Indirect CP violation in the B_s^0 system at LHCb

Wouter Hulsbergen,
on behalf of the LHCb collaboration
Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands

Meson-anti-meson mixing in the B_s^0 system is considered a sensitive prove of physics beyond the standard model. In this talk I summarize recent LHCb measurements of the mixing frequency, time-dependent CP violation, the B_s^0 lifetime and decay width difference and the flavour-specific asymmetry.

1 Introduction

Neutral mesons exhibit an intriguing phenomenon called flavour mixing: Because the weak interaction eigenstates are not the same as the eigenstates of the total hamiltonian, the flavour content of neutral mesons changes as a function of time. This process leads to CP violating effects that allow for stringent tests of the SM. Measurements of mixing phenomena in the B_s^0 system are particularly interesting, because, thanks to the fact that $m_B \gg \Lambda_{QCD}$, SM calculations have small uncertainty. Furthermore, new contributions to $b \to s$ transitions are so far relatively poorly constrained.

Pedagogical introductions to neutral meson mixing can be found elsewhere, e.g. in [1]. Here, we just introduce the notation. Consider the wave function $B^0(t)$ for a neutral meson that is the superposition of flavour eigenstates B^0 and $\overline{B}^0$. The time-evolution of its projections into flavour eigenstates is given by a Schrödinger equation (we adopt units such that $\hbar = c = 1$)

$$i \, \frac{\mathrm{d}}{\mathrm{d}t} \left(\begin{array}{c} \langle B^0 | B^0(t) \rangle \\ \langle \overline{B}^0 | B^0(t) \rangle \end{array} \right) = \left[M - \frac{i}{2} \Gamma \right] \left(\begin{array}{c} \langle B^0 | B^0(t) \rangle \\ \langle \overline{B}^0 | B^0(t) \rangle \end{array} \right) . \tag{1}$$

where M and Γ are 2x2 hermitian matrices. CPT invariance and the fact that the phases of the B^0 and $\overline{B}^0$ states can be chosen freely, make that the system can be described in terms of five physical real parameters, namely $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$, $|M_{12}$, $|\Gamma_{12}|$ and the phase $\phi_{12} = \arg(-M_{12}/\Gamma_{12})$. Usually, these are rewritten in terms of the eigenvalues of the two mass eigenstates, labeled by L for light and H for heavy. In particular, the experimental observables are the average mass and decay width

$$m \equiv \tfrac{1}{2} \left(m_H + m_L \right) = M_{11} \qquad\qquad \Gamma \equiv \tfrac{1}{2} \left(\Gamma_H + \Gamma_L \right) = \Gamma_{11}, \tag{2}$$

the mass difference and decay width difference

$$\Delta m \equiv m_H - m_L \simeq 2 |M_{12}| \qquad\qquad \Delta\Gamma \equiv \Gamma_L - \Gamma_H \simeq 2 |\Gamma_{12}| \cos\phi_{12} \tag{3}$$

and the so-called flavour-specific or semi-leptonic asymmetry, which is a dimensionless quantity that signal CP violation in the mixing amplitudes and is approximately given by

$$a_{\mathrm{fs}} \;\simeq\; \frac{|\Gamma_{12}|}{|M_{12}|} \sin\phi_{12} \, . \tag{4}$$

In the SM the B_s^0 meson mixing amplitudes are dominated by the 2nd order weak interaction diagrams shown in Fig. 1 (left). Recent calculations [2] give $\Delta\Gamma_s = 0.087 \pm 0.021\ \mathrm{ps}^{-1}$, $\Delta m_s = 17.3 \pm 2.6\ \mathrm{ps}^{-1}$, $\phi_{12}^s = 0.004 \pm 0.001$ and $a_{\mathrm{fs}}^s = (1.9 \pm 0.3) \cdot 10^{-5}$. In the following I present LHCb [3] measurements of these parameters using the 2011 dataset, which comprises about $1.0\,\mathrm{fb}^{-1}$ of proton-proton collisions at 7 TeV.

