Exclusive decays of the doubly heavy baryon Ξ_{bc}

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Exclusive decays of the Ξ_{bc}^+ with light meson production, $\Xi_{bc}^+ \to \Xi_{cc}^{++}\mathcal{R}$, are analyzed. In the framework of the factorization model, the matrix elements of the considered reactions are written as a product of $\Xi_{bc} \to \Xi_{cc}W$ and $W \to \mathcal{R}$ transition amplitudes. As a result, theoretical and experimental investigation of these decays allows us to test the physics of heavy and light quark sectors. Presented are the branching fractions of these reactions, as well as the distributions over the invariant mass of the light system and some other kinematical variables. Our calculations show that the probabilities of the considered reactions are high enough, so presented results could help with observations of the yet unseen Ξ_{bc} baryon.

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I. INTRODUCTION

Doubly heavy baryons (DHBs) are extremely interesting objects that allow us to take a fresh look at the problem of hadronization of heavy quarks. In valence approximation these particles are built from two heavy and one light quark (Q_1Q_2q), and one of the ways to describe such states is to consider two of the valence quarks (e.g., Q_1q) as a heavy diquark in an antitriplet color state. This leaves us with the effective heavy-quarkoniumlike particle $([Q_1q]_{\bar{3}_c}Q_2)$ and allows us to check all theoretical methods created for a heavy quarkonia description of a new set of objects.

There are a lot of theoretical works devoted to the spectroscopy of doubly heavy baryons [1–3], their production cross sections [4–6], lifetimes [7–10], and branching fractions of some exclusive decays [11–13]. A nice theoretical review for this class of particles can also be found in [14]. Until recently, however, such an interest was mostly theoretical since no DHB states were observed experimentally. The first experimental result was published by the SELEX Collaboration. In [15] it was announced that the Ξ_{cc}^+ baryon was observed in the $\Xi_{cc}^+ \to pD^+K^-$ decay channel. This result was not confirmed, but the LHCb Collaboration later managed to observe the other doubly charged Ξ_{cc}^{++} baryon in the $\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ decay channels [16,17].

Currently the Ξ_{cc}^{++} baryon is the only DHB particle to have been observed experimentally. We are hoping, however, that the discovery of some other particles of this family is ahead. As an interesting example, we would like to mention DHB states with mixed heavy flavors, e.g., $\Xi_{bc}^+ = (bcu)$. The cross section of its production is expected to be comparable to the cross section of B_c meson production, which has already been observed in hadronic experiments [18,19]. For this reason it will be very interesting to study in more detail some of the Ξ_{bc} baryon's decays.

This topic has also been widely discussed in the literature. In our paper we would like to consider in more detail the processes of light meson production in exclusive Ξ_{bc} decays. In our recent paper [20] this problem was studied in the framework of the spectral function approach. Such an approach, however, allows one to obtain only the distributions over the invariant mass of the light meson system and calculate the integrated branching fractions. For a comparison with future experimental data more detailed theoretical predictions (including distributions over other kinematical variables) will be required. This is the topic of our paper. As you can see in the above-mentioned paper, the branching fractions of light meson production $\Xi_{bc}^+ \to \Xi_{cc}^{++}$ transitions are large enough and, in addition, the Ξ_{cc}^{++} baryon has already been observed in experiment. This is why one could expect that these decays will be observed in the nearest future, so in our paper we will concentrate specifically on them.

The rest of the paper is organized as follows. In Sec. II the matrix elements of the considered decays are presented and the parametrization of the form factors used is given. In Sec. III we describe the spectral function formalism, provide expressions for light meson production vertices, and give predictions for integrated branching fractions and transferred momentum distributions obtained with different parametrizations of the form factors. In Sec. IV distributions over some other kinematical variables are presented and discussed. The results of our work are summarized in Sec. V.

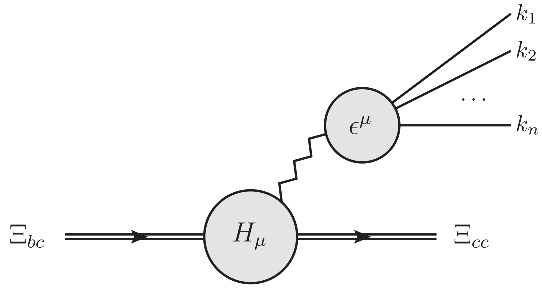

FIG. 1. Feynman diagram describing $\Xi_{bc}^+ \to \Xi_{cc}^{++}\mathcal{R}$ decay.

II. $\Xi_{bc}^+ \to \Xi_{cc}^{++}$ MATRIX ELEMENT AND FORM FACTORS

Let us consider an exclusive decay of Ξ_{bc}^+ baryon with the production of light particle system $\mathcal{R}$, which could be a semileptonic pair $\ell\nu_\ell$, a single π meson, ρ, or even some larger set of light mesons. At the leading order of the perturbation theory this process is described by the Feynman diagram shown in Fig. 1. The corresponding matrix element can be written in the form

$$\mathcal{M} = \frac{G_F V_{\mathrm{CKM}}}{\sqrt{2}} a_1 H^\mu \epsilon_\mu^{(\mathcal{R})}, \tag{1}$$

where $\epsilon_\mu^{\mathcal{R}}$ is the effective polarization vector of the system $\mathcal{R}$, H^μ is the matrix element of the $\Xi_{bc}^+ \to \Xi_{cc}^{++}$ transition, and the a_1 factor describes the effect of soft gluon rescattering [21]. It should be set equal to unity in the case of the semileptonic pair in the final state, and, since we are dealing with b-quark decay,

$$a_1 = 1.2 \tag{2}$$

in all other cases.

