PRECISION MEASUREMENT OF THE $B_s^0 - \bar{B}_s^0$ OSCILLATION FREQUENCY
$\Delta m_s$ WITH $B_s^0 \rightarrow D_s^- \pi^+$ DECAYS AT LHCB

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Decays of $B_s^0 \rightarrow D_s^- \pi^+$ allow to determine the oscillation frequency $\Delta m_s$ between the $B_s^0$ particle and $\bar{B}_s^0$ antiparticle states with high precision. This is a crucial input to constrain the CKM matrix and a manifestation of the quantum nature of physics. A new measurement of this frequency is presented, using a dataset corresponding to 6 fb$^{-1}$ of pp collisions, recorded by LHCb at a centre-of-mass energy of 13 TeV. The oscillation frequency is determined to be $\Delta m_s = 17.7683 \pm 0.0051 ($stat.$) \pm 0.0032 ($syst.$)$ ps$^{-1}$ and a combination with previous LHCb measurements yields $\Delta m_s^{LHCb} = (17.7656 \pm 0.0057)$ ps$^{-1}$.

1 Introduction

In nature, neutral mesons such as $B_s^0$ mix with their antiparticle, $\bar{B}_s^0$. This effect is well-described in the Schrödinger image, and is a beautiful example of the quantum nature of particles. Within the Standard Model, the mixing process is governed by the weak interaction and is only possible due to the non-zero off-diagonal elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. A precise measurement of the oscillation frequency $\Delta m_s$ adds a strict constraint on the CKM triangle apex, that is even more powerful when combined with the measurement of the $B_d^0 - \bar{B}_d^0$ oscillation frequency, $\Delta m_d$. Moreover, the value of $\Delta m_s$ is a crucial input parameter for measurements of $CP$ violation in decays such as $B_s^0 \rightarrow D_s^+ K^-$. The generally high precision of this measurement is possible due to the large ratio of the oscillation frequency and the lifetime of $B_s^0$ mesons. Given the current world averages of these parameters, $B_s^0$ and $\bar{B}_s^0$ oscillate on average approximately four times per mean lifetime. In addition to being a test of the Standard Model, a measurement of $\Delta m_s$ serves as a benchmark of the detector performances and data analysis methods.

Mixing of $B_s^0$ mesons was first observed by the CDF collaboration. The first measurement of $\Delta m_s$ carried out by the LHCb collaboration used a dataset corresponding to an integrated luminosity of $L_{int} = 1$ fb$^{-1}$. More recently, the LHCb collaboration measured $\Delta m_s$ using data collected during Run 1 and Run 2 with decays of $B_s^0 \rightarrow D_s^- \pi^+ \pi^- \pi^+ \pi^-$. The measurement presented in this document is based on the full Run 2 data sample, corresponding to an integrated luminosity of 6 fb$^{-1}$ which contains a total number of approximately 380 thousand signal decays of $B_s^0 \rightarrow D_s^- \pi^+$. This data sample allows for the most precise single measurement of $\Delta m_s$ as of today. Moreover, all measurements of $\Delta m_s$ that have been performed by LHCb are combined.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range of $2 < \eta < 5$, designed to study hadrons containing $b$ or $c$ quarks. It includes a high-precision tracking and vertex detection system, which consists of a silicon-strip vertex detector that surrounds the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole...
magnet, and three tracking stations placed downstream of the magnet that each feature an inner silicon-strip detector and an outer straw drift tube detector. A fundamental requirement for the presented analysis is LHCb’s excellent decay-time resolution of about 45 fs, which allows to measure the fast $B^0_s$ oscillation. Another crucial ingredient for the analysis is the distinction between kaons, pions, and protons, which the LHCb detector accomplishes with two ring-imaging Cherenkov detectors that are part of the particle identification (PID) system. LHCb’s trigger system features a hardware and a software stage, which together reduce the event rate to about 10 kHz. More details about the LHCb detector can be found elsewhere.

2 Mixing

The neutral $B^0_s$ meson system can be described as a superposition of the two flavour eigenstates, $|B^0_s\rangle$ and $|\overline{B}^0_s\rangle$. The time-evolution of the system is obtained by solving a Schrödinger equation in the heavy and light mass eigenstates $|H\rangle$ and $|L\rangle$, with masses $m_{H,L}$ and decay widths $\Gamma_{H,L}$, respectively. The solution for the flavour eigenstates can then be written in terms of the decay width $\Gamma_s = (\Gamma_H + \Gamma_L)/2$, the decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, the mass $m_s = (m_H + m_L)/2$ and the mass difference $\Delta m_s = m_H - m_L$. It provides a prediction for the decay-time dependent decay rates $\Gamma(B^0_s(t) \to f)$ of the $B^0_s$ mesons into an exclusive final state $f$.