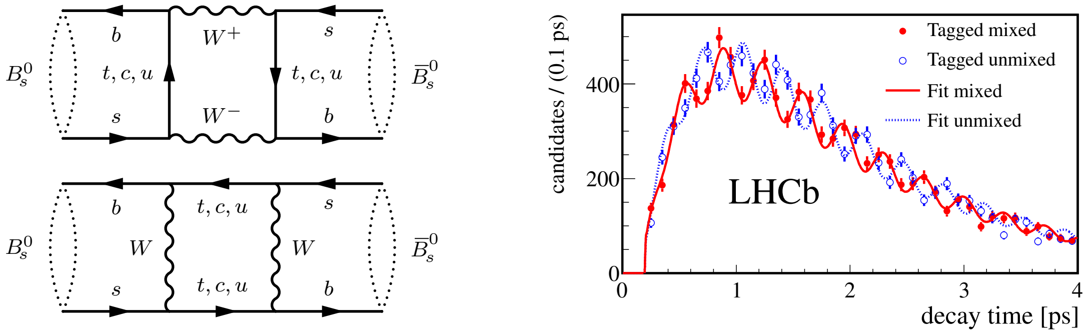

Figure 1: Left: Leading order diagrams for neutral meson mixing in the standard model. Right: decay time distribution for mixed and unmixed $B_s^0 \to D_s^+\pi^-$ candidates in $1.0\,\mathrm{fb}^{-1}$ of LHCb data [4].

2 Measurement of the B_s^0 oscillation frequency

The B_s^0 oscillation frequency Δm_s is measured in decays to $B_s^0 \to D_s^+\pi^-$ with the D_s^- decaying to $K^+K^-\pi^-$, $K^-\pi^+\pi^-$ or $\pi^-\pi^+\pi^-$. (Unless specifically indicated charged-conjugate modes are implied.) Flavour oscillations can be observed by comparing the flavour at the time of decay (which is determined by the charge of the $D_s^\pm$ in the final state) with the flavour at the time of production. The latter can be determined by exploiting the fact that the $\bar{b}$ and s quark in a B_s^0 meson are accompanied by respectively a b and $\bar{s}$ quark in the fragmentation. Identifying the flavour via decay products of the other b quark in the event is called opposite-side flavour tagging (OST), while relying on a reconstructed charged kaon close in phase space to the B_s^0 meson is called same-side flavour tagging (SST). Both these approaches are exploited in LHCb [5,6].

Depending on the flavour tags at production and at decay candidate events are labeled as 'mixed' (different flavour) or 'unmixed' (equal flavour). Ignoring experimental effects, the differential decay rates for mixed (plus sign) or unmixed (minus sign) events are given by

$$\frac{\mathrm{d}N_\pm}{\mathrm{d}t} \propto \frac{e^{-\Gamma_s t}}{2} \left[\cosh\left(\tfrac{1}{2}\Delta\Gamma_s\, t\right) \pm \cos\left(\Delta m_s\, t\right) \right]. \tag{5}$$

Figure 1 (right) shows the decay time distributions for mixed and unmixed $B_s^0 \to D_s^+\pi^-$ decays observed in $1.0\,\mathrm{fb}^{-1}$ of LHCb data. From a fit to these data the mixing frequency is found to be [4]

$$\Delta m_s = 17.768 \pm 0.023\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst})\ [\mathrm{ps}^{-1}] \tag{6}$$

which dominates the current world average. The systematic uncertainty is dominated by uncertainties in the length scale and momentum scale.

The distributions in Fig. 1 do not exactly follow the shape predicted by Eq. 5: The drop in efficiency at small lifetime is due to selection requirements aimed at reducing the large prompt background. The fact that the amplitude of the oscillation is not equal to unity is because of imperfections in the flavour tagging and the finite decay time resolution. Though less important for the Δm_s measurement, calibration of these effects is crucial for the measurement of time-dependent CP violation.

