$\Lambda_b \to \Lambda_c^*$ at $1/m_c^2$ heavy quark mass order

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We systematically compute the $\Lambda_b(p, s_b) \to \Lambda_c(2595)^+$ and $\Lambda_b(p, s_b) \to \Lambda_c(2625)^+$ form factors within the heavy quark effective theory (HQET) framework including $\mathcal{O}(1/m_c^2)$. Besides taking into account the Standard Model–like vector and axial contributions, we further determine tensor and pseudotensor form factors. Our work constitutes a step forward with respect to previous analyses allowing for a comprehensive study of the matrix element parametrization stemming from the HQET formalism. Finally, we demonstrate that the resulting form factors agree well with lattice quantum chromodynamics determinations stressing the need and relevance of the newly derived $1/m_c^2$ corrections.

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I. INTRODUCTION

The tree-level semileptonic decays involving the $b \to c$ transition hold a fundamental role in determining the modulus of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ [1–14]. They also serve as a valuable tool for investigating lepton-flavor-universality violation. In the latter scenario, the calculation of mesonic form factors is crucial for predicting the $R_{D^{(*)}}$ ratios [15–17], which currently exhibit a significant 3σ tension with the current experimental average [18–20]. However, the exploration of baryonic decays can offer a complementary way to probe new physics (NP) beyond the standard model (SM) in comparison to the mesonic counterparts (see Refs. [21–26]).

As first pointed out in [27,28], the low energy dynamics of mesons and baryons containing a heavy quark enjoys a spin-flavor symmetry where symmetry-breaking effects can be taken into account in a well-defined expansion in the inverse of the heavy quark masses [29].

In the context of the heavy quark effective theory (HQET) a comprehensive computation of weak-decay form factors for the ground-state baryons $\Lambda_b \to \Lambda_c$ and mesons $B \to D^{(*)}$ processes was first derived, respectively, in [30,31]. Instead, the focus of our study revolves around $\Lambda_b \to \Lambda_c^*$ decays. The computation of the form factors was initially laid out in [32], employing the heavy quark expansion (HQE) to capture effects up to first order in the inverse of the heavy quark masses $\mathcal{O}(1/m_{c,b})$. Building upon this foundation, the authors of [33] extended the effort, introducing a novel form factor definition and incorporating short-distance corrections up to $\mathcal{O}(\alpha_s)$.

In a recent advancement, the authors of Ref. [34] achieved higher precision by computing the form factors up to $\mathcal{O}(1/m_{c,b}, \alpha_s)$, including the contributions of NP form factors arising from tensor and pseudotensor mediating currents. This computation was carried out using the definitions established in [32]. See also [35–37] for applications of the HQET to $\Lambda_b \to \Lambda_c^{(*)}$ processes.

Furthermore, the full set of $\Lambda_b \to \Lambda_c^*$ form factors has also been established through lattice computations. Initial efforts by [38] were further refined by [39]. These computations have provided data predominantly in the near-zero recoil region $w \lesssim 1.05$, where $w = v \cdot v'$, with v and v' representing the velocities of the initial and final states.

Examining the compatibility of lattice results with HQET predictions, the authors of [34] identified significant discrepancies in the fitting process. This prompted us to go beyond the constraints of the first-order approximation, incorporating terms up to $\mathcal{O}(1/m_c^2)$. At the same time, we independently cross-validated outcomes for the NP form factors, utilizing the framework established in [33] as the form factor basis for our analysis. One of the main achievements of this work is to show that the newly computed $1/m_c^2$ order is needed to reconcile lattice quantum chromodynamics (LQCD) results with HQET computations.

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The work is organized in the following way. In Sec. II, we first revisit the notation employed for the hadronic form factors and the on-shell amplitudes and then provide a brief overview of the HQET. This section helps set the stage for the systematic computation of hadronic matrix elements contributing to baryonic decay processes.

In Sec. III we reexamine and confirm the first-order determination of the vector and axial form factors presented in [33]. Furthermore, we include the chromomagnetic corrections and present the results for the tensor and pseudotensor form factors. Moving on to Sec. IV, our attention shifts to the novel determination of the $\mathcal{O}(1/m_c^2)$ contributions for the full set of form factors. The analysis takes advantage of the residual chiral (RC) framework as well as the vanishing chromomagnetic (VC) limit [16].

