Precision measurement of the oscillation frequency in the B_s^0–$\overline{B}_s^0$ system

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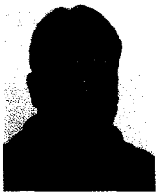

A measurement of the B_s^0–$\overline{B}_s^0$ oscillation frequency, which is equivalent to the mass difference Δm_s of the B_s^0 mass eigenstates, is presented. Using a dataset, corresponding to an integrated luminosity of 1.0 fb^{-1}, collected by the LHCb experiment at the LHC in 2011, a total of about 34,000 $B_s^0 \to D_s^- \pi^+$ signal candidates are reconstructed. The average decay time resolution is 44 fs and the effective tagging efficiency in this channel is $\varepsilon_{\mathrm{eff}} = 3.5\%$. The oscillation frequency is measured to be $\Delta m_s = 17.768 \pm 0.023$ (stat) $\pm$ 0.006 (syst) ps^{-1}, which is the most precise measurement to date.

1 Introduction

In the search for physics beyond the Standard Model of particle physics (BSM) there are two conceptually different strategies at particle colliders. Direct searches aim at producing new heavy particles and thus require to be performed at the highest possible energies. Indirect searches focus on precision measurements of quantum loop induced processes in the Standard Model. In the heavy quark sector there are very accurate theoretical predictions for these processes. It is therefore an excellent place to perform these searches since BSM particles can contribute to the loop diagrams and any deviation from the prediction would be a clear sign of BSM [1].

One place to look for BSM is the B_s^0 mixing sector. The B_s^0 mass eigenstates B_{H}^0 and B_{L}^0 are linear combinations of the flavour eigenstates B_s^0 and $\overline{B}_s^0$.

$$\left|B_{\mathrm{L}}^0\right\rangle = p\left|B_s^0\right\rangle + q\left|\overline{B}_s^0\right\rangle \quad (1)$$

$$\left|B_{\mathrm{H}}^0\right\rangle = p\left|B_s^0\right\rangle - q\left|\overline{B}_s^0\right\rangle \quad (2)$$

Therefore the simplified Schroedinger equation describing the time evolution of B_s^0 and $\overline{B}_s^0$ mesons

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix} \quad (3)$$

has off-diagonal elements in the mass M and decay width Γ matrices. This gives rise to B_s^0–$\overline{B}_s^0$ oscillations [2]. The dominant Feynman diagrams are shown in Figure 1. The measurement

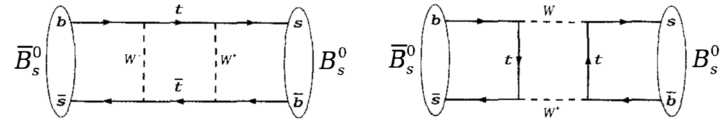

Figure 1: Dominant Feynman diagrams for B^0_s–$\overline{B}^0_s$ oscillations in the Standard Model

of the oscillation frequency which is equivalent to the the mass difference Δm_s between the mass eigenstates B^0_{L} and B^0_{H}, is an essential input to all time-dependent CP asymmetry measurements in the B^0_s system, such as the B^0_s mixing phase in the decays $B^0_s \to J/\psi K^+K^-$and $B^0_s \to J/\psi\pi^+\pi^-$ [3] and the measurement of the CKM angle γ in the decay $B^0_s \to D^\pm_s K^\mp$ [4].

2 Analysis strategy

For this analysis a dataset, corresponding to an integrated luminosity of 1 fb^{-1}, taken by the LHCb experiment in 2011, was used. B^0_s candidates are reconstructed in the decay channel $B^0_s \to D^-_s\pi^+$, using five different D^-_s decay modes, $D^-_s \to \phi(K^+K^-)\pi^-$, $D^-_s \to K^{*0}(K^+\pi^-)K^-$, $D^-_s \to K^+K^-\pi^-$ non resonant, $D^-_s \to K^-\pi^+\pi^-$ and $D^-_s \to \pi^-\pi^+\pi^-$. The combined number of signal candidates is about 34,000. The reconstructed B^0_s invariant mass is used to separate signal from background (see Figure 2). The measurement of Δm_s is performed decay-time-dependent. So the final fit is a two-dimensional maximum likelihood fit in invariant mass and decay time.

