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Precision measurement of Δm_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 (Δm_d). The measurement is performed in two semi-leptonic decays: $B^0 \to D^- \mu^+ \nu_\mu$ and $B^0 \to D^{*-} \mu^+ \nu_\mu$, where $D^- \to K^+ \pi^- \pi^-, D^{*-} \to \overline{D}^0 (\to K^+ \pi^-) \pi^-$ modes were exploited. The combined measurement of Δm_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 measurment of Δm_d to date.

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Particle-antiparticle mixing occurs in the neutral B^0-$\overline{B}^0$ system. The B^0 meson ($\bar{b}d$) is a superposition of two different mass eigenstates, the difference in mass between the two is denoted Δm_d, the "mixing frequency". The decay rates of B^0 meson (whether it mixed or not to $\overline{B}^0$) into the final state (f) depend on the decay time of the B^0 meson [1]:

$$N(unmixed) = N(B^0 \to f)(t) \propto e^{-\Gamma t}\,(1+\cos(\Delta m_d t))\;,$$
$$N(mixed) = N(B^0 \to \overline{B}^0 \to f)(t) \propto e^{-\Gamma t}\,(1-\cos(\Delta m_d t))\;,$$
$$A(t) = \frac{N(unmixed)-N(mixed)}{N(unmixed)+N(mixed)} \propto \cos(\Delta m_d t) \tag{1}$$

The Time-dependent asymmetry, $A(t)$, provides a direct way to measure Δm_d experimentally. In the Standard Model (SM), B^0-$\overline{B}^0$ mixing is allowed through an exchange of a W boson in the box diagram represented in Figure 1. Latest Δm_d measurements are performed at Belle [1], BaBar [2]

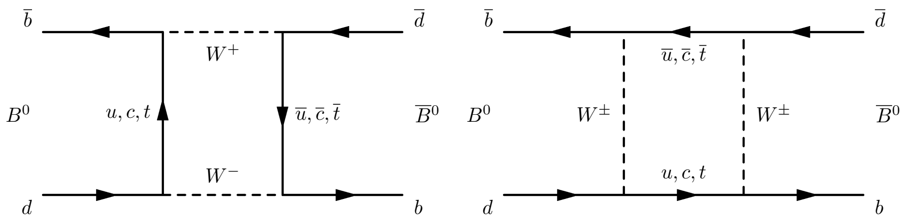

Figure 1: Feynman loop diagrams representing the mixing phenomena in Standard Model.

and at LHCb [3]. The World average for Δm_d reported by the HFAG group [13] is $(510\pm3)\,\text{ns}^{-1}$. Δm_d is related to CKM matrix elements $V_{\text{td}}, V_{\text{tb}}$ in SM. A precise Δm_d measurement would therefore contribute to the determination of these CKM elements [2].

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 Δm_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 Δm_d with very high statistical precision. Two main ingredients are necessary to perform Δm_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 μ 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 ($q = \pm1$) and estimates a probability of mis-tagging the flavour.

[1] ignoring the small CP violation effects and decay width of the mass eigenstates

[2] but 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 [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) [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^+}) [6]. The data sample is divided into 4 categories selected according to their mistag probability in order to increase the statistical uncertainty on Δm_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 [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.