Finally, in Sec. V, we compare our analytic results to LQCD data [39] and demonstrate that our predictions align remarkably well with the lattice results. Our findings and outlook are summarized in the conclusions presented in Sec. VI. Several technical details are summarized in the appendixes.

II. NOTATION AND THEORETICAL FRAMEWORK

This section is dedicated to setting up the notation that we will use for the hadronic form factors and the on-shell amplitudes. Furthermore, to keep the work self-contained we provide a brief overview of the HQET.

A. $\Lambda_b \to \Lambda_c^*$ transitions

In the following we examine a suitable parametrization for the matrix elements stemming from the underlying currents mediating the transitions:

$$\begin{aligned}&\Lambda_b(p,s_b)\to\Lambda_c(2595)^+(k,J_z\equiv s_c)\ \text{ with }\ J^P=1/2^-,\\&\Lambda_b(p,s_b)\to\Lambda_c(2625)^+(k,J_z\equiv s_c+\lambda_c)\ \text{ with }\ J^P=3/2^-.\end{aligned} \tag{1}$$

Here p and k are the four momenta of the initial and final states, respectively. The momentum transfer is given by $q^\mu \equiv p^\mu - k^\mu$. With J^P we denote the angular momentum and parity of the Λ_c^* states, while s_b and J_z are the rest-frame helicities. For the $\Lambda_c(2625)^+$ state, J_z is the composition of the rest-frame helicity s_c of a $1/2^+$ spinor and the polarization of the vector $\eta(\lambda_c)$ (see Appendix C).

The most general decomposition of the hadronic matrix elements for vector, axial, tensor, and pseudotensor currents mediating the transition $\Lambda_b \to \Lambda_c(2595)^+$ reads as

$$\begin{aligned}\langle\Lambda_c(2595)^+(k,\eta(\lambda_c),s_c)|\bar{c}\gamma^\mu b|\Lambda_b^0(p,s_b)\rangle &= +\bar{u}_\alpha^{(1/2)}(k,\eta(\lambda_c),s_c)\left[\sum_i f_i(q^2)\Gamma_{V,i}^{\alpha\mu}\right]u(p,s_b),\\
\langle\Lambda_c(2595)^+(k,\eta(\lambda_c),s_c)|\bar{c}\gamma^\mu\gamma_5 b|\Lambda_b^0(p,s_b)\rangle &= -\bar{u}_\alpha^{(1/2)}(k,\eta(\lambda_c),s_c)\left[\sum_i g_i(q^2)\gamma_5\Gamma_{A,i}^{\alpha\mu}\right]u(p,s_b),\\
\langle\Lambda_c(2595)^+(k,\eta(\lambda_c),s_c)|\bar{c}i\sigma^{\mu\nu}q_\nu b|\Lambda_b^0(p,s_b)\rangle &= -\bar{u}_\alpha^{(1/2)}(k,\eta(\lambda_c),s_c)\left[\sum_i t_i(q^2)\Gamma_{T,i}^{\alpha\mu}\right]u(p,s_b),\\
\langle\Lambda_c(2595)^+(k,\eta(\lambda_c),s_c)|\bar{c}i\sigma^{\mu\nu}q_\nu\gamma_5 b|\Lambda_b^0(p,s_b)\rangle &= -\bar{u}_\alpha^{(1/2)}(k,\eta(\lambda_c),s_c)\left[\sum_i t_i^5(q^2)\gamma_5\Gamma_{T5,i}^{\alpha\mu}\right]u(p,s_b),\end{aligned} \tag{2}$$

where $\bar{u}_\alpha^{(1/2)}$ is the spin-1/2 projection of a Rarita-Schwinger object, denoted as $u_\alpha^{\mathrm{RS}}(k,\eta,s)$ (see Appendix A). The full set of $\Lambda_b \to \Lambda_c^*(2595)$ form factors is given by $f_i(q^2), g_i(q^2), t_i(q^2), t_i^5(q^2)$.

