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Three-body non-leptonic B decays and QCD factorization

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Abstract

We extend the framework of QCD factorization to non-leptonic B decays into three light mesons, taking as an example the decay $B^+ \to \pi^+\pi^+\pi^-$. We discuss the factorization properties of this decay in different regions of phase space. We argue that, in the limit of very large b-quark mass, the central region of the Dalitz plot can be described in terms of the $B \to \pi$ form factor and the B and π light-cone distribution amplitudes. The edges of the Dalitz plot, on the other hand, require different non-perturbative input: the $B \to \pi\pi$ form factor and the two-pion distribution amplitude. We present the set-up for both regions to leading order in both α_s and Λ_{QCD}/m_b and discuss how well the two descriptions merge. We argue that for realistic B-meson masses there is no perturbative center in the Dalitz plot, but that a systematic description might be possible in the context of two-pion states. As an example, we estimate the $B \to \rho\pi$ branching fraction beyond the quasi-particle approximation. We also discuss the prospects for studies of three-body and quasi-two-body non-leptonic B decays from QCD.

1. Introduction

Three-body non-leptonic decays of heavy mesons constitute a large portion of the branching fraction. For B mesons, three-body non-leptonic branching ratios and CP asymmetries have been

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measured for a large number of channels, most notably by BaBar, Belle and LHCb [1–6], and more is expected to come from LHC run 2 and from Belle II [7]. On the theory side, three-body non-leptonic B decays are interesting for several phenomenological applications, such as the study of CP violation and the extraction of the CKM angles α and γ (see e.g. [8,9]). While in most cases there is a dominance of quasi-two-body final states, in some decay channels the contributions from non-resonant three-particle states seems to be rather large [10]. The study of the interference pattern of the resonances in Dalitz plots is a well established method to determine CP asymmetries [11,12], while further information can be inferred on strong resonances, such as masses, widths and quantum numbers [13].

There are, however, two obvious problems in the quasi-two-body interpretation of resonant effects in multi-body decays, one practical and one conceptual. From the practical point of view, any parametrization of resonant structures is model dependent, as no universal line-shape for strong resonances is accurate, especially for broad states. On the conceptual level, the mere separation of resonant and non-resonant contributions is not clear-cut, most prominently in the case of non-leptonic decays where non-factorizable effects exist.

In the case of two-body non-leptonic B decays, the heavy-quark limit has been exploited systematically in the context of QCD factorization [14–18] or Soft-Collinear Effective Theory (SCET) [19–23], where the matrix elements factorize into a convolution of perturbative hard kernels, form factors and meson distribution amplitudes on the light cone. Corrections to factorization arise at subleading orders in the heavy-quark/large-energy expansion, and remain a source of uncertainty which is difficult to estimate. Some potentially important non-factorizable effects might be related to nearly on-shell intermediate states, such as charm-loops or rescattering effects from light mesons. Phenomenological investigations of such effects have limited potential, mainly because the kinematics of two-body decays is fixed. On the other hand, three-body decays have at their disposal a wide phase space where the energy dependence of such effects can be studied, with the potential of providing a deeper understanding of factorization and hadronic effects in B decays.

It is fair to say that the theoretical description of three-body B decays is still in the stage of modeling. Common methods reflecting the state of the art are the isobar model [24,25] and the K-matrix formalism [26]. In these approaches, resonances are modeled and the non-resonant contributions are often described by an empirical distribution in order to reproduce the full range of the phase space [27]. In the context of factorization, in Refs. [28–30] the matrix elements were factorized naively and the resulting local correlators were computed in the framework of Heavy-Meson Chiral Perturbation Theory (HMChPT), but no attempt was made to address the breakdown of factorization or HMChPT in the respective regions of phase space where they are not expected to apply. Other recent work relying on pQCD [31], seems to reproduce experimental values for CP asymmetries integrated in certain regions of phase space [32]. However, if the conceptual issues regarding the pQCD approach [33,34] cannot be resolved, its predictive power remains limited. In the future, novel model-independent approaches that directly access CP violation (such as the Miranda procedure [12,35]) or methods based on flavor symmetries [36, 37] could become interesting; however, for a quantitative description of the differential Dalitz distributions including amplitude phase information, a QCD-based approach is unavoidable.

In the present letter we take a step in this direction, and study the factorization properties of charmless three-body and the corresponding quasi-two body B decays.[1] For that purpose,

[1] The main ideas developed here have been discussed qualitatively by M. Beneke [38] and I. Stewart [39].