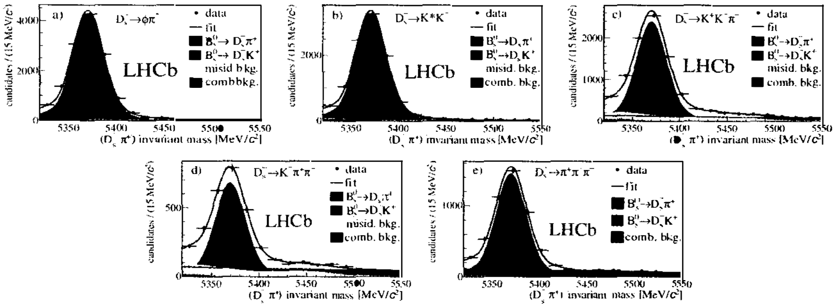

Figure 2: Invariant mass distributions for $B^0_s \to D^-_s\pi^+$candidates with the D^-_smeson decaying as a) $D^-_s \to \phi(K^+K^-)\pi^-$, b) $D^-_s \to K^{*0}(K^+\pi^-)K^-$, c) $D^-_s \to K^+K^-\pi^-$ non resonant, d) $D^-_s \to K^-\pi^+\pi^-$, and e) $D^-_s \to \pi^-\pi^+\pi^-$. The various background components are described in the text.

Another important ingredient for the analysis is the knowledge whether the B^0_s meson decayed in the same flavour as it was produced with (unmixed) or it decayed in the opposite flavour (mixed). The flavour at decay is given directly by the charge of the $D^\pm_s$ meson since it is a flavour specific final state. The flavour at production is given by so called flavour tagging algorithms which will be discussed in some detail in the following section.

The analysis has been performed "blinded", which means that during the analysis process the result of Δm_s was shifted by an unknown number and only after the analysis was finalized was the result revealed.

3 Decay Time Resolution & Flavour Tagging

The challenge of measuring the B_s^0–$\overline{B}_s^0$ oscillation frequency is that, since it is so fast, an excellent decay time resolution is required. The decay time is measured as

$$t = \frac{Lm}{p}. \tag{4}$$

The decay time resolution is dominated by the accuracy to determine the decay vertex and found to be 44 fs.

The flavour of the B_s^0 meson at production is provided by flavour tagging algorithms. These are divided into two categories, opposite and same side tagging algorithms. The opposite side tagger take advantage of the fact that b quarks are predominantly produced in $b\bar{b}$ pairs at the LHC. So by partially reconstructing the second b hadron in the event the flavour of the signal B_s^0 candidate can be deduced. For this, b decay products such as charged leptons and kaons are used as well as an inclusive reconstruction of the b decay vertex charge[5].

Same side flavour tagging algorithms take advantage of the fact that for the hadronization of a B_s^0, an s quark has to be created from the vacuum. Since this is also only possible by creating an $s\bar{s}$ pair, an $\bar{s}$ quark should be close to the B_s^0 meson in phase space. This $\bar{s}$ quark forms in about 50% of the cases a charged kaon which can be detected and by determining its charge the B_s^0 flavour can be concluded[6].

All flavour tagging algorithms have two figures of merit. First there is the tagging efficiency ε_{tag} which is the fraction of B_s^0 candidates for which the algorithms give a decision. Secondly there is the mistag probability ω which is the fraction of B_s^0 candidates for which the decision given by the algorithm is wrong. These two values are combined to the effective tagging efficiency

$$\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}}(1 - 2\omega)^2, \tag{5}$$

which is the factor by which the statistical power of the dataset is reduced due to imperfect flavour tagging. In this analysis, ε_{eff} is found to be $(2.6 \pm 0.4)\%$ for the opposite side and $(1.2 \pm 0.3)\%$ for the same side tagging algorithm. Uncertainties are statistical only.

