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International Europhysics Conference on HEP

Designer mesons for exploring factorization in b decays

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ABSTRACT: I explain how various aspects of factorization in exclusive b decays can be studied with mesons having a small decay constant or spin greater than one.

1. Testing factorization

An outstanding task in heavy-flavor physics is to understand the strong-interaction dynamics in exclusive decays of b mesons or baryons. Often this is a condition *sine qua non* for extracting information on CP violation or possible physics beyond the standard model. A highly successful tool for this task is the concept of factorization [1], where a quark-antiquark pair created in the decay of the b-quark forms a meson independently of the remaining process (Fig. 1a). To make full use of this tool we need to understand how well it works quantitatively, and under which circumstances, i.e., for which decay channels.

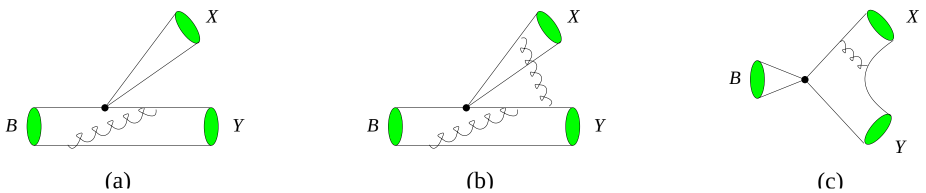

Figure 1: Example diagrams for (a) the factorization mechanism, (b) non-factorizing gluon exchange, (c) annihilation.

To be specific let us decompose a decay amplitude into its factorizing and non-factorizing parts, $\mathcal{A} = \mathcal{A}_{\text{fact}} + \mathcal{A}_{\text{non}}$. Mechanisms contributing to $\mathcal{A}_{\text{non}}$ are for instance non-factorizing gluon exchange (Fig. 1b), annihilation (Fig. 1c), intrinsic charm in the meson wave functions [2], or so-called charming penguins [3]. In decays where factorization works well we have $|\mathcal{A}_{\text{non}}| \ll |\mathcal{A}_{\text{fact}}|$, and to infer on the size of $\mathcal{A}_{\text{non}}$ from the measured branching ratio is not easy. An alternative strategy is to take channels where $\mathcal{A}_{\text{fact}}$ is absent or suppressed because of some symmetry: then $\mathcal{A}_{\text{non}}$ is much more "visible". Information from such channels can then be used to estimate $\mathcal{A}_{\text{non}}$ in decays where one can argue that the non-factorizing decay mechanisms contribute with similar size.

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2. Decays into designer mesons

A wide range of mesons is almost designed to “switch off” the factorizing piece of the decay amplitude [4, 5]. Several mesons have small or zero coupling to the vector and the axial vector currents for symmetry reasons. An example are the scalars $a_0(980)$ and $a_0(1450)$, whose decay constants are proportional to the tiny difference of the u and d quark masses and vanish in the limit of exact isospin symmetry. Other examples are b_1, $\pi(1300)$, and to a lesser degree K_0^*. Unfortunately, there is no experimental information on these decay constants, but the theory estimates in Table 1 suggest that they might be accessible in τ-decays at present or planned facilities. In the heavy quark sector, the decay constant of the χ_{c0} is zero because of charge conjugation invariance, and there is a charmed axial meson whose decay constant vanishes in the heavy-quark limit [6].

X	$a_0(980)$	$a_0(1450)$	$\pi(1300)$	$K_0^*(1430)$
f_X [MeV]	1.1	0.7	≤ 7.2	42
$B(\tau \to \nu_\tau X)$	$3.8 \cdot 10^{-6}$	$3.7 \cdot 10^{-7}$	$\leq 7.3 \cdot 10^{-5}$	$7.7 \cdot 10^{-5}$

Table 1: Theory estimates of decay constants as compiled in [4] and the corresponding branching ratios for $\tau \to \nu_\tau X$. In our convention $f_\pi \approx 131$ MeV.

The suppression of $\mathcal{A}_{\text{fact}}$ for these mesons is circumvented in decays with penguin operators involving the scalar or pseudoscalar current. All quark-antiquark currents in the effective Hamiltonian for b decays have however spin zero or one, and for mesons of higher spin such as $X = a_2, \pi_2, \rho_3, K_2^*, D_2^*, \chi_{c2}$ we strictly have $\mathcal{A}_{\text{fact}} = 0$.

To suppress the factorization mechanism one must chose the flavor structure of a decay mode so that the designer meson X has to be emitted from the weak current and cannot pick up the spectator from the B as does meson Y in Fig. 1a. In Table 2 we list some of the many channels satisfying this criterion. To know how important non-factorizing mechanisms are in these modes may help us understand the dynamical origins of factorization itself, because arguments based on color transparency [7] and arguments starting from the color structure ($1/N_c$ counting) [8] do not apply to the same decays. Note that the decay $B^+ \to K^+ \chi_{c0}$, where factorization follows from color transparency to the extent that the χ_{c0} has a small radius, has recently been observed [9]. If the emitted meson X is made from light quarks, color transparency predicts non-factorizing interactions to be small if the energy-mass ratio E_X/m_X is large. This can be tested by comparing channels with designer mesons of different mass.