The matrix element of the $\Xi_{bc} \to \Xi_{cc}$ transition is written using the corresponding form factors, and it can be done in several ways. In [22,23], for example, the parametrization

$$H_\mu = \bar{u}(P_1)\left[f_1(q^2)\gamma_\mu + i\frac{q^\mu}{M_1}\sigma_{\mu\nu}f_2(q^2) + \frac{q_\mu}{M_1}f_3(q^2)\right]u(P_2) + \bar{u}(P_1)\left[g_1(q^2)\gamma_\mu + i\frac{q^\mu}{M_1}\sigma_{\mu\nu}g_2(q^2) + \frac{q_\mu}{M_1}g_3(q^2)\right]\gamma_5 u(P_2) \tag{3}$$

was adopted. Here the notation

$$\sigma_{\mu\nu} = \frac{i}{2}(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu) \tag{4}$$

is introduced, $P_{1,2}$ and $q = P_1 - P_2$ are the momenta of the final and initial baryons and the transferred momentum,

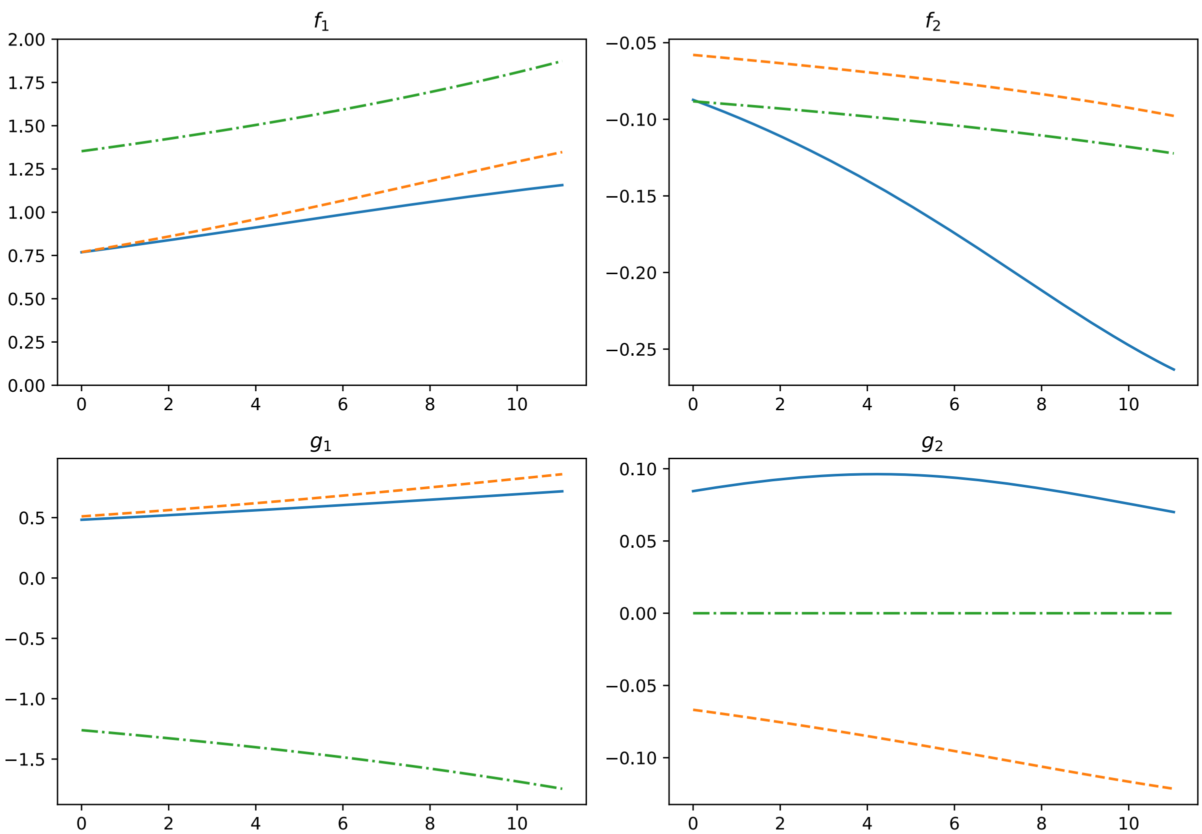

FIG. 2. Form factors of the $\Xi_{bc}^+ \to \Xi_{cc}^{++}$ transition as a function of squared transferred momentum q^2 (in GeV^2). Solid, dashed, and dash-dotted lines correspond to [W_17], [H_20], and [O_00] form factor sets, respectively.

TABLE I. Form factor parameters in the case of a $\Xi_{bc}^{+} \to \Xi_{cc}^{++}$ transition.

	On_00			W_17			H_20		
	$F(0)$	α_1	α_2	$F(0)$	α_1	α_2	$F(0)$	α_1	α_2
f_1	1.36	1.12	2.36	0.76	2.40	−0.57	0.77	2.94	1.84
f_2	−0.09	1.12	2.36	−0.08	7.37	9.30	−0.06	1.84	4.73
g_1	−1.26	1.12	2.36	0.48	1.88	1.16	0.51	2.38	2.75
g_2	−0.00	1.12	2.36	0.08	2.84	−16.21	−0.07	3.33	1.62

respectively, and M_1 is the mass of the initial particle. In [11,24], on the other hand, the vertex of the weak decay is parametrized as

$$H_\mu = \bar{u}(P_1)[G_1^V(q^2)\gamma_\mu + v_{1\mu}G_2^V(q^2) + v_{2\mu}G_3^V(q^2)]u(P_2)+ \tag{5}$$

$$\bar{u}(P_1)\gamma_5[G_1^A(q^2)\gamma_\mu + v_{1\mu}G_2^A(q^2) + v_{2\mu}G_3^A(q^2)]u(P_2), \tag{6}$$

where $v_{1,2} = P_{1,2}/M_{1,2}$ are the invariant velocities of the initial and final baryons. The following relations can be used to switch from one parametrization to the other:

$$f_1 = G_1^V + (M_1 + M_2)\left(\frac{G_2^V}{2M_1} + \frac{G_3^V}{2M_2}\right), \tag{7}$$

$$f_2 = -\frac{G_2^V}{2M_1} - \frac{G_3^V}{2M_2}, \tag{8}$$

$$f_3 = -\frac{G_2^V}{2M_1} + \frac{G_3^V}{2M_2,}, \tag{9}$$

$$g_1 = -G_1^A - (M_1 - M_2)\left(\frac{G_1^A}{2M_1} + \frac{G_2^A}{2M_2}\right), \tag{10}$$

$$g_2 = \frac{G_2^A}{2M_1} + \frac{G_3^A}{2M_2}, \tag{11}$$

$$g_3 = \frac{G_2^A}{2M_1} - \frac{G_3^A}{2M_2}. \tag{12}$$

In the following form factors presented in [11,22,23] will be used, and we will mark them as [On_00], [W_17], and [H_20], respectively. The parametrization (3) will be used for all these form factor sets. Because of vector and partial current conservation the contributions of the $f_3(q^2)$, $g_3(q^2)$ form factors are negligible, while the q^2 dependence of all others is shown in Fig. 2. All of these form factors can be written approximately in the form

$$F(q^2) = F(0)\left[1 + \alpha_1\frac{q^2}{M_1^2} + \alpha_2\left(\frac{q^2}{M_1^2}\right)^2\right], \tag{13}$$

where the $F(0)$, $\alpha_{1,2}$ parameters are as given in Table I.

