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Measurements of $\Delta m_{d,s}$ and $\Delta\Gamma_d$ at LHCb.

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In this proceedings the latest measurements of the mixing properties of the neutral B mesons performed by the LHCb collaboration are presented. These includes the most precise measurements of the mixing frequencies Δm_d and Δm_s and the measurement of the decay width difference between the two mass eigenstates $B^0_{d,L}$ and $\bar{B}^0_{d,H}$ mesons, $\Delta\Gamma_d$. The implications of these measurements to the determination of the CKM matrix elements $|V_{ts}|$ and $|V_{td}|$ are also mentioned.

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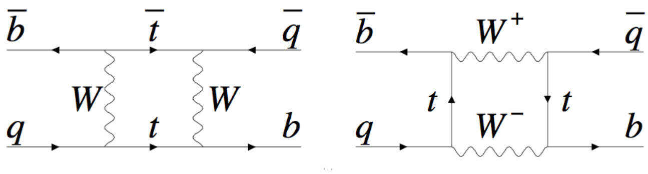

Figure 1: Dominant box diagrams for the $B^0 \leftrightarrow \bar{B}^0$ transitions.

In the Standard Model (SM) neutral B mesons (B_q^0, with $q = d,s$) can mix with their antiparticles through $\Delta F = 2$ transitions represented by the box diagrams shown in Fig 1. The properties of the mass eigenstates, $B_{q,H}$ and $B_{q,L}$, such as the mass difference, Δm_q, and the decay width difference, $\Delta\Gamma_q$, depend on the elements of the CKM matrix according to the following expressions [1]:

$$\begin{aligned}\Delta m_q &\propto m_W^2 m_{B_q} \hat{\mathscr{B}}_{B_q} f_{B_q}^2 (V_{tq}^* V_{tb})^2, \qquad q = d,s \qquad (1)\\ \Delta\Gamma_q &\propto m_b^2 m_{B_q} \hat{\mathscr{B}}_{B_q} f_{B_q}^2 \left((V_{tq}^* V_{tb})^2 + V_{tq}^* V_{tb} V_{cq}^* V_{cb} \mathscr{O}(m_c^2/m_b^2) + (V_{cq}^* V_{cb})^2 \mathscr{O}(m_c^4/m_b^4)\right),\end{aligned}$$

where m_W, m_{B_q}, m_c and m_b are the masses of the W-boson, B_q-meson and c and b-quarks, respectively. The terms $\hat{\mathscr{B}}_{B_q} f_{B_q}^2$ are hadronic matrix elements that are computed with Lattice QCD techniques. Currently, the computational precision of such terms limits the precision of the CKM matrix elements determination from Eq. 1. Better constraints on the ratio $|V_{ts}|^2/|V_{td}|^2$ are achieved from the $\Delta m_s/\Delta m_d$ ratio, given that some of the theoretical uncertainties related to the $\hat{\mathscr{B}}_{B_q} f_{B_q}^2$ terms cancel.

In the following the most recent LHCb measurements of Δm_d, Δm_s and $\Delta\Gamma_d$ are presented.

1. Measurement of the $B_q^0 - \bar{B}_q^0$ mixing frequency

The best precision for the measurement of the $B_q^0 - \bar{B}_q^0$ mixing frequency Δm_q is achieved by fitting the time dependent mixing asymmetry in the decay of a B_q^0 meson to a flavour specific final state[1], which is proportional to $\cos(\Delta m_q t)$. This measurement requires an accurate determination of the B decay time, t, and the identification of the flavour of the neutral B meson at production (*flavour tagging*). The statistical significance of an asymmetry measurement is driven by the event statistics and signal purity, the decay time resolution σ_t, and the tagging effective efficiency $\varepsilon_{\text{tag}}^{\text{eff}} \equiv \varepsilon_{tag}(1-2\omega)^2$, given by a combination of the efficiency, ε_{tag}, and the mistag fraction, ω. Typical values at LHCb are: $\sigma_t = 45-55$ fs and $\varepsilon_{\text{tag}}^{\text{eff}} = 3-6\%$, depending on the reconstruction channel.

