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On the ultimate precision of meson mixing observables

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Abstract

Meson mixing is considered to be an ideal testing ground for new physics searches. Experimental precision has greatly increased over the recent years, exceeding in several cases the theoretical precision. A possible limit in the theoretical accuracy could be a hypothetical breakdown of quark–hadron duality. We propose a simple model for duality violations and give stringent phenomenological bounds on its effects on mixing observables, indicating regions where future measurements of $\Delta\Gamma_d$, a_{sl}^d and a_{sl}^s would give clear signals of new physics. Finally, we turn our attention to the charm sector, and reveal that a modest duality violation of about 20% could explain the huge difference between HQE predictions for D mixing and experimental data.

1. Introduction

Despite having passed numerous tests, the standard model of particle physics leaves many fundamental questions unanswered which might be resolved by extensions of this model. Flavour physics is an ideal candidate for general indirect new physics searches, as well as for dedicated CP-violating studies, which might shed light on the unsolved problem of the baryon asymmetry in the Universe. For this purpose hadronic uncertainties on flavour observables have to be under

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control. Various flavour experiments have achieved a high precision in many observables, in several cases challenging the precision of theory calculations. LHCb in particular, as an experiment designed to study beauty and charm physics, contributes to the currently impressive status of experimental precision. As we attempt to test the SM to the highest level of precision, the question of how sure we can be about any deviations from the current theoretical predictions being evidence of new physics comes to the fore. Such a question is the subject we tackle in this paper.

Many current theory predictions rely on the Heavy Quark Expansion (HQE), and we will examine how the idea of quark–hadron duality – which is assumed by the HQE – can be tested. We will use current data from B mixing, the dimuon asymmetry, and B meson lifetimes to constrain violations of quark–hadron duality, and then see how this affects the predicted values of other observables. We also investigate how the current trouble with inclusive predictions of mixing in the charm sector can be explained through a mild violation of quark–hadron duality.

We discuss what improvements could be made in both theory and experiment in order to further constrain duality violating effects, and what level of precision would be necessary to properly distinguish between genuine new physics and merely a non-perturbative contribution to the SM calculation. In this spirit, we also provide a first attempt at improving the theory prediction, using the latest results and aggressive error estimates to see how theory uncertainties could reduce in the near future.

Our paper is organised as follows: in Sec. 2 we explain the basic ideas of duality violation in the HQE. We introduce in Sec. 2.1 a simple parameterisation for duality violation in B mixing and we derive bounds on its possible size. The dimuon asymmetry and the lifetime ratio $\tau(B_s^0)/\tau(B_d^0)$ can provide complementary bounds on duality violation, which is discussed in Sect. 2.2 and Sect. 2.3. The bounds in the B system depend strongly on the theory uncertainties, hence we present in Sect. 3 a numerical update of the mixing observables with an aggressive error estimate for the input parameters. In Sec. 4 we study possible effects of duality violation in D-mixing. We conclude in Sec. 5 with a short summary and outlook.

2. Duality violation

In 1979 the notion of duality was introduced by Poggio, Quinn and Weinberg [1] for the process $e^+ + e^- \to hadrons$.[1] The basic assumption is that this process can be well approximated by a quark level calculation of $e^+ + e^- \to q + \bar{q}$. In this work we will investigate duality in the case of decays of heavy hadrons, which are described by the heavy quark expansion (see e.g. [4–11] for pioneering papers and [12] for a recent review). The HQE is a systematic expansion of the decay rates of b hadrons in inverse powers of the heavy quark mass.

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \frac{\Lambda^4}{m_b^4}\Gamma_4 + \dots , \tag{2.1}$$

with Λ being of the order of the hadronic scale.[2] One finds that there are no corrections of order Λ/m_b and that some corrections from the order Λ^3/m_b^3 onwards are enhanced by an additional phase space factor of $16\pi^2$. The HQE assumes quark hadron duality, i.e. that the hadron decays can be described at the quark level. A violation of duality could correspond to

[1] The concept of duality was already used in 1970 for electron proton scattering by Bloom and Gilman [2,3].

[2] One gets different values of Λ for different observables. The numerical value of Λ has to be determined by an explicit calculation. For the case of $\Delta\Gamma_s$ one gets e.g. $\Lambda/m_b \approx 1/5$ [13] and thus $\Lambda \approx 1$ GeV.