Exploring factorization in designer decays is complementary to the classical factorization tests with modes like $\bar{B} \to D^+ \pi^-$, $\bar{B} \to D^+ a_1^-$, etc. To obtain meaningful constraints on $\mathcal{A}_{\text{non}}$ there one needs high precision, both in the measurement and the theory calculation, with decay constants and form factors being crucial ingredients. In designer decays, where the branching ratio gives rather direct information on $\mathcal{A}_{\text{non}}$, one can relax these requirements. The price to pay is typically a lower branching fraction and the requirement to handle multi-particle final states. Angular analysis may be necessary, e.g., in order to

decay mode	factorization should hold according to color transparency	$1/N_c$ counting
$\bar{B}^0 \to D^+ a_0^-$	yes	yes
$\bar{B}^0 \to D^+ D_{s2}^-$	no	yes
$B^+ \to K^+ \chi_{c0}$	yes	no
$\bar{B}^0 \to \pi^0 D_2^{*0}$	no	no
$\bar{B}_s \to D_s^+ a_0^-$	yes	yes
$\bar{B}_s \to D_s^+ D_2^{*-}$	no	yes
$\bar{B}_s \to \eta\, \chi_{c0}$	yes	no
$\bar{B}_s \to K^0 D_2^{*0}$	no	no
$\Omega_b \to \Omega_c\, a_0^-$	yes	yes
$\Lambda_b \to \Lambda_c D_{s2}^-$	no	yes
$\Lambda_b \to \Lambda\, \chi_{c0}$	yes	no
$\Omega_b \to \Xi^- D_2^{*0}$	no	no

Table 2: Selected decays into designer mesons where the factorizing contribution is suppressed.

separate suppressed decays into K_0^* or K_2^* from allowed ones into K_1^* since the three states are nearly mass degenerate and decay predominantly into $K\pi$.

In analogy to usual factorization tests [10] it is actually not necessary to separate resonant production of designer mesons from continuum production: the suppression of $\mathcal{A}_{\text{fact}}$ holds for instance just as well for a K_2^* as for $K\pi$ continuum state with angular momentum $J = 2$.

3. Decays into heavy-light states and hard non-factorizing interactions

B decays into a D or D^* and a light meson X emitted by the weak current allow the application of powerful theory concepts. Among them is QCD factorization [11], where $\mathcal{A}_{\text{non}}$ can be separated into a soft part $\mathcal{A}_{\text{non, soft}}$ that is power suppressed in $1/m_b$ and a part $\mathcal{A}_{\text{non, hard}}$ of order α_s due to hard interactions. The latter corresponds to diagrams as in Fig. 1b and can be calculated if one knows the meson distribution amplitude $\varphi_X(u)$ describing the transition from the $q\bar{q}$ pair to the meson X. Such a mechanism evades the suppression discussed above. In Fig. 1b an interaction takes place between the creation of the $q\bar{q}$ pair at the b decay vertex and its hadronization into the meson X. Even if X has small or zero coupling to the *local* quark-antiquark current of the b decay, its distribution amplitude $\varphi_X(u)$ need not be small since it involves the corresponding *nonlocal* current. In fact, $|\varphi_X(u)|^2$ is related to the probability that X fluctuates into a current $q\bar{q}$ pair, and we used this relation in [4] to estimate the size of the meson distribution amplitudes. Experimental constraints on these important quantities could be obtained in the process $e^+e^- \to e^+e^- X$ when one of the lepton beams receives a large invariant momentum transfer Q^2. This has already been exploited for the mesons π, η and η' [12].

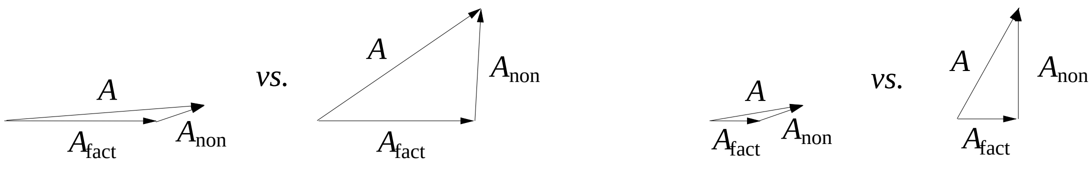
In Table 3 we estimate branching ratios for some decay modes, both in naive and in QCD factorization. We find non-factorizing contributions $\mathcal{A}_{\text{non, hard}}$ of similar size for decays into designer mesons and for modes like $\bar{B} \to D^+\pi^-$, where they only amount to a few percent of the large amplitude $\mathcal{A}_{\rm fact}$. In designer channels, on the other hand, $\mathcal{A}_{\rm non,\,hard}$ can be comparable to or bigger than $\mathcal{A}_{\rm fact}$, as comparison of the naive and QCD factorization results in Table 3 shows. To be sure, our rate estimates are fraught with uncertainties from the unknown decay constants and distribution amplitudes, and also with a strong renormalization scale dependence of $\mathcal{A}_{\rm non,\,hard}$ at leading order in α_s. Most important is however that $\mathcal{A}_{\rm non,\,hard}$ is *tiny* on the scale of, say, the amplitude for $\bar{B} \to D^+\pi^-$ and may well be overshadowed by the soft factorization breaking described by $\mathcal{A}_{\rm non,\,soft}$. Whether this is the case could be revealed by data on the branching ratios for designer channels. Since calculating $\mathcal{A}_{\rm non,\,soft}$ is extremely hard for theory, this would be valuable information indeed. Note that for some channels even the small rates we estimated should be within current experimental reach, and measurement would be even easier if $\mathcal{A}_{\rm non,\,soft}$ were large compared with our estimates of $\mathcal{A}_{\rm fact} + \mathcal{A}_{\rm non,\,hard}$.