1.1 Measurement of Δm_d

The most precise LHCb measurement of Δm_d [2] exploits the full Run I statistics (corresponding to an integrated luminosity of 3 fb^{-1}) and the large branching ratios of semileptonic decays $B^0 \to D^- \mu^+ \nu_\mu$[2] and $B^0 \to D^{*-} \mu^+ \nu_\mu$, that are efficiently selected online by the muon trigger. For both channels, a high level of signal purity is achieved by selecting events in which a $D^{(*)-}$ candidate is reconstructed in its decay to $K^-\pi^+\pi^-$ final state and forms a common vertex with

[1]A flavour specific is a final state accessible only by one of the B flavour eigenstates.

[2]Inclusion of charge conjugated modes is implicit in the text.

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a μ^+, displaced from the primary vertex (PV). The main sources of background are B^+ decays to $D^{(*)-}\pi^+\mu^+\nu_\mu$, that differs from the signal final state only from the presence of an additional charged pion and random combination of tracks in the event. Background due to D^0 from B decays associated with a random π^- is also present in the case of $D^{*-}\mu^+\nu_\mu$ channel. A suppression of the B^+ background is applied by means of a multivariate selection based on a Boosted Decision Tree (BDT) in order to reduce the systematic uncertainty on Δm_d. The BDT is trained on simulated samples of signal and $B^+ \to D^{*-}\pi^+\mu^+\nu_\mu$ decays. The BDT output is used both to reject background and to determine the remaining background fraction, which amounts to about 6 and 3% of the signal for the $B^0 \to D^-\mu^+\nu_\mu$ and $B^0 \to D^{*-}\mu^+\nu_\mu$ channels, respectively. In total the signal yields are about 1.6M and 0.8M for the two channels, respectively.

The reconstruction of the B^0 decay time is determined from the measurement of the decay length, L, and the B momentum, p_B, as $t = (M_B \cdot L)/(p_B \cdot c)$, where M_B is the nominal B mass and c the speed of light. The B momentum is obtained by scaling the reconstructed momentum p_B^{rec} by an average correction factor k, evaluated using simulation, which accounts for the missing neutrino: $p_B = p_B^{\text{rec}}/k$. The remaining large event-by-event fluctuations are responsible for the limited decay time resolution, which is properly accounted by the fit. The identification of the B^0 flavour at production relies on several Opposite-side tagging algorithms (OST) that exploit the decays of the b hadron produced opposite to the signal [3]. To gain in statistical sensitivity, the samples are split in 4 categories on increasing mistag fraction ω. The measured effective tagging efficiency is about 2.4%

The fit strategy proceeds as follows. First, $D^{(*)-}$ mesons from semileptonic B^0 or B^+ decays are disentangled from the remaining background by a fit to the invariant mass distributions of the selected candidates. Then, the mixing frequency Δm_d is determined by a fit to the B^0 decay time distributions of mixed and unmixed candidates weighted for the signal *sWeights* determined in the previous step exploiting the cancellation of the background by means of the *sPlot* procedure [4].

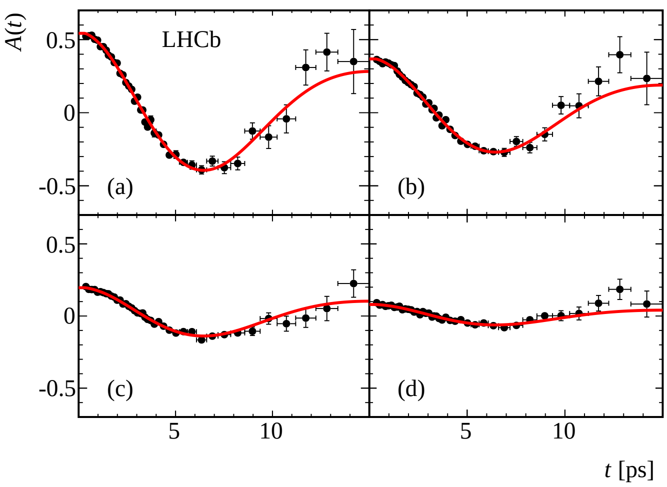

Figure 2: Mixing asymmetry for the 2012 $B^0 \to D^-\mu^+\nu_\mu$ sample in the four tagging categories.