III. SPECTRAL FUNCTION FORMALISM AND q^2 DISTRIBUTIONS

To describe in detail all kinematics of decay it is necessary to use various numerical methods. If we are interested in q^2 distributions or the values of the integrated branching fractions only, it is possible to obtain the analytical expressions with the help of the spectral function formalism. This method was successfully used, for example, for descriptions of τ-lepton [25,26] or B_c meson [27–31] decays.

In the framework of this approach the transferred momentum distribution is written in the form

$$\frac{d\Gamma}{dq^2} = H_T^2\rho_T^{(\mathcal{R})} + H_L^2\rho_L^{(\mathcal{R})}, \tag{14}$$

where transverse and longitudinal squared matrix elements $H_{T,L}^2$ are equal to

$$\begin{aligned}
H_T^2 = H^\mu H^{\nu*}(q_\mu q_\nu - q^2 g_{\mu\nu}) = \frac{1}{2M_1^2}&[f_1^2 M_1^2(-2q^4 + 2q^2M_-^2 - q^2M_+^2 + M_-^2M_+^2)\\
&+ 12f_1f_2q^2M_+(q^2 - M_-^2)M_1 - 4f_2^2q^2(q^4 - q^2M_-^2 + 2q^2M_+^2 - 2M_-^2M_+^2)\\
&+ g_1^2(M_- + M_+)^2(-2q^4 - q^2M_-^2 + 2q^2M_+^2 + M_-^2M_+^2) + 12g_1g_2q^2M_-(M_+^2 - q^2)(M_- + M_+)\\
&- 4g_2^2q^2(q^4 + 2q^2M_-^2 - q^2M_+^2 - 2M_-^2M_+^2)],\\
H_L^2 = H^\mu H^{\nu*}q_\mu q_\nu = 2[f_1^2&M_-^2(M_+^2 - \mathrm{q}^2) + g_1^2M_+^2(M_- - \mathrm{q}^2)],
\end{aligned} \tag{15}$$

$$M_\pm = M_1 \pm M_2, \tag{16}$$

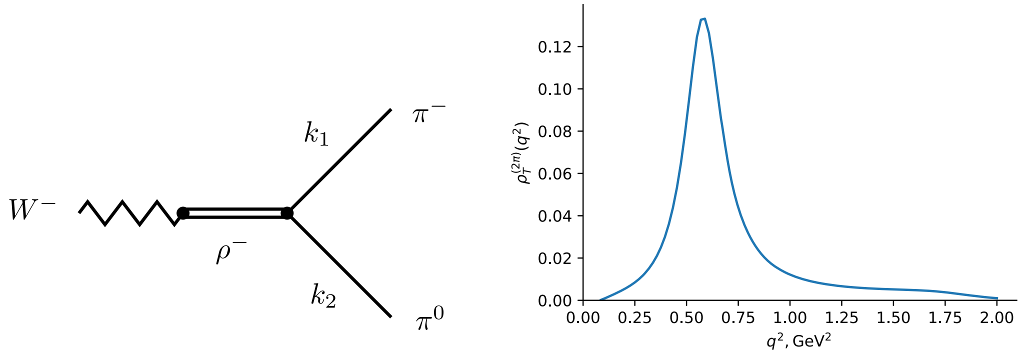

FIG. 3. Feynman diagram for the $W \to 2\pi$ transition and the corresponding spectral function.

while the spectral functions $\rho_{L,T}(q^2)$ are defined by the expression

$$\frac{1}{2\pi}\int \delta^4\left(q-\sum k_i\right)\prod \frac{d^3k_i}{2e_i(2\pi)^3}\epsilon_\mu^{(\mathcal{R})}\epsilon_\nu^{*(\mathcal{R})} = \rho_L^{(\mathcal{R})}q_\mu q_\nu + \rho_T^{(\mathcal{R})}(q_\mu q_\nu - q^2 g_{\mu\nu}). \tag{17}$$

The explicit form of the spectral functions depends on the final state $\mathcal{R}$.

In some simple cases it is easy to obtain analytical expressions for these spectral functions. If we are considering the production of the single π meson, for example, the effective polarization vector in Eq. (1) is equal to

$$\epsilon_\mu^{(\pi)} = f_\pi q_\mu, \tag{18}$$

so we have

$$\rho_T^{(\pi)} = 0, \qquad \rho_L^{(\pi)} = f_\pi^2\delta(q^2 - m_\pi^2). \tag{19}$$

In the case of single ρ meson production the expressions are

$$\epsilon_\mu^{(\rho)} = f_\rho m_\rho \epsilon_\mu, \qquad \rho_L^{(\rho\pi)} = 0, \qquad \rho_T^{(\rho)} = f_\rho^2\delta(q^2 - m_\rho^2). \tag{20}$$

For semileptonic decays we have

$$\epsilon_\mu^{(\ell\nu)} = \bar{u}(k_1)\gamma_\mu(1-\gamma_5)v(k_2), \quad \rho_L^{(\ell\nu)} = 0, \quad \rho_T^{(\ell\nu)} = \frac{1}{6\pi^2}, \tag{21}$$

where the mass of the final lepton ℓ is neglected.