4 Measurement of Δm_s

As discussed in the previous sections the main challenges to measure Δm_s are the decay time resolution and the flavour tagging. The decay time probability density function is

$$\mathcal{P}_t \propto \Gamma_s e^{-\Gamma_s t} \frac{1}{2}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + q\,[1 - 2\omega]\cos(\Delta m_s t)\right] \otimes\, R(\sigma_t), \tag{6}$$

with the B_s^0 decay width Γ_s and decay width difference $\Delta\Gamma_s$ and the tagging decision q, which is +1 for unmixed events and -1 for mixed. It is convoluted with a resolution model $R(\sigma_t)$. The effects of the imperfect tagging and resolution on the significance to measure Δm_s is:

$$\sigma(\Delta m_s) \propto \sqrt{\varepsilon_{\text{eff}}}\, e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}. \tag{7}$$

This is illustrated in Fig 3, where the oscillation is shown for events with perfect tagging and resolution, events with a realistic resolution and events with a realistic tagging and resolution. The corresponding distribution in data together with the fit result is shown in Fig. 4. The result of the measurement of Δm_s is[7]

$$\Delta m_s = 17.768 \pm 0.023 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}, \tag{8}$$

which is in good agreement with the previous result reported by the LHCb experiment[8] and the current world average, 17.69 ± 0.08 ps^{-1}[9].

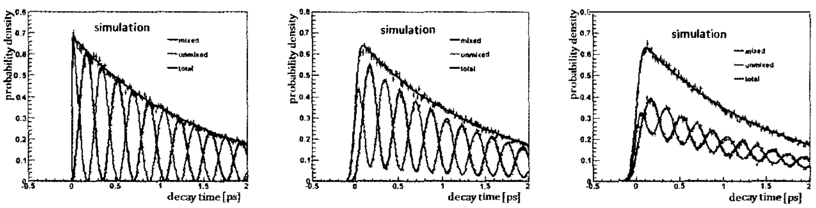

Figure 3: Decay time distributions with the B_s^0–$\overline{B}_s^0$ oscillation for events with perfect tagging and resolution (left), perfect tagging and realistic resolution (middle) and realistic tagging and resolution (right).

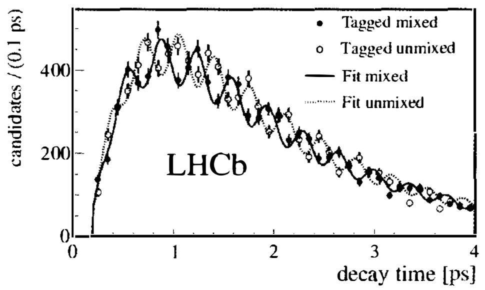

Figure 4: Decay time distribution for candidates tagged as mixed (different flavour at decay and production; red, continuous line) or unmixed (same flavour at decay and production; blue, dotted line). The data and the fit projections are plotted.

5 Acknowledgement

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6 References

1. R. Aaij, *et al.*, and A. Bharucha et al. Implications of LHCb measurements and future prospects. 2012. to appear in Eur. Phys. J. C.
2. Alexander Lenz and Ulrich Nierste. Theoretical update of $B_s - \overline{B}_s$ mixing. *JHEP*, 06:072, 2007.
3. R Aaij et al. Measurement of CP violation and the B_s^0 meson decay width difference with $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays. 2013. submitted to Phys. Rev. D.
4. Measurement of the time-dependent CP-violation parameters in $B_s^0 \to D_s^\pm K^\mp$, Oct 2012. LHCb-CONF-2012-029.
5. R. Aaij et al. Opposite-side flavour tagging of B mesons at the LHCb experiment. *Eur.Phys.J.*, C72:2022, 2012.
6. Optimization and calibration of the same-side kaon tagging algorithm using hadronic B_s^0 decays in 2011 data, Nov 2012. LHCb-CONF-2012-033.
7. R. Aaij et al. Precision measurement of the B_s^0–$\overline{B}_s^0$ oscillation frequency with the decay $B_s^0 \to D_s^-\pi^+$. *New Journal of Physics*, 15(5):053021, 2013.
8. R. Aaij et al. Measurement of the B_s^0-$\overline{B}_s^0$ oscillation frequency Δm_s in $B_s^0 \to D_s^-(3)\pi$ decays. *Phys.Lett.*, B709:177–184, 2012.
9. J. Beringer et al. Review of particle physics. *Phys.Rev.*, D86:010001, 2012.