Signal and B^+ contributions are described by the corresponding decay rate parameterisations,

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each one convolved with a resolution model that accounts for the time resolution and multiplied by an acceptance function that describes the effect of the trigger and offline selection and reconstruction. The resolution models and the acceptance functions are extracted from simulation and from a combination of data and simulation, respectively. The fit is performed simultaneously on the four tagging categories but separately for the two decays modes and year of data taking (2011 and 2012). Figure 2 show the mixing asymmetries in the four tagging categories for the 2012 $B^0 \to D^- \mu^+ \nu_\mu$ sample analysed. The mixing amplitude decreases from Fig 2a) to Fig 2d) as a consequence of the increased average mistag $\langle\omega\rangle$ of the four tagging categories: $A(t) \propto (1-2\langle\omega\rangle)\cos(\Delta m_d t)$.

The four independent determinations of Δm_d are combined by means of a weighted average that also accounts for the systematic uncertainties, mainly due to to the contamination of B^+ background, the k-factor correction and other fit-related uncertainties. The result is $\Delta m_d = (505.0 \pm 2.1 \pm 1.0)\,\mathrm{ns}^{-1}$, which represents the most precise determination of Δm_d and dominates the new world average, (506.4 ± 1.9) ns^{-1} [5].

1.2 Measurement of Δm_s

The most precise LHCb measurement of Δm_s [6] exploits 1 fb^{-1} of Run I statistics (corresponding to 2011 data taking) and the flavour specific decay $B_s^0 \to D_s^- \pi^+$, reconstructed in five D_s decay modes: three $KK\pi$ ($\phi\pi$, K^*K and non-resonant $KK\pi$), $K\pi\pi$ and $\pi\pi\pi$. Multivariate selections are applied both at trigger level and offline to optimise the signal selection and to discriminate the signal from the background. The selected B_s^0 candidates consist of mainly signal, b-hadron decays in which a final state particle is mis-identified or not reconstructed, and random combination of tracks. The B_s^0 decay time is determined from the measured decay length, invariant mass and momentum, similarly to what discussed in Sec. 1.1. An excellent average decay time resolution $\langle\sigma_t\rangle$ of 44 fs is achieved in this decay channel, thanks to the excellent performances of the LHCb tracking and vertex detectors and the fact that the decay is fully reconstructed. It allows to resolve the fast $B_s^0 - \bar{B}_s^0$ oscillations and to measure Δm_s precisely. To determine the flavour of the B_s^0 meson at production, the same-side kaon (SSKT) tagging algorithm is used in addition to OST ones [7]. The SSKT exploits the charged kaons produced in association with the signal B_s^0 meson during the hadronization process, whose charge and kinematic properties are highly correlated with the signal ones. The combined tagging performance is measured to be $\varepsilon_{\rm tag}^{\rm eff} = 3.5 \pm 0.5\%$.

The value of Δm_s is obtained from a simultaneous fit to the distributions of mass and decay time of mixed and unmixed B_s^0 candidates for the five D_s^0 decay channels. The fit accounts for the different signal and background contributions which are parametrised by functional shapes optimised using either simulation (signal, b-hadron background) or data (combinatorial). Signal and b-hadron background parameterisations are convolved with a resolution model that accounts for the time resolution, measured event-by-event, and multiplied by an acceptance function that describe the effect of the trigger and offline selection and reconstruction. The resolution model is calibrated using a data-driven method that exploits a combination of promptly produced D_s and π from the interaction point. The acceptance function is taken from simulation. To gain in statistical sensitivity, in addition to the tagging decision, the events are weighted by the probability that the decision is wrong, η, which is computed event-by-event by the flavour tagging algorithms. Figure 3 show the time distribution of mixed and unmixed B_s^0 candidates, where the wiggles due to oscillations are clearly visible both in data and in the superimposed fit projections.