In more interesting and complicated cases it is not possible to obtain the analytical expressions for the spectral functions, so we should use some model approaches. Available experimental data, for example, the processes of the light meson production in exclusive τ-lepton decays can also be very helpful. For these processes the q^2 distributions is equal to

$$\frac{d\Gamma(\tau \to \nu_\tau \mathcal{R})}{dq^2} = \frac{G_F^2}{16\pi}\frac{(m_\tau^2 - q^2)^2}{m_\tau^3}(m_\tau^2 + 2q^2)\rho_T^{(\mathcal{R})}(q^2). \tag{22}$$

From the analysis of the experimental distribution over this variable one can get information about both the form of the transversal spectral function and its normalization.

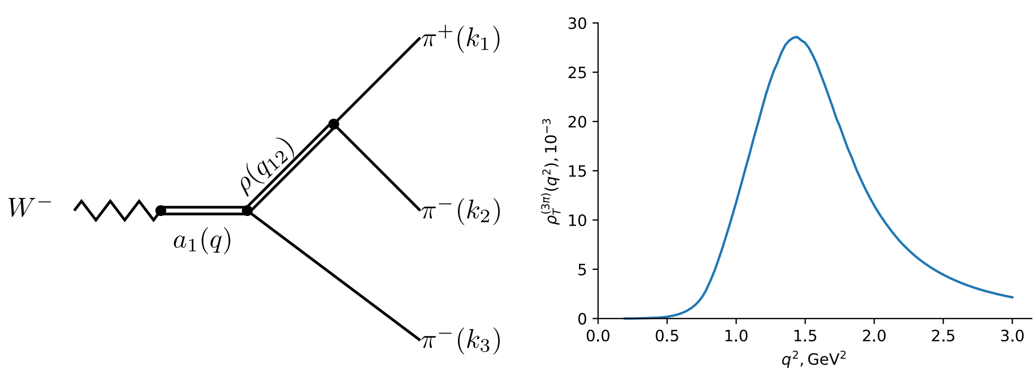

FIG. 4. Feynman diagram for the $W \to \pi^-\pi^-\pi^+$ transition and the corresponding spectral function.

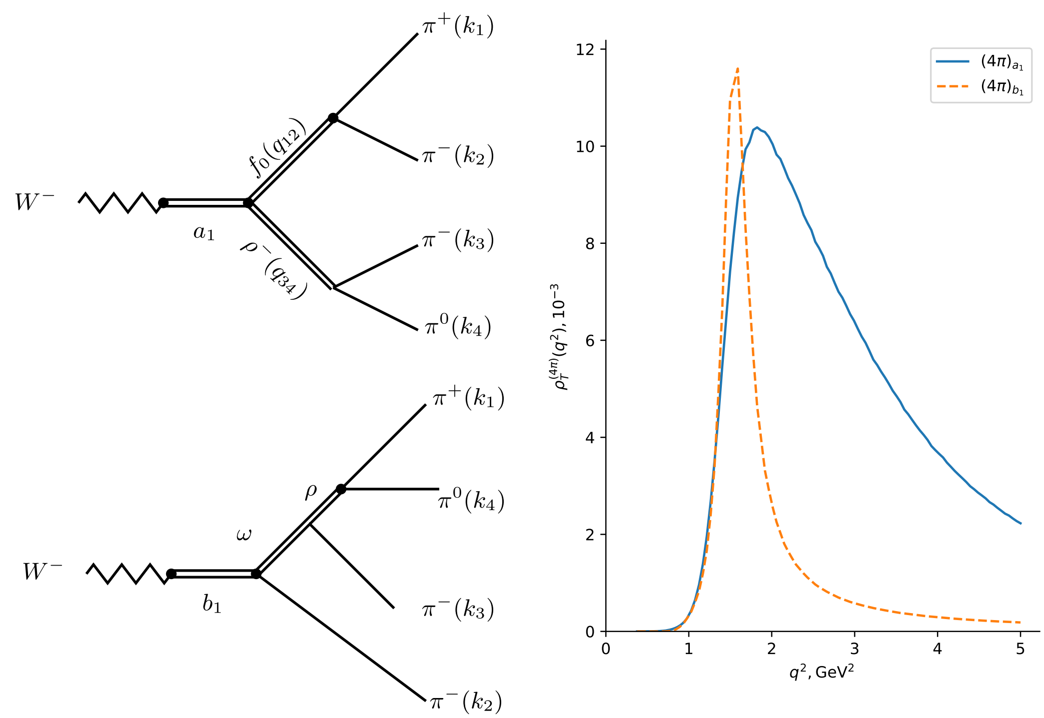

FIG. 5. Feynman diagrams for the $W \to \pi^-\pi^-\pi^+\pi^0$ transition and the corresponding spectral function $W \to 4\pi$.

Let us first consider the exclusive production of the $\pi^-\pi^0$ pair. In the resonance approach this process is described by the diagram shown in Fig. 3. As you can see in this diagram, we are saturating the process under consideration by the contributions of the ρ meson and its excitations. Up to overall normalization the analytical form of the corresponding amplitude can be guessed from the quantum numbers of the particles participating in the reaction:

$$\epsilon_\mu^{(2\pi)} \sim (k_1 - k_2)_\mu \hat{D}_\rho(q^2) = (k_1 - k_2)_\mu [D_\rho(q^2) + \beta D_{\rho'}(q^2)]. \tag{23}$$

Here q is the total momentum of the pionic pair, $k_{1,2}$ are the momenta of the final pions, the Lorentz structure of the expression is caused by the fact that these particles are in the P-wave state, and the propagator of the virtual resonance is written in the Flatte form [25,26,32]

$$D_\rho(q^2) = \frac{m_\rho^2}{m_\rho^2 - q^2 - i m_\rho \Gamma_\rho(q^2)}, \tag{24}$$

where the energy-dependent ρ meson width

$$\Gamma_\rho(q^2) = \left(\frac{1 - 4m_\pi^2/q^2}{1 - 4m_\pi^2/m_\rho^2}\right)^{3/2} \Gamma_\rho^{\mathrm{exp}} \tag{25}$$

was introduced. The propagator of the excited ρ is defined in a similar way, and, according to [33], the mixing parameter β is equal to

