inefficiencies in the tagging, e.g. the choice of wrong tagging particle tracks, have to be measured in the context of CP measurements. The tagging efficiency $\epsilon_{tag}$ is the fraction of events with a tagging decision, the mistag fraction $\omega$ represents the probability for an incorrectly assigned tag. The overall tagging power that reflects the statistical precision is given by $\epsilon_{tag}(1 - 2\omega)^2$.

The mistag fraction $\omega$ is calibrated on the self-tagging channel $B^+ \to J/\psi K^+$ for the opposite-side taggers. The tagging power of the combined opposite side taggers is found to be around 2.3%, while the same-side tagger for $B_0^s$ mesons (same-side kaon tagger) adds about 1% of tagging power and the same-side tagger for $B^0/B^+$ mesons (same-side pion tagger) adds around 0.5%.

3 Neutral $B$ meson mixing

Measurements of neutral $B$ meson mixing require a decay time dependent analysis of the mixing behaviour. Reconstructed $B$ candidates are categorised by their mixing state: they are defined as unmixed (mixed) if their production flavour matches (does not match) the flavour at decay. This knowledge can be used to determine the oscillation frequency $\Delta m_q$, with $q = d$ ($q = s$) in the $B^0$ ($B_0^s$) system, by using the time-dependent mixing asymmetry

$$A_{mix}(t) = \frac{N_{unmixed}(t) - N_{mixed}(t)}{N_{unmixed}(t) + N_{mixed}(t)} = \cos (\Delta m_q t) ,$$

where $N_{(un)mixed}(t)$ is the number of (un)mixed candidates at $B$ decay time $t$. Due to the imperfections in tagging, the accessible amplitude of the asymmetry is reduced by $(1 - 2\omega)$. The amplitude is additionally damped due to the decay time resolution. At LHCb, this dampening has to be considered for measurements involving $B_0^s$ mixing but is negligible in $B^0$ mixing related analyses.

3.1 Measurement of $\Delta m_s$ in $B_0^s \to D_s^-\pi^+$ decays

The measurement of the $B_0^s$ oscillation frequency $\Delta m_s$ at LHCb is performed using 340 pb$^{-1}$ of data collected in $\sqrt{s} = 7$ TeV pp collisions [6,7]. Around 9100 $B_0^s \to D_s^-\pi^+$ decays with subsequent decays of $D_s^- \to \phi\pi^- (\phi \to K^+K^-)$, $D_s^- \to K^{*0}(892)K^-$ ($K^{*0}(892) \to K^+\pi^-$), and the non-resonant $D_s^- \to K^+K^-\pi^-$ are reconstructed. The analysis is performed using the combination of opposite-side taggers and the same-side kaon tagger as well as using only the same-side kaon tagger. The resulting projection of the time-dependent mixing asymmetry is shown in Fig. A decay time resolution of 45 fs was measured. The analysis yields the most precise measurement of $\Delta m_s$ with

$$\Delta m_s = 17.725 \pm 0.041 \text{ (stat.)} \pm 0.026 \text{ (syst.)} \text{ps}^{-1},$$
where the largest systematic uncertainty is related to the uncertainty of the length scale.

\[
A_{\text{mix}}(t \mod (2\pi/\Delta m_s)) \quad \text{[ps]}
\]

Figure 1: Mixing asymmetry for \(B^0_s\) signal candidates as a function of decay time, modulo \((2\pi/\Delta m_s)\), for the fit using only the same-side tagger (left) and the combination of opposite- and same-side taggers (right). The fitted signal asymmetries are superimposed.

3.2 Measurement of \(\Delta m_d\) in \(B^0 \to J/\psi K^{*0}\) and \(B^0 \to D^- \pi^+\) decays

The basic analysis strategy for measuring \(\Delta m_d\) is very similar to the analysis strategy for the measurement of \(\Delta m_s\), however, as the \(B^0 - \overline{B}^0\) oscillations are about 35 times slower than \(B^0_s - \overline{B}^0_s\) oscillations, the decay time resolution has an inferior role in this analysis. From a dataset of 1.0 fb\(^{-1}\) collected at \(\sqrt{s} = 7\) TeV pp collisions about 88,000 decays of \(B^0 \to D^- \pi^+\) (\(D^- \to K^+ \pi^- \pi^-\)) and approximately 39,000 decays of \(B^0 \to J/\psi K^{*0}(892)\) (\(J/\psi \to \mu^- \mu^+, K^{*0}(892) \to K^+ \pi^-\)) are reconstructed. A combination of the opposite-side taggers with the same-side pion tagger is used. The multi-dimensional fit to the distributions of the reconstructed mass and the decay time yields

\[
\Delta m_d(B^0 \to D^- \pi^+) = 0.5178 \pm 0.0061 \text{ (stat.)} \pm 0.0037 \text{ (syst.)} \text{ps}^{-1}\] and
\[
\Delta m_d(B^0 \to J/\psi K^{*0}) = 0.5096 \pm 0.0114 \text{ (stat.)} \pm 0.0022 \text{ (syst.)} \text{ps}^{-1}.
\]