3 Measurements of time-dependent CP violation

Decays to CP eigenstates like $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi f^0$ can be used to constrain the CP violating phase ϕ_{12}. The decay rate for decays with an initial flavour tag as B_s^0 (plus sign) or $\overline{B}_s^0$ (minus sign) is given by

$$\frac{\mathrm{d}N_\pm}{\mathrm{d}t} \;\propto\; e^{-\Gamma_s t}\left[\,\cosh\left(\tfrac{1}{2}\Delta\Gamma_s\, t\right) \;-\; \eta_f\cos\phi_f\sinh\left(\tfrac{1}{2}\Delta\Gamma_s\, t\right) \;\mp\; \eta_f\sin\phi_f\sin\left(\Delta m_s\, t\right)\right] \tag{7}$$

where η_f is the CP eigenvalue of the final state and the phase ϕ_f can be expressed in the phase of M_{12} and phases of elements of the CKM matrix. In the SM $\phi_f = \phi_s^{c\bar{c}s} = -0.036 \pm 0.002$ both for $B_s^0 \to J/\psi\phi$ and for $B_s^0 \to J/\psi f^0$[2]. New contributions to the mixing diagram will alter M_{12} and thereby the phases $\phi_{12,s}$ and $\phi_s^{c\bar{c}s}$.

The $J/\psi f^0(980)$ final state is CP-odd ($\eta_f = -1$). A recent Dalitz analysis has shown that this holds to a good extend for the entire $J/\psi\pi^+\pi^-$ final state[7]. The phenomenology of the $B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$ decay is more complicated. In the K^+K^- invariant mass range near to ϕ(1020 resonance the K^+K^- pair is predominantly in a P-wave state, but a small contribution from an S-wave exists[8]. Final states with different angular momenta lead to different values for η_f. In order to extract $\phi_s^{c\bar{c}s}$ these contributions are disentangled using the observed decay angles, requiring a so-called 'time-dependent angular analysis' of the data.

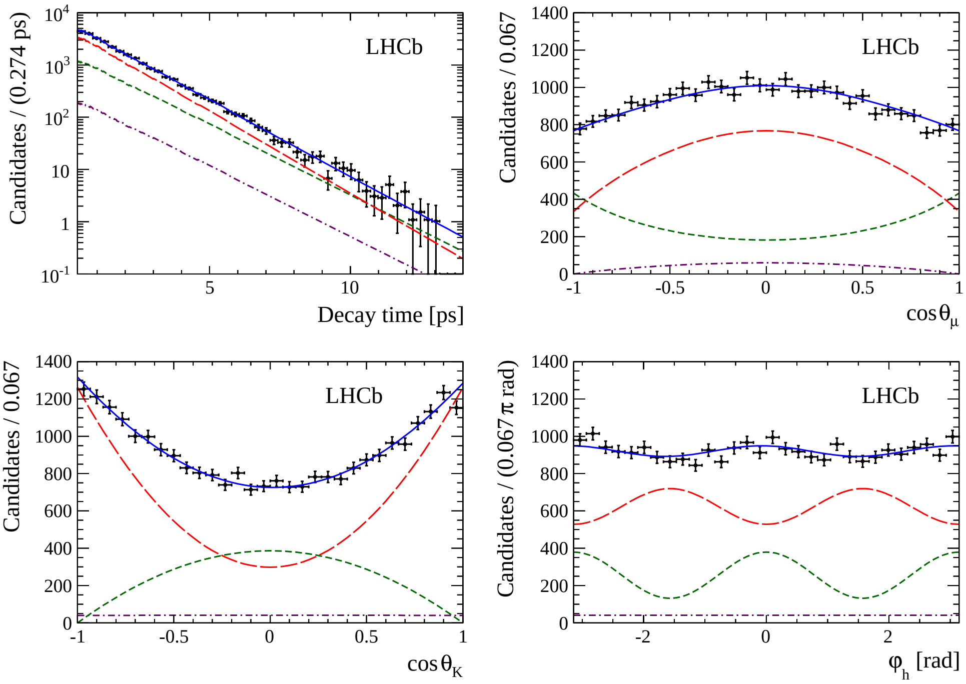

Figure 2: Background subtracted decay-time and helicity-angle distributions for $B_s^0 \to J/\psi K^+K^-$ decays in $1.0\,\mathrm{fb}^{-1}$ of LHCb data[9]. The solid blue line represents the fitted function, composed of CP-even (long-dashed red), CP-odd (short-dashed green) and S-wave (dotted-dashed purple) contributions.