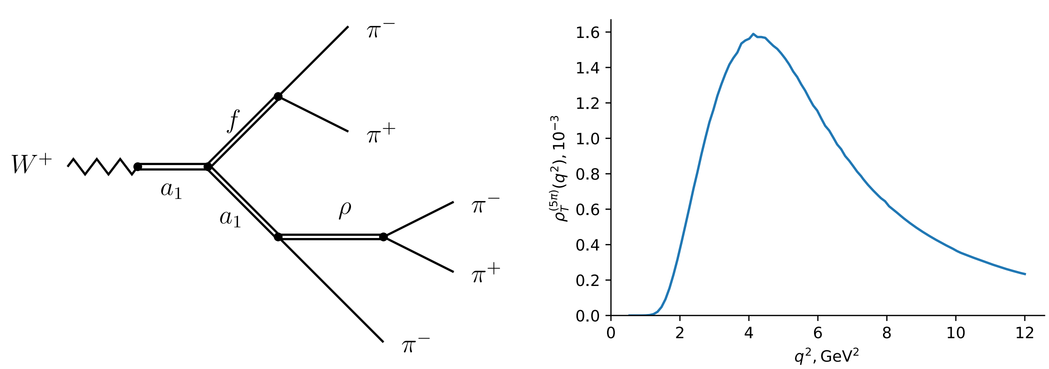

FIG. 6. Feynman diagram and spectral function of the $W \to 5\pi$ transition.

TABLE II. The branching fractions of $\Xi_{bc}^{+} \to \Xi_{cc}^{++}\mathcal{R}$ decays (in %).

$\mathcal{R}$	[On_00]	[W_17]	[H_20]
2π	1.86	0.41	0.47
3π	1.29	0.29	0.33
$(4\pi)_{a_1}$	1.16	0.27	0.29
$(4\pi)_{b_1}$	0.31	0.07	0.08
5π	0.33	0.07	0.08

$$\beta = -0.108. \tag{26}$$

The normalization of the amplitude (23) is determined by the experimental value of the branching fraction

$$\mathrm{Br}(\tau \to \nu_\tau \pi^- \pi^0) = 25.49\%. \tag{27}$$

Obtained in this way, the spectral function is shown in the right panel of Fig. 3.

If the production of three π mesons is considered, in the resonance approximation one can take into account the diagram shown in Fig. 4 only. The analytical expression for the corresponding amplitude is

$$\mathcal{A}_\mu^{(3\pi)} \sim D_{a_1}(q^2)\hat{D}_\rho[q_{12}^2]\left[g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right](k_1 - k_2)^\nu + \{k_2 \leftrightarrow k_3\}, \tag{28}$$

where the particles' momenta are shown in the figure, symmetrization is performed over the identical π^- mesons, the virtual a_1 meson propagator is equal to

$$D_{a_1}(q^2) = \frac{m_{a_1}^2}{m_{a_1}^2 - q^2 + i m_{a_1}\Gamma_{a_1}(q^2)}, \tag{29}$$

and the propagator of the ρ meson and its excitations is as in Eq. (24). The normalization branching fraction is equal to

$$\mathrm{Br}(\tau \to \nu_\tau \pi^- \pi^- \pi^+) = 9.31\%. \tag{30}$$

and the q^2 dependence of the spectral function $\rho_T^{(3\pi)}$ can be found in the right panel.

According to the Feynman diagrams shown in Fig. 5, production of a 4π system can occur via either a_1 or b_1 virtual resonance. The matrix element of the first process can be written in the form

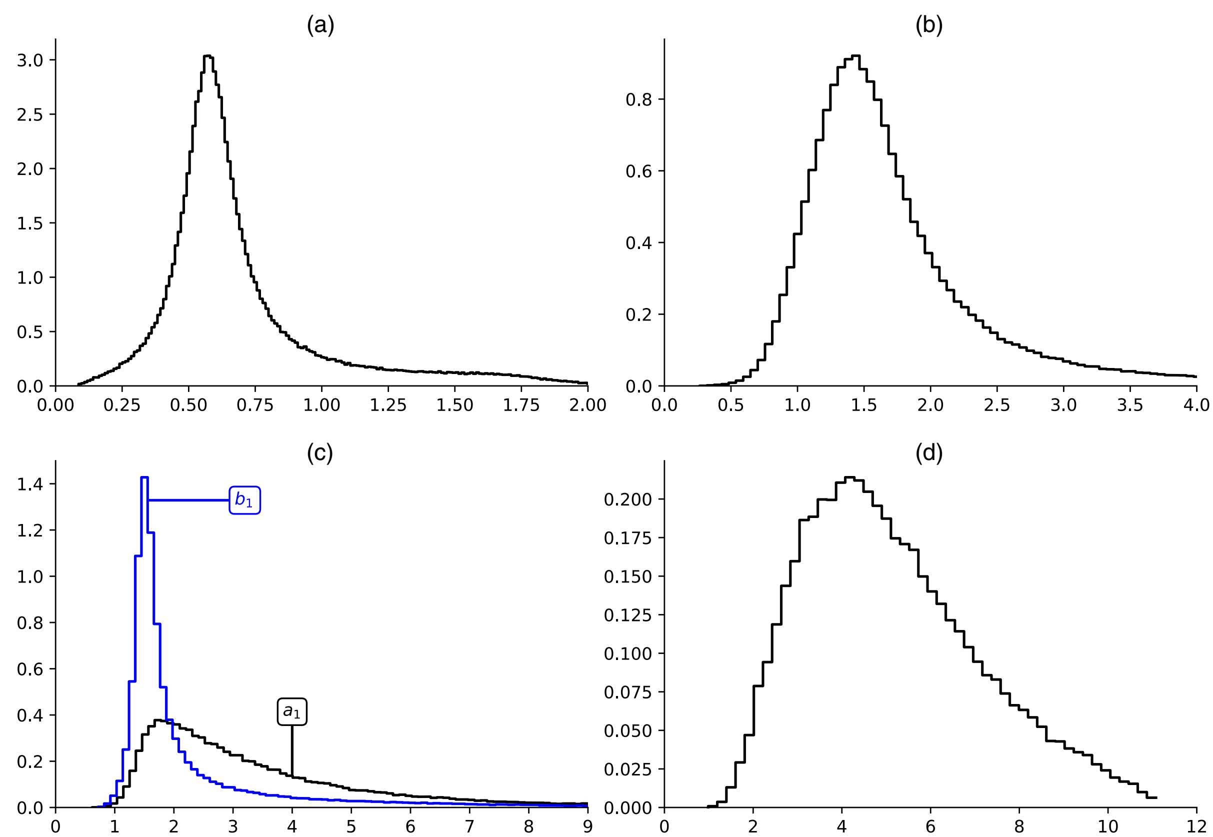

FIG. 7. Normalized distributions of the $\Xi_{bc}^{+} \to \Xi_{cc}^{++}\mathcal{R}$ branching fractions over the squared transferred momentum q^2 (in GeV^2) for different final states. (a)–(d) correspond to final states $\mathcal{R} = 3\pi$, 3π, 4π, and 5π, respectively. Only results of [On_00] for factors set are given.