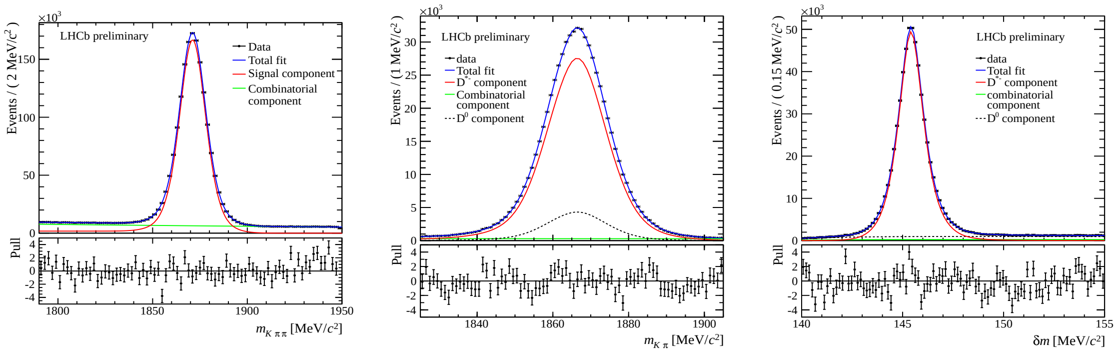

Figure 2: D^- invariant mass distributions in 2012 data for the $B^0 \to D^-\mu^+\nu_\mu$ candidates (Left), D^0 invariant mass distributions(Centre) and $m_{D^{*-}} - m_{D^0}$ (Right) for $B^0 \to D^{*-}\mu^+\nu_\mu$ candidates. Projections of the fit function are superimposed for (blue line) the full 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.

Δm_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:

$$\mathscr{P}(t,q) = (1 - f_{B^+})\mathscr{S}(t,q) + f_{B^+}\mathscr{B}^+(t,q), \tag{2}$$

where the time distribution for signal and background are given by

$$\mathscr{S}(t,q) = \mathscr{N}\left(e^{-\Gamma_d t}\left(1+q(1-2\omega_{\text{sig}})\cos\Delta m_d t\right)\otimes R(t)_{\text{sig}}\otimes F_{\text{sig}}(k)\right)\times a(t),$$
$$\mathscr{B}^{+}(t,q) = \mathscr{N}_{\mathrm{B}^+}\left(e^{-\Gamma_u t}\left(\frac{1+q}{2}-q\omega_{\mathrm{B}^+}\right)\otimes R_{\mathrm{B}^+}(t)\otimes F_{\mathrm{B}^+}(k)\right)\times a(t), \quad (3)$$

where $\mathscr{N}$ and $\mathscr{N}_{\mathrm{B}^+}$ are normalization factors, $\Gamma_{\mathrm{d}} = 1/\tau_{\mathrm{B}^0}$ and $\Gamma_u = 1/\tau_{\mathrm{B}^+}$ are fixed in the fit, mistag fractions for signal and B^+components, ω_{sig} and ω_{B^+}, are free in the fit, $R_{\text{sig},\mathrm{B}^+}(t)$ account for the detector decay time resolution, $F_{\text{sig},\mathrm{B}^+}(k)$ 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 $\mathrm{B}^0 \to \mathrm{D}^{(*)-}\mu^+\nu_\mu$ decays.

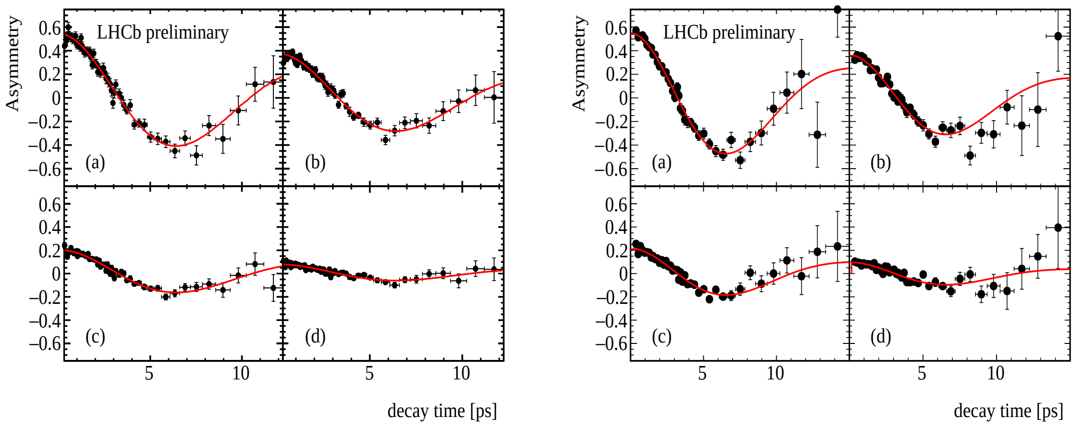

Figure 3: Mixing asymmetry projections in 2012 data in the four tagging categories for $\mathrm{B}^0 \to \mathrm{D}^-\mu^+\nu_\mu$ (Left) and $\mathrm{B}^0 \to \mathrm{D}^{*-}\mu^+\nu_\mu$ (Right). The average mistag per category is increasing when going from (a) to (d)