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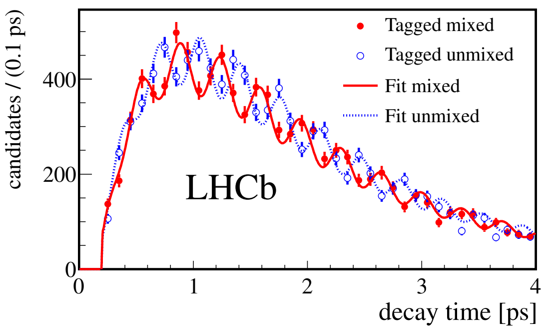

Figure 3: Decay time distribution of $B_s^0 \to D_s^- \pi^+$ candidates tagged as mixed (red filled points) or unmixed (empty blue points). The fit projections are also shown for mixed (unmixed) candidates as a red continuous line (blue dotted line).

The resulting mixing frequency is $\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\,\mathrm{ps}^{-1}$, and represents the most precise measurement to date of such quantity. Its precision is dominated by the statistical uncertainty. The main systematic uncertainties are related to the imperfect knowledge of the longitudinal (z) scale of the detector and of the overall momentum scale.

2. Measurement of the decay width difference $\Delta\Gamma_d$

The decay rates of the mass eigenstates $B_{q,H}$ and $B_{q,L}$ to a final state f can be different due to CP violation. As a consequence the untagged decay rate, $\Gamma(B_q^0(t) \to f)$ and the effective lifetime, $\tau^{\mathrm{eff}}_{B_q^0 \to f}$, are sensitive to the decay width difference $\Delta\Gamma_q \equiv \Gamma_{q,L} - \Gamma_{q,H}$ in a way that depends on the CP parameter $A^f_{\Delta\Gamma}$ [8]

$$\Gamma(B_q^0(t) \to f) \propto e^{-\Gamma_q t}\left[\cosh(\Delta\Gamma_q t/2) + A^f_{\Delta\Gamma}\sinh(\Delta\Gamma_q t/2)\right] \propto e^{-t/\tau^{\mathrm{eff}}_{B_q^0\to f}}, \tag{2.1}$$

$$\tau^{\mathrm{eff}}_{B_q^0\to f} = \frac{1}{\Gamma_q}\frac{1}{1-y_q^2}\left[\frac{1+2A^f_{\Delta\Gamma}y_q + y_q^2}{1+A^f_{\Delta\Gamma}y_q}\right] \qquad \text{with}\, y_q \equiv 2\Delta\Gamma_q \cdot \Gamma_q\,. \tag{2.2}$$

For example, by comparing the effective lifetime τ^{eff} measured in B_d^0 decays to the flavour specific decay $J/\psi K^{*0}$ ($A_{\Delta\Gamma} = 0$) with the value obtained in the CP eigenstate $J/\psi K_s^0$ ($A_{\Delta\Gamma} \simeq \cos(2\beta)$, where β is the known angle of the CKM unitarity triangle), LHCb measured $\Delta\Gamma_d$ and $\Delta\Gamma_d/\Gamma_d$ [9]. The measurement is performed using 1 fb^{-1} of the Run I data sample collected in 2011. A crucial aspect for this measurement is to precisely control the detector acceptance, reconstruction and selection efficiencies that depend upon the b-hadron decay time. For this reason, both trigger and offline selections avoid as much as possible requirements that can bias the decay time. The B candidates are formed selecting $J/\psi \to \mu^+\mu^-$ decays which form a common vertex, displaced from the PV, with the reconstructed K^{*0} (K_s^0) particles decaying to $K^+\pi^-$ ($\pi^+\pi^-$).