decay mode	naive factorization	QCD factorization	
		$\mu = m_b$	$\mu = \frac{1}{2}m_b$
$\bar{B}^0 \to D^+ a_0(980)$	$1.1 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$4.0 \cdot 10^{-6}$
$\bar{B}^0 \to D^+ a_0(1450)$	$8.6 \cdot 10^{-8}$	$5.8 \cdot 10^{-7}$	$2.1 \cdot 10^{-6}$
$\bar{B}^0 \to D^+ a_2$	0	$3.5 \cdot 10^{-7}$	$1.7 \cdot 10^{-6}$
$\bar{B}^0 \to D^+ \pi(1300)$	$9.1 \cdot 10^{-6}$	$9.3 \cdot 10^{-6}$	$9.6 \cdot 10^{-6}$
$\bar{B}^0 \to D^+ \pi_2$	0	$1.4 \cdot 10^{-9}$	$8.1 \cdot 10^{-9}$
$\bar{B}^0 \to D^+ K_0^*(1430)$	$2.0 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$	$2.1 \cdot 10^{-5}$
$\bar{B}^0 \to D^+ K_2^*$	0	$1.9 \cdot 10^{-8}$	$9.2 \cdot 10^{-8}$

Table 3: Branching ratio estimates in naive factorization and in QCD factorization to $O(\alpha_s)$ with two choices for the factorization scale μ. We find similar values for the corresponding decays $\bar{B}^0 \to D^{*+}X^-$, $\bar{B}_s \to D_s^+ X^-$, and $\bar{B}_s \to D_s^{*+} X^-$.

4. Decays into light-light states and penguins

B decays into two light mesons present a much greater complexity in the electroweak and the strong dynamics. Among the questions currently under debate is the importance of annihilation graphs (Fig. 1c) with penguin operators, which could have a strong impact on the study of *CP* violation. Whether annihilation graphs can be reliably calculated is controversial: whereas in QCD factorization they are $1/m_b$ corrections and can only be estimated [13], their evaluation for $B \to K\pi$ in the pQCD approach of Li et al. [14] found them to be substantial and with a large phase relative to the factorizing contribution. Notice that depending on that phase one can obtain the same branching fraction with a small or a large contribution from $\mathcal{A}_{\rm non}$, see Fig. 2a. Hints concerning the two scenarios sketched there could be obtained in the designer modes $\bar{B} \to \pi^+ K_2^{*-}$ and $B^- \to \pi^- K_2^{*0}$. Compared with $B \to \pi K$ the factorizing amplitude $\mathcal{A}_{\rm fact}$ would be suppressed but not $\mathcal{A}_{\rm non}$, where penguin annihilation contributes, and the total amplitude would be quite different in the two cases, see Fig. 2b.



(a) (b)

Figure 2: (a) The same $|\mathcal{A}|$ can be obtained with largely different values of $\mathcal{A}_{\rm non}$, depending on its phase. (b) Suppressing $\mathcal{A}_{\rm fact}$ but not $\mathcal{A}_{\rm non}$ leads to distinct results for $|\mathcal{A}|$ in the two scenarios.

5. More use for designer mesons

Designer mesons are a versatile tool to suppress selected contributions in b decay processes. This can be used to explore the dynamics of factorization, but there are other possibilities. One example is to extract the CKM phase $2\beta + \gamma$ using the interference between mixing and decay in $B^0/\bar{B}^0 \to D^\pm a_0^\mp$ or similar channels [15]. In contrast to the well-studied case of $B^0/\bar{B}^0 \to D^\pm \pi^\mp$, the designer channels can have large interference effects, the price to pay being a lower total event rate. Ways to investigate *CP* violation in decays to light-light final states with designer mesons have been proposed in [16]. With the experimental possibilities at present and in the near future, decays into designer mesons should provide various possibilities to study important aspects of B physics.

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