A similar parametrization can be applied to the hadronic matrix element for the transition to the $\Lambda_c(2625)^+$ state:

$$\begin{aligned}\langle\Lambda_c(2625)^+(k,\eta(\lambda_c),s_c)|\bar{c}\gamma^\mu b|\Lambda_b^0(p,s_b)\rangle &= +\bar{u}_\alpha^{(3/2)}(k,\eta(\lambda_c),s_c)\left[\sum_i F_i(q^2)\Gamma_{V,i}^{\alpha\mu}\right]u(p,s_b),\\
\langle\Lambda_c(2625)^+(k,\eta(\lambda_c),s_c)|\bar{c}\gamma^\mu\gamma_5 b|\Lambda_b^0(p,s_b)\rangle &= -\bar{u}_\alpha^{(3/2)}(k,\eta(\lambda_c),s_c)\left[\sum_i G_i(q^2)\gamma_5\Gamma_{A,i}^{\alpha\mu}\right]u(p,s_b),\\
\langle\Lambda_c(2595)^+(k,\eta(\lambda_c),s_c)|\bar{c}i\sigma^{\mu\nu}q_\nu b|\Lambda_b^0(p,s_b)\rangle &= -\bar{u}_\alpha^{(3/2)}(k,\eta(\lambda_c),s_c)\left[\sum_i T_i(q^2)\Gamma_{T,i}^{\alpha\mu}\right]u(p,s_b),\\
\langle\Lambda_c(2595)^+(k,\eta(\lambda_c),s_c)|\bar{c}i\sigma^{\mu\nu}q_\nu\gamma_5 b|\Lambda_b^0(p,s_b)\rangle &= -\bar{u}_\alpha^{(3/2)}(k,\eta(\lambda_c),s_c)\left[\sum_i T_i^5(q^2)\gamma_5\Gamma_{T5,i}^{\alpha\mu}\right]u(p,s_b).\end{aligned} \tag{3}$$

Here $\bar{u}_\alpha^{(3/2)}$ is the spin 3/2 projection of a Rarita-Schwinger spinor and $F_i(q^2), G_i(q^2), T_i(q^2), T_i^5(q^2)$ are the $\Lambda_b \to \Lambda_c^*(2625)$ form factors.

Following [34], we express the matrix elements of the currents via on-shell amplitudes, by contracting them with states having well-defined polarization. The relevant Dirac structures $\Gamma^{\alpha\mu}_{V(A,T,T5),i}$ are listed in Appendix B. Then, the on-shell amplitudes are defined as

$$\mathcal{A}_\Gamma(s_b, s_c, \lambda_c, \lambda_q) \equiv \langle \Lambda_c^*(s_c, \eta(\lambda_c))|\bar{c}\Gamma^\mu \varepsilon_\mu^*(\lambda_q) b|\Lambda_b(s_b)\rangle, \tag{4}$$

where for the SM-like currents $\Gamma^\mu = \gamma^\mu, \gamma^\mu\gamma_5$, Eq. (4) coincides with helicity amplitudes and the polarization vectors $\varepsilon_\mu^*(\lambda_q)$ constitute a basis for the exchange of a virtual W boson with polarization $\lambda_q \in \{t, 0, +1, -1\}$ (see Appendix C). However, in the case where the decay is mediated by the (pseudo)tensor current $\bar{c}\sigma^{\mu\nu}b$ ($\bar{c}\sigma^{\mu\nu}\gamma_5 b$), it becomes necessary to establish a basis for the exchange of a fictitious particle with $J^P = 1^- \bigoplus 1^+$, momentum q^μ, and mass $\sqrt{q^2}$. As outlined in [34], a suitable representation for the polarization is given by $q_\nu \varepsilon_\mu(\lambda_q)$.

To systematically calculate the full set of form factors, we match the on-shell amplitudes with fixed total angular momentum J of the Λ_c^* state in the full QCD theory to the HQET ones. More details on the computation of the on-shell amplitudes can be found in Appendix B. The next sections will provide an overview of the HQET and a detailed analysis of the matrix elements that are needed to express the on-shell amplitudes up to the next-to-next-to-leading order within the HQE framework.

B. Heavy quark effective theory in a nutshell

We now provide a concise overview of the fundamentals of the HQET framework that we will use throughout this work. We will employ the notation of Refs. [16,29]. At the heart of the HQET there is a heavy quark Q with mass m_Q, inside a hadron almost on-shell. This permits the following decomposition in terms of the large and small component fields Q_+ and Q_-:

$$Q_+^v(x) = e^{im_Q v\cdot x}\Pi_+ Q(x), \quad Q_-^v(x) = e^{im_Q v\cdot x}\Pi_- Q(x), \tag{5}$$

with $\Pi_\pm = (1 \pm \not{v})/2$ projector operators, and v denoting the heavy quark velocity which is defined up to reparametrizations. In fact, the effective Lagrangian is invariant under $v \to v' = v + k/m_Q$, where k is a residual momentum of order $\Lambda_{\rm QCD}$ [29,40].