$$\mathcal{A}_\mu^{(4\pi,a_1)} \sim D_{a_1}(q^2)D_f(q_{12}^2)D_\rho(q_{34}^2)\left[g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right](k_3-k_4)^\nu + \{k_2 \leftrightarrow k_3\}, \tag{31}$$

where $q_{12} = k_1 + k_2$ and $q_{34} = k_3 + k_4$ are the momenta of the f_0 and ρ mesons, respectively, and the Flatte parametrization of the f_0 meson propagator is equal to

$$D_f(q) = \frac{m_f^2}{m_f^2 - q^2 + im_f\Gamma_f(q^2)},$$
$$\Gamma_f(q^2) = \left(\frac{1-4m_\pi^2/q^2}{1-4m_\pi^2/m_f^2}\right)^{1/2}\Gamma_f^{\mathrm{exp}}. \tag{32}$$

As you can see, the exponent in the expression for the running width of the f_0 meson is different than that of the ρ meson [see Eq. (24)]. The reason is that in the decay of the f_0 meson the final particles are in the S wave. The amplitude of the $W \to b_1 \to 4\pi$ transition, on the other hand, can be written as

$$\mathcal{A}_\mu^{(4\pi,b_1)} \sim D_{b_1}(q^2)D_\omega(q_{123}^2)D_\rho(q_{12})e_{\mu\nu\alpha}q_{123}^\nu q_{12}^\alpha(k_1-k_2)^\beta, \tag{33}$$

where q_{123} and q_{12} are the momenta of the virtual ω and ρ mesons, respectively, and all propagators are as defined in relations (24), (29), and (32). Owing to the smallness of the ω meson's width, these two channels do not interfere with each other and the coupling constants can be determined from the branching fractions of the corresponding τ-lepton decays:

$$\mathrm{Br}[\tau \to a_1\nu_\tau \to 4\pi] = 2.74\%, \tag{34}$$

$$\mathrm{Br}[\tau \to b_1\nu_\tau \to 4\pi] = 1.8\%. \tag{35}$$

Let us finally discuss production of the 5π meson system. The matrix element of this transition is (see the right panel of Fig. 6 for the corresponding Feynman diagram)

$$\mathcal{A}_\mu^{(5\pi)} \sim D_{a_1}(q^2)D_{a_1}(q_{123}^2)D_f(q_{45}^2)D_\rho(q_{13}^2)\left[\frac{q_\mu q_\nu}{q^2} - g_{\mu\nu}\right] \times \left[\frac{q_{123}^\nu q_{123}^\alpha}{q_{123}^2} - g^{\nu\alpha}\right](k_1-k_3)_\alpha + \text{permutation}, \tag{36}$$

where the particles' momenta are shown in Fig. 6 and the overall normalization can be determined from the branching fraction