In the special case of flavour-specific decays, such as $B^0_s \to D^+\pi^-$, direct decays from the same initial flavour into a $CP$ conjugate final state $-B^0_s \to D^+\pi^-$ in this case $-$ are heavily suppressed. Therefore, the electric charge of the final state particles unambiguously determines the flavour at decay. Additionally, information about the initial flavour can be obtained through flavour tagging techniques which exploit the decays of hadronization partners of the signal $B^0_s$ meson. Knowing both the initial and final flavour of the decays allows to distinguish all possible decay rates.

As of today, direct and indirect $CP$ violation can be neglected for decays of $B^0_s \to D^-\pi^+$, such that the decay-time dependent decay rate of the process reads like

$$\Gamma(B^0_s(t) \to D^-\pi^+) = \frac{1}{2} N e^{-\Delta\Gamma_s t} \left[ \cos(\Delta m_s t) + \cosh \left( \frac{\Delta\Gamma_s t}{2} \right) \right],$$

with a normalization factor $N$. The $CP$ conjugate process is described with the same formula, except for a potentially different normalization factor. Both of these processes are henceforth referred to as unmixed decays. The mixed decays, $B^0_s \to \overline{B}^0_s \to D^+\pi^-$ and the charge conjugate process, only differ by a relative sign in front of the trigonometric term. Since the direct decay is suppressed in flavour specific decays, they are labelled as $\overline{B}^0_s \to D^-\pi^+.$

3 Measurement

The measurement is performed on a dataset that corresponds to an integrated luminosity of $380 \text{ fb}^{-1}$. It has been recorded at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ with the LHCb detector. To improve the signal-to-noise ratio, an event selection is applied, making use of different kinematic variables of the data sample, as well as the excellent particle identification information that is obtained from LHCb’s RICH detectors. In addition, a boosted decision tree (BDT) is used to greatly reduce the number of random track combinations in the data sample.

The good mass resolution that is obtained after these selections is exploited to statistically extract the signal component of the sample via the sPlot method. Both, the invariant $B^0_s$ and invariant $D^-\pi^+$ mass distributions are therefore fitted simultaneously using a maximum-likelihood fit, as shown in fig. 1. The event weights are used to extract a decay-time distribution corresponding to $380 \text{ fb}^{-1}$ signal decays is obtained.

The initial flavour is measured by a combination of six flavour tagging algorithms. Since not all events can be tagged and the algorithms have a certain fraction of wrongly tagged events,
this results in an effective tagging efficiency of $\sim 6\%$. The decay-time uncertainty is described with a Gaussian resolution function and calibrated using $D_s^-\pi^+$ pairs originating from the $pp$ interaction region. Additionally, detector effects and the BDT selection introduce a decay-time dependent efficiency, which is modelled with a set of cubic spline functions.

The resulting decay-time distribution, split into unmixed decays $B_s^0 \rightarrow D_s^-\pi^+$, mixed decays $B_s^0 \rightarrow D_s^-\pi^+$, and untagged decays is shown in fig. 2. The measurement yields

$$\Delta m_s = (17.7683 \pm 0.0051 \pm 0.0032) \text{ ps}^{-1},$$

where the first uncertainty is statistical and the second is systematic. Due to the high precision of this measurement, the systematic uncertainties need to be controlled to unprecedented levels. The dominant systematic uncertainty originates from the imperfect knowledge of the detector alignment. Additionally, even well-established data analysis tools such as the sPlot method significantly contributes to the uncertainty budget. Therefore, the measurement of $\Delta m_s$ provides an excellent benchmark for both detector performance and data analysis tools.

Figure 1 – Distributions of the invariant $B_s^0$ (left) and $D_s^-$ (right) masses, with the maximum likelihood fit result superimposed. The fit allows to statistically extract the decay-time distribution of a pure signal sample.

Figure 2 – Decay-time distribution of unmixed (blue), mixed (red) and untagged (grey) signal decay. The data points are nicely described with a cosine oscillation across the full range.
Ultimately, the presented measurement of $\Delta m_s$ is combined with other LHCb measurements of the same parameter$^{5,6,7,8}$, as shown in fig. 3, taking correlated systematic uncertainties into account. It results in the world’s most precise determination of the $B^0_s$–$\bar{B}^0_s$ oscillation frequency as of today, $\Delta m_s^{\text{LHCb}} = (17.7656 \pm 0.0057) \text{ ps}^{-1}$.

![Figure 3 – Combination of several LHCb measurements of $\Delta m_s$, and the individual results. The average is clearly dominated by the most precise measurement presented here.](image)

4 Conclusion

The results presented here include the most precise single measurement of the oscillation frequency $\Delta m_s = (17.7683 \pm 0.0051 \pm 0.0032) \text{ ps}^{-1}$, as well as the most precise single experiment determination of the parameter, $\Delta m_s^{\text{LHCb}} = (17.7656 \pm 0.0057) \text{ ps}^{-1}$. It is a crucial ingredient to CKM triangle measurements and a good benchmark for future detector and analysis developments. More than that, it is a beautiful example of quantum effects in particle physics.

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