Precision measurement of $\Delta m_d$ using semi-leptonic decays at LHCb

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Using the full data set collected during Run I, LHCb measured the oscillation frequency of $B^0$ mesons ($\Delta m_d$). The measurement is performed in two semi-leptonic decays: $B^0 \rightarrow D^- \mu^+ \nu_{\mu}$ and $B^0 \rightarrow D^+ \mu^+ \nu_{\mu}$, where $D^- \rightarrow K^+ \pi^- \pi^-$, $D^+ \rightarrow D^0 (\rightarrow K^+ \pi^-) \pi^-$ modes were exploited. The combined measurement of $\Delta m_d$ is given as: $\Delta m_d = (503.6 \pm 2.0 \text{(stat)} \pm 1.3 \text{(syst)}) \text{ns}^{-1}$. This is the most precise measurement of $\Delta m_d$ to date.

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Particle-antiparticle mixing occurs in the neutral $B^0$-$\bar{B}^0$ system. The $B^0$ meson is a superposition of two different mass eigenstates, the difference in mass between the two is denoted $\Delta m_d$, the "mixing frequency". The decay rates of $B^0$ meson (whether it mixed or not to $\bar{B}^0$) into the final state ($f$) depend on the decay time of the $B^0$ meson $t$:

$$N(\text{unmixed}) = N(B^0 \to f)(t) \propto e^{-\Gamma t} (1 + \cos(\Delta m_d t)),$$

$$N(\text{mixed}) = N(B^0 \to \bar{B}^0 \to f)(t) \propto e^{-\Gamma t} (1 - \cos(\Delta m_d t)),$$

$$A(t) = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} \propto \cos(\Delta m_d t) \quad (1)$$

The Time-dependent asymmetry, $A(t)$, provides a direct way to measure $\Delta m_d$ experimentally. In the Standard Model (SM), $B^0$-$\bar{B}^0$ mixing is allowed through an exchange of a W boson in the box diagram represented in Figure 1. Latest $\Delta m_d$ measurements are performed at Belle [1], BaBar [2] and at LHCb [3]. The World average for $\Delta m_d$ reported by the HFAG group [13] is $(510 \pm 3) \text{ ns}^{-1}$. $\Delta m_d$ is related to CKM matrix elements $V_{td}, V_{tb}$ in SM. A precise $\Delta m_d$ measurement would therefore contribute to the determination of these CKM elements.

LHCb is a single-arm spectrometer covering the forward region in pseudo-rapidity ($2 < \eta < 5$) [5]. Copious number of b quarks are produced in pairs at LHCb, thereby allowing a precise study of CP violation and rare decays in the beauty sector.

During Run I, LHCb collected a data sample which corresponds to an integrated luminosity of $3 \text{ fb}^{-1}$ of proton-proton collisions taken in 2011 at $\sqrt{s} = 7 \text{ TeV}$ and in 2012 at $\sqrt{s} = 8 \text{ TeV}$. This sample is used to perform the measurement of $\Delta m_d$ discussed in this paper. The full analysis is reported in Ref. [6].

High branching fractions and excellent muon identification at LHCb make $B^0 \to D^{(*)-} \mu^+ \nu_\mu$ decays ideal to measure $\Delta m_d$ with very high statistical precision. Two main ingredients are necessary to perform $\Delta m_d$ measurement: the determination of the mixing state of the $B^0$ meson and the reconstruction of its decay time.

The $B^0 \to D^{(*)-} \mu^+ \nu_\mu$ are flavour-specific decays therefore the mixing state of $B^0$ is known: the flavour of $B^0$ at decay is inferred from $\mu$ charge, while the flavour at production is obtained from the Flavour Tagging algorithm (FT) at LHCb [7], the latter uses the correlation in charge of the b$\bar{b}$ pair to infer the flavour of the $B^0$ meson. FT algorithm assigns a flavour to the $B^0$ meson ($q = \pm 1$) and estimates a probability of mis-tagging the flavour.

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1Ignoring the small CP violation effects and decay width of the mass eigenstates
2but will be influenced by large theoretical uncertainty [4]
The momentum of the $B^0$ meson decaying semi-leptonically is unknown due to the missing neutrino in the final state, therefore its decay time is unknown too. $B^0$ momentum is corrected using $k$-factor method \cite{8} where a correction factor is determined from simulation. The correction in data is determined by parameterising the $k$-factor as a function of the invariant mass of the $B^0$ meson in simulation.

Tight requirements on the transverse momentum ($p_T$) and impact parameter (IP) with respect to primary vertex are applied to reconstructed particles in the final states. A Multi-variate classifier is developed using a Boosted Decision Tree (BDT) \cite{9, 10} to reject background events from $B^+ \to D^{(*)} - \mu^+ \pi^+ + \nu_{\mu} X$ decays where $B^+$ proceeds to a similar final state as the signal with additional charged pions dominated by higher charm resonances. The BDT uses isolation criteria of charged tracks in the final state and Kinematics of higher charm resonances to distinguish between signal and $B^+ \to D^{(*)} - \mu^+ \pi^+ + \nu_{\mu} X$ decays. In addition to reducing the background levels, the BDT distribution provides a handle to estimate the fraction of the remaining $B^+ \to D^{(*)} - \mu^+ \pi^+ + \nu_{\mu} X$ background ($f_{B^+}$) \cite{6}. The data sample is divided into 4 categories selected according to their mistag probability in order to increase the statistical uncertainty on $\Delta m_d$.