Extensive studies were carried out to evaluate the systematic uncertainties on Δm_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 $0.8\,\text{ns}^{-1}$, 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 $4\,\text{ns}^{-1}$ on Δm_d. Uncertainties on this bias are propagated to Δm_d as systematic uncertainty. Possible B^0_s and Λ_b decays into the same final state as the signal are neglected in 3, this has small systematic uncertainty on Δm_d. Neglecting CP violation and $\Delta\Gamma$ in 1 is found to have no systematic uncertainty.

The combined value of Δm_d measurement is obtained by averaging individual measurements of Δm_d from $\mathrm{B}^0 \to \mathrm{D}^-\mu^+\nu_\mu$ and $\mathrm{B}^0 \to \mathrm{D}^{*-}\mu^+\nu_\mu$ in 2011 and 2012 samples, giving:

$$\Delta m_d = (503.6 \pm 2.0(\text{stat}) \pm 1.3(\text{syst}))\,\text{ns}^{-1}.$$

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This represents the most precise measurement of Δm_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

[1] BELLE Collaboration, K. Abe et al., Improved measurement of CP-violation parameters $\sin 2\phi(1)$ and $|\lambda|$, B meson lifetimes, and B0 -anti-B0 mixing parameter Δm_d Phys. Rev. D71 (2005) 072003;

[2] BaBar Collaboration, B. Aubert et al., Measurement of the B^0 lifetime and the B^0-$\overline{B}^0$ oscillation frequency using partially reconstructed $B^0 \to D^{*-}\mu^+\nu_\mu$ Phys. Rev. D73 (2006) 012004;

[3] LHCb collaboration, R. Aaij et al., Measurement of the B^0-$\overline{B}^0$ oscillation frequency Δm_d with the decays $B^0 \to D^-\pi^+$ and $B^0 \to J/\psi K^{*0}$, Phys. Lett. B719, 318(2013);

[4] J. Charles, et al., CKMfitter Group, Eur. Phys. J. C 41 (2005) 1, http://dx.doi.org/10.1140/epjc/s2005-02169-1, arXiv:hep-ph/0406184;

[5] LHCb collaboration, A. A. Alves Jr. et al., The LHCb detector at the LHC, JINST 3 (2008) S08005

[6] The LHCb collaboration, R. Aaij et al., A precise measurement of the B^0 meson oscillation frequency, LHCb-CONF-2015-003;

[7] LHCb collaboration, R. Aaij et al., Opposite-side flavour tagging of B mesons at the LHCb experiment, Eur. Phys. J. C72 (2012) 2022

[8] G. A. Giurgiu, B Flavor Tagging Calibration and Search for B_s^0 oscillations in Semileptonic Decays with the CDF Detector at Fermilab, FERMILAB-THESIS-2005-41;

[9] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, Classification and regression trees, Wadsworth international group, Belmont, California, USA, 1984.

[10] R. E. Schapire and Y. Freund, A decision-theoretic generalization of on-line learning and an application to boosting, Jour. Comp. and Syst. Sc. 55 (1997) 119

[11] M. Pivk and F. R. Le Diberder, sPlot: A statistical tool to unfold data distributions, Nucl. Instrum. Meth. A555 (2005) 356

[12] LHCb collaboration, R. Aaij et al., Precision measurement of the B_s^0 oscillation frequency in the decay $B_s^0 \to D_s^-\pi^+$, New J. Phys. 15 (2013) 053021,arXiv:1304.4741.;

[13] Y. Amhis et al., Averages of b-hadron, c-hadron, and tau-lepton properties as of summer 2014, arXiv:1412.7515, http://www.slac.stanford.edu/xorg/hfag/ ;

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