Indirect $CP$ violation in the $B^0_s$ system at LHCb

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Meson-anti-meson mixing in the $B^0_s$ 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 $B^0_s$ 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 $B^0_s$ 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 $\bar{B}^0$. The time-evolution of its projections into flavour eigenstates is given by a Schrödinger equation (we adopt units such that $\hbar = c = 1$)

$$ i \frac{d}{dt} \begin{pmatrix} \langle B^0 | B^0(t) \rangle \\ \langle \bar{B}^0 | B^0(t) \rangle \end{pmatrix} = \begin{bmatrix} M - i \frac{2}{\Gamma} \end{bmatrix} \begin{pmatrix} \langle B^0 | B^0(t) \rangle \\ \langle \bar{B}^0 | B^0(t) \rangle \end{pmatrix}. $$

(1)

where $M$ and $\Gamma$ are 2x2 hermitian matrices. $CPT$ invariance and the fact that the phases of the $B^0$ and $\bar{B}^0$ 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 $\phi_{12} = \text{arg}(-M_{12}/\Gamma_{12})$. 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

$$ m \equiv \frac{1}{2} (m_H + m_L) = M_{11} \quad \quad \Gamma \equiv \frac{1}{2} (\Gamma_H + \Gamma_L) = \Gamma_{11}, $$

(2)

the mass difference and decay width difference

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

(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

$$ a_{fs} \simeq \frac{|\Gamma_{12}|}{|M_{12}|} \sin \phi_{12}. $$

(4)
In the SM the $B^0_s$ meson mixing amplitudes are dominated by the 2nd order weak interaction diagrams shown in Fig. 1 (left). Recent calculations give $\Delta \Gamma_s = 0.087 \pm 0.021 \text{ ps}^{-1}$, $\Delta m_s = 17.3 \pm 2.6 \text{ ps}^{-1}$, $\phi^{0}_{12} = 0.004 \pm 0.001$ and $a^{s}_{b} = (1.9 \pm 0.3) \cdot 10^{-5}$. In the following I present LHCb measurements of these parameters using the 2011 dataset, which comprises about 1.0 fb$^{-1}$ of proton-proton collisions at 7 TeV.

2 Measurement of the $B^0_s$ oscillation frequency

The $B^0_s$ oscillation frequency $\Delta m_s$ is measured in decays to $B^0_s \rightarrow D^{\pm}_s \pi^\mp$ with the $D^{\pm}_s$ decaying to $K^+ K^- \pi^\mp$, $K^-\pi^+\pi^- \text{ or } \pi^-\pi^+\pi^-$. (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 $D^{\pm}_s$ in the final state) with the flavour at the time of production. The latter can be determined by exploiting the fact that the $b$ and $s$ quark in a $B^0_s$ 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 $B^0_s$ meson is called same-side flavour tagging (SST). Both these approaches are exploited in LHCb.

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

$$\frac{dN_+}{dt} \propto e^{-\Gamma_s t} \left[ \cosh \left( \frac{1}{2} \Delta \Gamma_s t \right) \pm \cos \left( \Delta m_s t \right) \right].$$

(5)

Figure 1 (right) shows the decay time distributions for mixed and unmixed $B^0_s \rightarrow D^{\pm}_s \pi^\mp$ decays observed in 1.0 fb$^{-1}$ of LHCb data. From a fit to these data the mixing frequency is found to be

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

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

$$\frac{dN_\pm}{dt} \propto e^{-\Gamma_s t} \left[ \cosh \left( \frac{1}{2} \Delta \Gamma_s t \right) - \eta_f \cos \phi_f \sinh \left( \frac{1}{2} \Delta \Gamma_s t \right) \mp \eta_f \sin \phi_f \sin \left( \Delta m_s t \right) \right]$$

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

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 extent for the entire $J/\psi \pi^+\pi^-$ final state. The phenomenology of the $B_s \rightarrow J/\psi(1020) \rightarrow \mu^+\mu^- K^+K^-$ decay is more complicated. In the $K^+K^-$ invariant mass range near to $\phi(1020)$ resonance the $K^+K^-$ pair is predominantly in a P-wave state, but a small contribution from an S-wave exists. Final states with different angular momenta lead to different values for $\eta_f$. In order to extract $\phi_s^{\text{CKM}}$ 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 $B_s^0 \rightarrow J/\psi K^+K^-$ decays in 1.0 fb$^{-1}$ of LHCb data. 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 $B_s^0 \rightarrow J/\psi K^+K^-$ decays, with the fitted function superimposed. From a combination with the $B_s^0 \rightarrow J/\psi f^0$ data, the following values for $\phi_s^{\text{CKM}}$ and the lifetime parameters are extracted,

$$\phi_s^{\text{CKM}} = 0.01 \pm 0.07 \text{ (stat) } \pm 0.01 \text{ (syst) rad},$$

$$\Gamma_s = 0.661 \pm 0.004 \text{ (stat) } \pm 0.006 \text{ (syst) ps}^{-1},$$

$$\Delta \Gamma_s = 0.106 \pm 0.011 \text{ (stat) } \pm 0.007 \text{ (syst) ps}^{-1},$$
These results are in good agreement with the SM prediction. The measurement of $\phi_s^{\text{CSS}}$ dominates the current world average. Those for $\Gamma_s$ 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 $B^0 \to \phi \phi$ 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 $\phi_s^{\text{CSS}}$ is expected to be close to zero, $|\phi_s^{\text{CSS}}| < 0.02$, due to a cancellation of the phases arising from $B^0 \bar{B}^0$ 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 $\phi_s^{\text{CSS}} \in [-2.46, -0.76]$ at 68% C.L.\textsuperscript{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 $\phi_{12}$, or, equivalently, the flavour-specific asymmetry $a_s$. LHCb has measured $a_s^s$ in decays of $B^0_s \to D^+_s \mu^− \nu_\mu X$\textsuperscript{11}. The asymmetry in the yields of $D^+_s \mu^+$ and $D^+_s \mu^-$ events is related to $a_s^s$ by

$$
\frac{N(D^+_s \mu^+) - N(D^+_s \mu^-)}{N(D^+_s \mu^+) + N(D^+_s \mu^-)} = \frac{a_s^s}{2} + \left( \frac{a_s^s}{2} - a_{\text{prod}} \right) \left[ \int_0^\infty \frac{dt}{t} e^{-\Gamma_s t} \cos(\Delta m_s t) \int_0^\infty \frac{dt}{t} e^{-\Gamma_s t} \cosh(\frac{1}{2} \Delta \Gamma_s t) \right]
$$

(9)

where $a_{\text{prod}}$ is the production asymmetry. The latter is expected to be 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

$$
a_s^s = (-0.24 \pm 0.54 \pm 0.33)\% \quad (\text{prel.})
$$

(10)

is extracted\textsuperscript{11}, in good agreement with the SM expectation and the most precise measurement of $a_s^s$ in $B^0_s$ 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 $B^0_s \bar{B}^0_s$ 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.

References

11. LHCb Collaboration, R. Aaij et al., LHCb-CONF-2012-022.