A fit to the invariant mass distribution of $D^{(*)-}$ and the mass difference between the $D^{*-}$ and $D^0$ for the $B^0 \to D^{*-} \mu^+ \nu_{\mu}$ channel. A subtraction of combinatorial background is achieved using sPlot technique \cite{11}, each candidate is assigned a weight (called sWeight) that corresponds to the probability of being $B \to D^{(*)-}$ candidate, Figure 2 shows the projections of the fits performed on these mass distributions.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{$D^-$ invariant mass distributions in 2012 data for the $B^0 \to D^- \mu^+ \nu_{\mu}$ candidates (Left), $D^0$ invariant mass distributions(Centre) and $m_{D^{*-}} - m_{K^0}$ (Right) for $B^0 \to D^{*-} \mu^+ \nu_{\mu}$ candidates. Projections of the fit function are superimposed for (blue line) the full PDF and its components: (red line) signal $D^-$ ($D^{*-}$) from $B$ decays and (green line) combinatorial background. The corresponding distributions of the normalized residuals of data with respect to the fit (pulls) are shown below each plot.}
\end{figure}

$\Delta m_d$ parameter is determined by a binned likelihood fit to the time-dependent asymmetry using the sWeighted events. Fits are performed in each decay mode and each year separately. The PDF used in the likelihood fits is:

$$\mathcal{P}(t,q) = (1 - f_{B^+})\mathcal{I}(t,q) + f_{B^+}\mathcal{D}^+(t,q),$$

(2)
where the time distribution for signal and background are given by
\[
\mathcal{S}(t, q) = \mathcal{N} \left( e^{-\Gamma_d^2} (1 + q(1 - 2\omega_{\text{sig}}) \cos \Delta m_d t) \otimes R(t)_{\text{sig}} \otimes F_{\text{sig}}(k) \right) \times a(t),
\]
\[
\mathcal{B}^+(t, q) = \mathcal{N}_{B^+} \left( e^{-\Gamma_u^2} \left( \frac{1+q}{2} - q\omega_{B^+} \right) \otimes R_u(t) \otimes F_{B^+}(k) \right) \times a(t),
\]
where \( \mathcal{N} \) and \( \mathcal{N}_{B^+} \) are normalization factors, \( \Gamma_d = 1/\tau_{B^0} \) and \( \Gamma_u = 1/\tau_{B^+} \) are fixed in the fit, mistag fractions for signal and \( B^+ \) components, \( \omega_{\text{sig}} \) and \( \omega_{B^+} \), are free in the fit, \( R_{\text{sig},B^+}(t) \) account for the detector decay time resolution, \( F_{\text{sig},B^+}(k) \) account for the decay time resolution which induced by k-factor method, finally \( a(t) \) time-dependent acceptance function. Figure 3 shows the time-dependent asymmetry projections per tagging category for \( B^0 \to D^{(*)} \mu^+ \nu_\mu \) decays.

![Figure 3](image)

**Figure 3:** Mixing asymmetry projections in 2012 data in the four tagging categories for \( B^0 \to D^- \mu^+ \nu_\mu \) (Left) and \( B^0 \to D^{*-} \mu^+ \nu_\mu \) (Right). The average mistag per category is increasing when going from (a) to (d).

Extensive studies were carried out to evaluate the systematic uncertainties on \( \Delta m_d \). Each systematic uncertainty is evaluated using a large number of parametric simulations. Knowledge of momentum scale calibration [12] at LHCb experiment is found to cause a systematic uncertainty of 0.8 ns\(^{-1}\), which represents the largest contribution to the systematic uncertainty for this analysis. A significant systematic uncertainty comes from the assumption on the decay time acceptance of \( B^+ \) backgrounds. Effects from mis-modeling of decay time resolution functions (k-factor, detector effects) are evaluated by varying the semi-leptonic branching fractions in simulation samples and accounting for differences between data and simulation. The correlation between the decay time and the \( F_{\text{sig}}(k) \) distribution induces a bias of about 4 ns\(^{-1}\) on \( \Delta m_d \). Uncertainties on this bias are propagated to \( \Delta m_d \) as systematic uncertainty. Possible \( B^0_s \) and \( \Lambda_b \) decays into the same final state as the signal are neglected in 3, this has small systematic uncertainty on \( \Delta m_d \). Neglecting CP violation and \( \Delta \Gamma \) in 1 is found to have no systematic uncertainty.

The combined value of \( \Delta m_d \) measurement is obtained by averaging individual measurements of \( \Delta m_d \) from \( B^0 \to D^- \mu^+ \nu_\mu \) and \( B^0 \to D^{*-} \mu^+ \nu_\mu \) in 2011 and 2012 samples, giving:
\[
\Delta m_d = (503.6 \pm 2.0(\text{stat}) \pm 1.3(\text{syst})) \text{ns}^{-1}.
\]
This represents the most precise measurement of $\Delta m_d$ to date. The HFAG group performed a new world average including this measurement $^3$, it is found to be: $\Delta m_d(\text{world}) = (505.5 \pm 2.0)\,\text{ns}^{-1}$.

References

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$^3$the new average was not available publicly at the time of the conference, it will appear soon in Ref. [13]