A simultaneous fit to the invariant mass m and the decay time t (see Fig. 4) is performed accounting for the signal and the combinatorial background contributions, and for the decay time resolution, which is $\langle\sigma_t\rangle = 45$ and 65 fs for the $B_s^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi K_s^0$, respectively.

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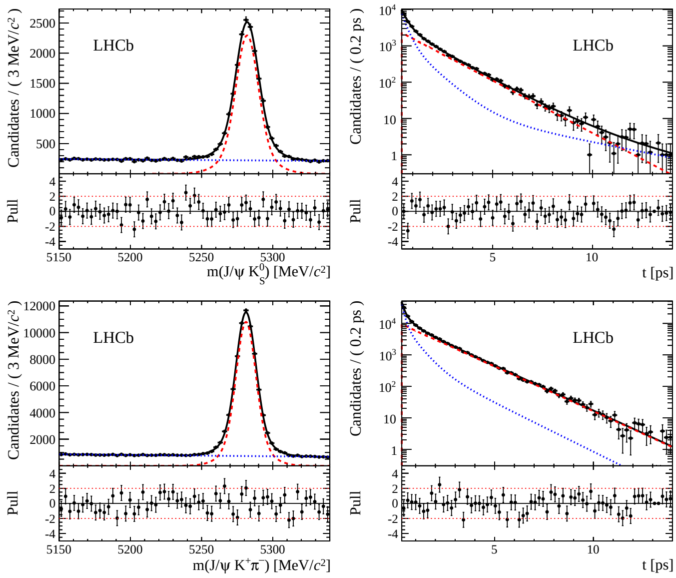

Figure 4: Invariant mass (left) and decay time (right) distributions for $B^0_d \to J/\psi K^{*0}$ (top) and $B^0_s \to J/\psi K^0_s$ (bottom) candidates. The fit function (black, continuous line) consists of the signal (red, dashed line) and combinatorial background (blue, dotted line) contributions.

The resulting measurements are: $\tau^{\rm eff}_{B^0_d \to J/\psi K^{*0}} = 1.524 \pm 0.006 \pm 0.004$ ps and $\tau^{\rm eff}_{B^0_d \to J/\psi K^0_S} = 1.499 \pm 0.013 \pm 0.005$ ps, corresponding to a signal yield of about 70.5k and 17.5k, respectively. Using these values and $\beta = (21.5 \pm 0.8)^\circ$ [5], a fit of $\Delta\Gamma_d$ and Γ_d with Eq. 2.2 leads to $\Delta\Gamma_d = 0.656 \pm 0.003 \pm 0.002$ ps^{-1}, $\Gamma_d = -0.029 \pm 0.016 \pm 0.007$ ps^{-1} and $\Delta\Gamma_d/\Gamma_d = -0.044 \pm 0.025 \pm 0.011$, consistent with the SM expectation and the current world-average value [5], which is now dominated by the ATLAS result [10].

3. Conclusion

Mixing properties of $B^0 - \bar{B}^0$ mesons were recently measured with increased precision by LHCb. In particular, the measurements of the mixing frequency Δm_d and Δm_s have reached precisions of less than 5 per mill. These measurements allow to put constraints on the ratio of the CKM elements $|V_{ts}|/|V_{td}|$ that determines the apex of the unitarity triangle. The precision on such ratio, though, is limited by the computational precision of the hadronic matrix elements. Recently, new Lattice QCD calculations [11] increased significantly the precision of such terms. As a consequence, new, improved constraints on the CKM elements are set $|V_{ts}|/|V_{td}| = 0.2052 \pm 0.0032$. With such progress, hints of tensions arise when comparing the CKM elements $|V_{ts}|$ and $|V_{td}|$ results from mixing measurements with results from tree-processes, as discussed in [12].

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