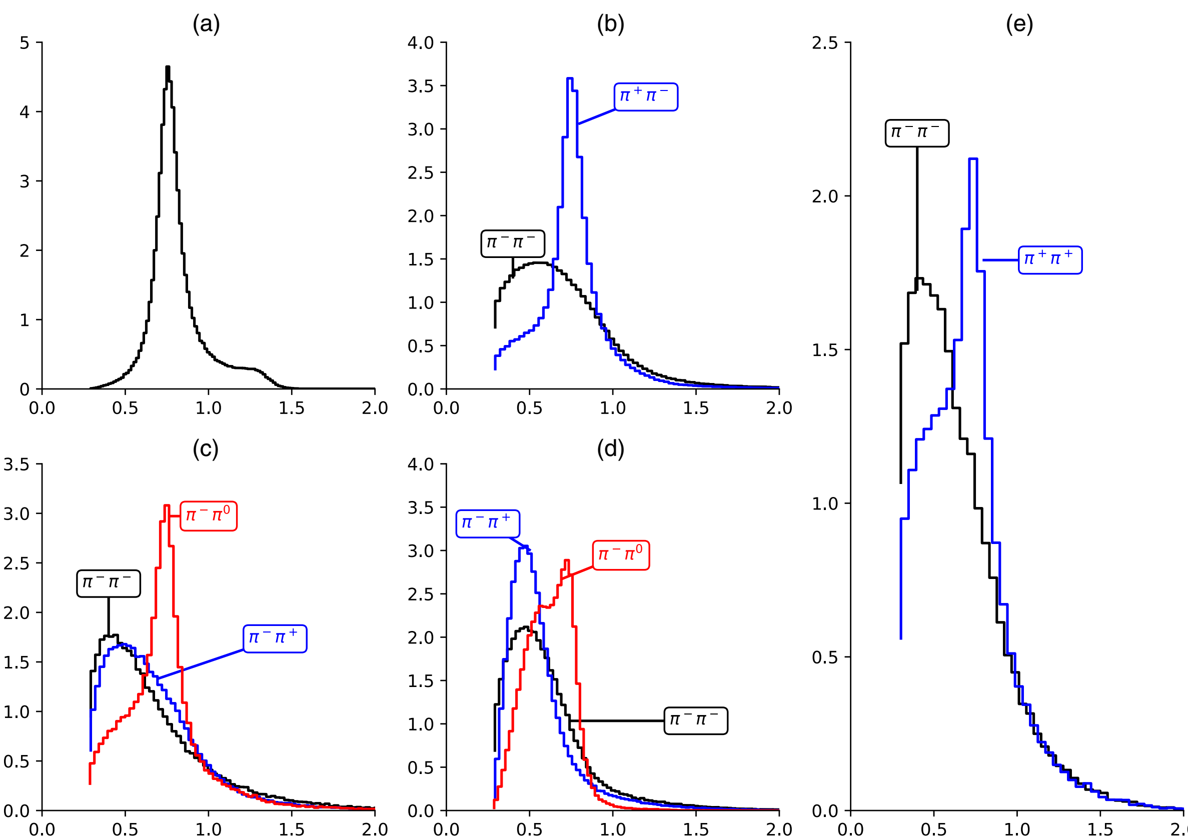

FIG. 8. Normalized distributions of the decays $\Xi_{bc}^+ \to \Xi_{cc}^{++}\mathcal{R}$ over the invariant mass $\pi\pi$ system (in GeV). (a)–(e) correspond to the final states $\mathcal{R} = 2\pi$, 3π, $(4\pi)_{a_1}$, $(4\pi)_{b_1}$, and 5π, respectively.

$$\mathrm{Br}(\tau \to \nu_\tau \pi^+\pi^+\pi^-\pi^-\pi^-) = 8.27 \times 10^{-4}. \quad (37)$$

The spectral function itself is shown in the right panel of the figure.

With the help of the above analytical expressions, spectral functions, and form factors it is easy to obtain in Table II branching fractions of the decays considered in our article. In these calculations the following values for Ξ_{bc}^+ mass and total lifetime [7,34] were used:

$$M_{\Xi_{bc}^+} = 6.943\ \mathrm{GeV}, \qquad \tau_{\Xi_{bc}^+} = 0.24 \pm 0.02\ \mathrm{ps}. \quad (38)$$

From the presented table it can be clearly seen that the branching fractions of some of the decays are rather large, so it could be possible to observe them experimentally. It is also worth mentioning that theoretical predictions depend strongly on the choice of form factor set. As a result, new experimental data about these decays could help us to see which model describes better the real physics of the doubly heavy baryons.

Distributions over the squared mass of the light mesons' system are shown in Fig. 7. Our calculations show that the forms of these distributions depend only slightly on the choice of form factors set, so only the normalized result for [On_00] the form factor set is shown in the figure.

IV. DISTRIBUTIONS OVER THE OTHER KINEMATICAL VARIABLES

In this section we will discuss distributions over some other kinematical variables (such as the invariant mass of the pion pair). It is clear that these distributions require complete information about the dynamics of the process, so the spectral function formalism cannot be used. Moreover, since we are working with decays with a large number of particles in the final state, one cannot use just any analytical method—only numerical calculations are appropriate. One of the convenient tools that can help in such situations is the Monte Carlo generator EvtGen [35,36] that is used by the LHCb Collaboration. Our group has created the required software models, and in the following we discuss the results obtained using these models. As mentioned above, the form of the normalized distributions depends only slightly on the choice of form factor set, so below we present only the result of the [11] parametrization.

Let us first consider distributions over the invariant mass of the π meson pair (see Fig. 8). It is clear from the figure that the form of the distribution depends both on the final state $\mathcal{R}$ and the charge of the mesons. In the case of three π meson production, for example, you can see a clear peak in the $m_{2\pi} \approx m_\rho$ region in the $m_{\pi^+\pi^-}$ distribution [see Fig. 8(b)], while in the case of $\Xi_{bc}^+ \to \Xi_{cc}^{++} a_1 \to \Xi_{cc}^{++} + 4\pi$ there is no sign of such a peak. The reason for such behavior is that in the former case $\pi^+\pi^-$ pair is produced in the decay of the virtual ρ meson (see the diagram in Fig. 4), while in the latter case this pair is produced in f_0 meson decay (presented in the diagram in Fig. 5). Since the width of the f_0 meson is rather large, the peak on the corresponding $m_{2\pi}$ distribution is hardly visible. According to the same diagram, on the other hand, $\pi^-\pi^0$ pair can be produced in ρ^- decay and the corresponding peak is clearly seen, as shown in the Fig. 8(c) distribution over the

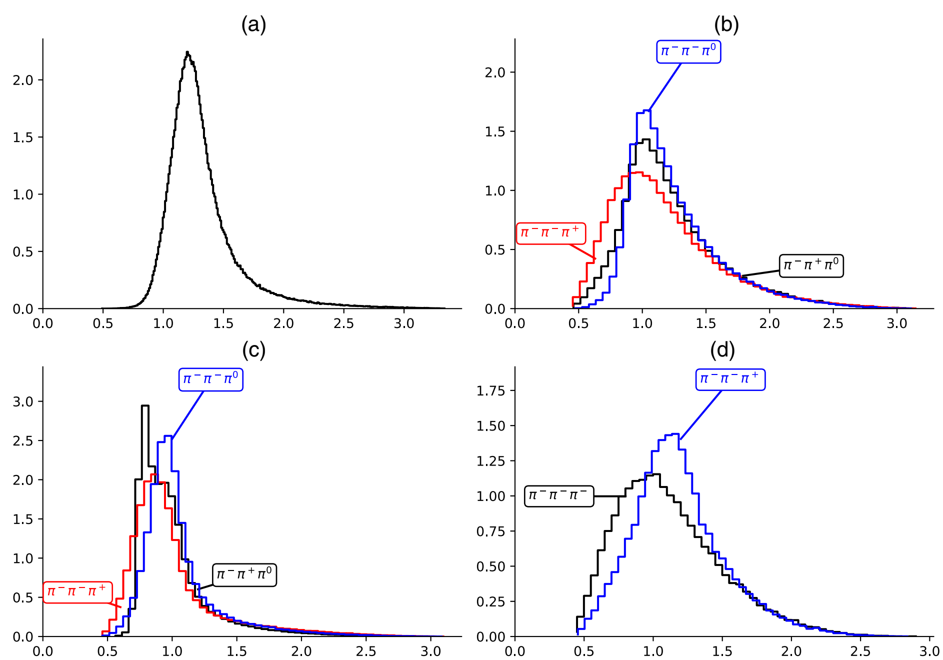

FIG. 9. Normalized distributions of the reactions $\Xi_{bc}^+ \to \Xi_{cc}^{++}\mathcal{R}$ over the invariant mass of three π mesons (in GeV). (a)–(d) correspond to the final states $\mathcal{R} = 3\pi$, $(4\pi)_{a_1}$, $(4\pi)_{b_1}$, and 5π, respectively.