The mixing asymmetries in the two channels and the resulting fit projections are shown in Fig. 2. The largest systematic uncertainties are related to the limited knowledge of the decay time distributions for the background components in the fit.
Combining both channels results in the currently most precise single measurement of this parameter,

$$\Delta m_d = 0.5156 \pm 0.0051 \text{ (stat.)} \pm 0.0033 \text{ (syst.)} \text{ps}^{-1},$$
in full agreement with previous measurements \([9]\).

Figure 2: Raw mixing asymmetry (black points) for (left) \(B^0 \rightarrow D^- \pi^+\) and (right) \(B^0 \rightarrow J/\psi K^{*0}\) candidates. The solid black line is the projection of the mixing asymmetry of the combined PDF.

4 Measurement of \(\sin 2\beta\) in \(B^0 \rightarrow J/\psi K_S^0\) decays

The CKM observable \(\sin 2\beta\) is one of the most precisely measured CP parameters. Its current world average is \(\sin 2\beta = 0.67 \pm 0.02 \pm 0.01\) \([9]\), where the most precise measurements were performed by the \(B\) factories Belle and BaBar.

For the LHCb measurement of \(\sin 2\beta\) \([10]\) around 8,000 \(B^0 \rightarrow J/\psi K_S^0\) (\(J/\psi \rightarrow \mu^- \mu^+\), \(K_S^0 \rightarrow \pi^+ \pi^-\)) decays with tagging information from the opposite side taggers are reconstructed in a data sample of 1 fb\(^{-1}\). The parameter \(\sin 2\beta\) is determined by measuring the time-dependent CP asymmetry

$$\mathcal{A}_{J/\psi K_S^0}(t) = \frac{\Gamma(B^0(t) \rightarrow J/\psi K_S^0) - \Gamma(B^0(t) \rightarrow J/\psi K_S^0)}{\Gamma(B^0(t) \rightarrow J/\psi K_S^0) + \Gamma(B^0(t) \rightarrow J/\psi K_S^0)} = S_{J/\psi K_S^0} \sin(\Delta m_d t) - C_{J/\psi K_S^0} \cos(\Delta m_d t),$$

where \(S_{J/\psi K_S^0} = \sqrt{1 - C_{J/\psi K_S^0}^2} \sin 2\beta\). A multi-dimensional fit of the data is performed. Fig. 3 shows the background corrected asymmetry and the fit projection. The
Figure 3: Time-dependent asymmetry \((N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})\). Here, \(N_{B^0}\) (\(N_{\bar{B}^0}\)) is the number of \(B^0 \to J/\psi K_S^0\) decays with a \(B^0\) (\(\bar{B}^0\)) flavour tag. The data points are obtained with the \(sPlot\) \([11]\) technique, assigning signal weights to the events based on a fit to the reconstructed mass distributions. The solid curve is the signal projection of the PDF. The green shaded band corresponds to the one standard deviation statistical error.

The measurement yields

\[
S_{J/\psi K_S^0} = 0.73 \pm 0.07 \text{ (stat)} \pm 0.04 \text{ (syst)},
\]

\[
C_{J/\psi K_S^0} = 0.03 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst)},
\]

where the largest systematic uncertainties are related to the uncertainty of the flavour tagging calibration and the background parameterisation. This is the first significant measurement of \(CP\) violation in \(B^0 \to J/\psi K_S^0\) decays at a hadron collider. The result is in agreement with the world averages \([9]\).

5 Conclusion

LHCb has collected 1.0 fb\(^{-1}\) of data from \(pp\) collisions at a centre-of-mass energy of \(\sqrt{s} = 7\) TeV. The time-dependent measurements of \(\Delta m_s\), \(\Delta m_d\), and \(\sin 2\beta\) with this dataset demonstrate the excellent performance of LHCb in terms of signal selection, decay time resolution, and flavour tagging.
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