Figure 2 shows distributions of the decay time and decay angles of background-subtracted $B_s^0 \to J/\psi K^+K^-$ decays, with the fitted function superimposed. From a combination with the $B_s^0 \to J/\psi f^0$ data, the following values for $\phi_s^{c\bar{c}s}$ and the lifetime parameters are extracted[9],

$$\begin{aligned}
\phi_s^{c\bar{c}s} &= 0.01 \pm 0.07\ \text{(stat)} \pm 0.01\ \text{(syst)}\ \text{rad},\\
\Gamma_s &= 0.661 \pm 0.004\ \text{(stat)} \pm 0.006\ \text{(syst)}\ \text{ps}^{-1},\\
\Delta\Gamma_s &= 0.106 \pm 0.011\ \text{(stat)} \pm 0.007\ \text{(syst)}\ \text{ps}^{-1},
\end{aligned} \tag{8}$$

These results are in good agreement with the SM prediction. The measurement of $\phi_s^{c\bar{c}s}$ dominates the current world average. Those for Γ_s and $\Delta\Gamma_s$ are the most precise from a single experiment. Systematic uncertainties are dominated by uncertainties of the decay angle and decay time acceptance.

The decay $B_s^0 \to \phi\phi$ also gives access to a CP violating phase, but in this case the transition proceeds predominantly through a $b \to s\bar{s}s$ penguin amplitude. In the SM, the phase $\phi_s^{s\bar{s}s}$ is expected to be close to zero, $|\phi_s^{s\bar{s}s}| < 0.02$, due to a cancellation of the phases arising from $B_s^0\overline{B}_s^0$ oscillations and decay. A first analysis of approximately 1200 candidates in $1.0\,\text{fb}^{-1}$ of LHCb data restricts the phase to the interval $\phi_s^{s\bar{s}s} \in [-2.46, -0.76]$ at 68% C.L.[10]. The p-value of the SM prediction is 16%.

4 Measurement of the flavour-specific asymmetry

CP violation in mixing is characterized by a non-zero value of ϕ_{12}, or, equivalently, the flavour-specific asymmetry a_{fs}. LHCb has measured a_{fs}^s in decays of $B_s^0 \to D_s^+\mu^-\bar{\nu}_\mu X$[11]. The asymmetry in the yields of $D_s^-\mu^+$ and $D_s^+\mu^-$ events is related to a_{fs}^s by

$$\frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)}{N(D_s^-\mu^+) + N(D_s^+\mu^-)} = \frac{a_{\text{fs}}^s}{2} + \left(\frac{a_{\text{fs}}^s}{2} - a_{\text{prod}}\right) \frac{\int_0^\infty \text{d}t\, e^{-\Gamma_s t}\cos(\Delta m_s t)}{\int_0^\infty \text{d}t\, e^{-\Gamma_s t}\cosh(\frac{1}{2}\Delta\Gamma_s t)} \tag{9}$$

where a_{prod} is the production asymmetry. The latter is expected to of the order of 1% at the LHC but with large uncertainty. However, thanks to the large oscillation frequency, the integral on the right-hand-side is small. From the observed asymmetry a preliminary value of

$$a_{\text{fs}}^s \;=\; (-0.24 \pm 0.54 \pm 0.33)\% \quad \textit{(prel.)} \tag{10}$$

is extracted[11], in good agreement with the SM expectation and the most precise measurement of a_{fs} in B_s^0 decays to date. The dominating systematic uncertainty stems from uncertainties in the relative efficiency of positively and negatively charged particles and is controlled by regularly reversing the direction of the magnetic field of the spectrometer.

5 Concluding remarks

I have presented recent LHCb results constraining contributions of beyond the standard model physics in $B_s^0\overline{B}_s^0$ oscillations. All measurements are in good agreement with SM expectations. The analysis of the 2012 dataset, which is approximately twice as large as the 2011 dataset presented here, is in full swing.

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