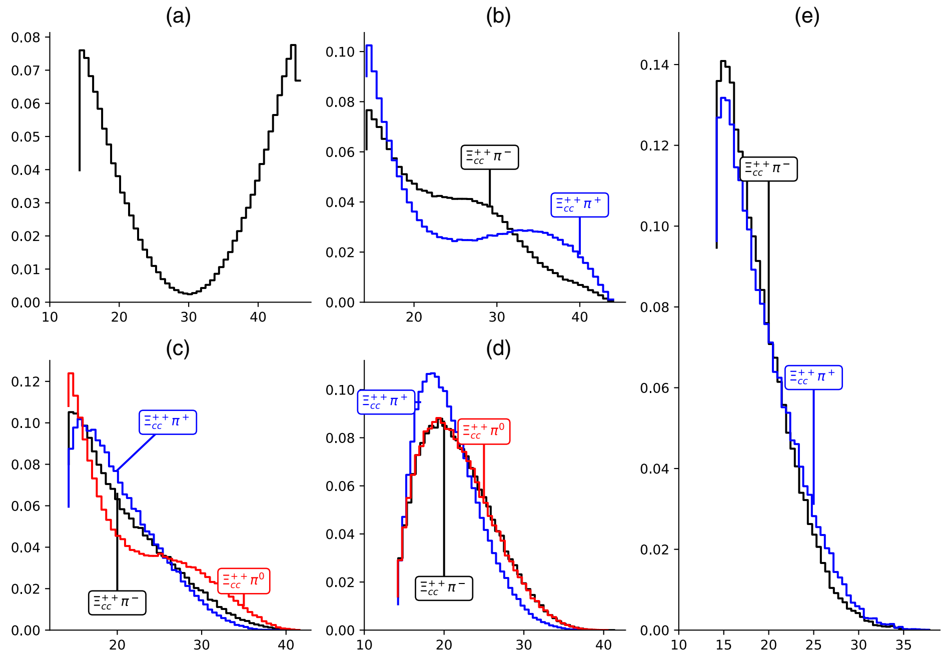

FIG. 10. Normalized distributions of the decays $\Xi_{bc}^{+} \to \Xi_{cc}^{++}\mathcal{R}$ over the squared invariant mass $\Xi_{cc}\pi$ system (in GeV^2). (a)–(e) correspond to the final states $\mathcal{R} = 2\pi$, 3π, $(4\pi)_{a_1}$, $(4\pi)_{b_1}$, and 5π, respectively.

invariant mass of this pair. It is easy to check that the same behavior is observed for all other reactions and final states: whenever any π meson pair is produced in the decay of the ρ meson, there is a peak (probably modified a little bit by the combinatorial background) in the corresponding distribution.

The same is also true for the distributions over the invariant masses of three π mesons. In Fig. 9(c), for example, we can see a peak in $m_{\pi^+\pi^-\pi^0}$ distribution, caused by ω resonance as shown in the figure (due to the combinatorial background, the form of this peak is not symmetric). There is also a clear peak in $m_{\pi^-\pi^-\pi^+}$ distribution in the case of the $\mathcal{R} = 5\pi$ final state [Fig. 9(d)], which corresponds to a_1 resonance in Fig. 6.

Let us finally consider distributions over the invariant mass of the $\Xi_{cc}\pi$ pair. These distributions are shown in Fig. 10, and their behavior is much more interesting. In the case of the $\mathcal{R} = \pi^+\pi^-$ final state, for example, you can see two clear peaks near the end of the allowed region. It is clear that this distribution should be symmetric [the reflection the plot corresponds to the interchange $\pi^+ \leftrightarrow \pi^0$ that does not change the matrix element (23)], but the reason for the peaks is not evident. You can also see that in the case of the $\pi^+\pi^-\pi^-$ final state there is some peak in the $m_{\Xi\pi^-}$ distribution. According to the figures and matrix elements presented in the previous section, there are no virtual resonances in the corresponding channels, so we can say that the reason for such behavior is some interplay of the hadronic matrix elements of the $\Xi_{bc} \to \Xi_{cc}W$ and $W \to \mathcal{R}$ transitions, the phase space region, etc.

V. CONCLUSION

In this article we have analyzed some of the exclusive decays of the Ξ_{bc}^{+} baryon with the production of light mesons. In our previous paper [20] we considered this type of doubly heavy baryon decay with the help of a spectral function formalism and calculated their branching fractions and distributions over the invariant mass of the light meson system. According to the results presented in that article, the branching fractions of some such decays are high enough to observe them experimentally. It is clear, however, that for analysis of the experimental data it is required to know distributions over other kinematical variables. Such results cannot be obtained in the framework of the approach used in our previous paper, so a more detailed theoretical model is required.

In this paper we have preformed such an analysis by concentrating on some exclusive decays of Ξ_{bc}^{+}. This baryon was chosen since one could expect the experimental observation of this particle soonest. In our work we have calculated the branching fractions of the reactions $\Xi_{bc}^{+} \to \Xi_{cc}^{++}\mathcal{R}$, where the light meson system $\mathcal{R}$ could be 2π, 3π, 4π, or 5π. For all of these reactions the branching fractions have been calculated and the distributions over different kinematical variables have been presented. According to our results in the distributions over the masses of systems of two or three π mesons, some peaks caused by the virtual resonances (ρ, ω, a_1, etc.) should be clearly seen. It could be even more interesting to study the distributions over $\Xi_{cc}\pi$ masses, for which our model predicts some additional peaks that do not correspond to any intermediate particles.

It is worth mentioning that in our work the factorization approach was used, in which the matrix elements of the considered processes are written as a product of the $\Xi_{bc} \to \Xi_{cc} W$ and $W \to \mathcal{R}$ transitions. This assumption looks absolutely suitable for similar decays of the B_c meson. When baryon decays are discussed, however, the nonfactorizable diagrams should give some contributions. Although these contributions are color suppressed, their effect could be noticeable. In future work we are planing to consider these corrections in more detail.

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