The QCD Lagrangian for the heavy quark decomposes as follows:

$$\begin{aligned}\mathcal{L}_{\rm QCD} = {}& \bar{Q}_+^v iv\cdot D Q_+^v + \bar{Q}_+^v i\not{D}_\perp Q_-^v + \bar{Q}_-^v i\not{D}_\perp Q_+^v \\ & - \bar{Q}_-^v(iv\cdot D + 2m_Q)Q_-^v,\end{aligned} \tag{6}$$

where D^μ is the gauge covariant derivative of QCD and $D_\perp^\mu = D^\mu - (v\cdot D)v^\mu$ denotes the transverse derivative orthogonal to the heavy quark velocity. Q_+^v represents the nearly on-shell degree of freedom while Q_-^v corresponds to fluctuations suppressed by the heavy quark mass. Consequently, integrating out Q_-^v yields an effective theory for the large component Q_+^v of the heavy quark field, which reads

$$\mathcal{L}_{\rm HQET} = \bar{Q}_+^v iv\cdot D Q_+^v + \bar{Q}_+^v i\not{D}_\perp \frac{1}{iv\cdot D + 2m_Q} i\not{D}_\perp Q_+^v. \tag{7}$$

This form is well-suited for an expansion in terms of the inverse of (twice) the heavy quark mass given by

$$\mathcal{L}_{\rm HQET} = \sum_{n=0} \mathcal{L}_n/(2m_Q)^n. \tag{8}$$

By expanding Eq. (8) up to the second order, one finds [16,29,30]

$$\mathcal{L}_0 = \bar{Q}_+^v iv\cdot D Q_+^v, \tag{9}$$

$$\mathcal{L}_1 = -\bar{Q}_+^v\left[D^2 + Z\frac{g}{2}\sigma_{\alpha\beta}G^{\alpha\beta}\right]Q_+^v = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm mag}, \tag{10}$$

$$\mathcal{L}_2 = g\bar{Q}_+^v[Z_1 v_\beta D_\alpha G^{\alpha\beta} - iZ_2 v_\alpha \sigma_{\beta\gamma} D^\gamma G^{\alpha\beta}]Q_+^v. \tag{11}$$

Here, $igG^{\alpha\beta} = [D^\alpha, D^\beta]$ is the field strength and $\sigma^{\alpha\beta} \equiv \frac{i}{2}[\gamma^\alpha, \gamma^\beta]$. The coefficients Z, Z_1, and Z_2 are renormalization factors. Their deviation from unity becomes significant when addressing corrections at $\mathcal{O}(\alpha_s/m_Q)$ and beyond (see Refs. [29,31,41,42]). For the scope of our study, these deviations can be disregarded.

Furthermore, a source term $\bar{J}Q$ for the full QCD can now be written in terms of $Q_\pm^v$ as

$$\begin{aligned}\bar{\mathcal{J}}Q \equiv \bar{J}^v \mathcal{J}_{\rm HQET} Q_+^v &= \bar{J}^v\left[1 + \frac{1}{iv\cdot D + 2m_Q} i\not{D}_\perp\right]Q_+^v \\ &= \bar{J}^v\left[1 + \Pi_-\left(\frac{i\not{D}}{2m_Q} - \frac{\not{D}\not{D}}{4m_Q^2} + \cdots\right)\right]Q_+^v,\end{aligned} \tag{12}$$

where $J^v = e^{im_Q v\cdot x}J$.

Identifying the coefficients $\mathcal{J}_n$ in the current $\mathcal{J}_{\rm HQET} = 1 + \Pi_- \sum_{n=1} \mathcal{J}_n/(2m_Q)^n$ with the expansion above we get, up to second order [16]

$$\mathcal{J}_1 = i\not{D}, \tag{13}$$

$$\mathcal{J}_2 = -\not{D}\not{D}. \tag{14}$$

The conjugate is defined as

$$\bar{\mathcal{J}}_n \equiv \gamma^0 \bar{\mathcal{J}}_n^{\dagger} \gamma^0, \tag{15}$$

with $\overleftarrow{\mathcal{J}}$ ($\overrightarrow{\mathcal{J}}$) indicating the action of the derivatives to the left and right, respectively.

In this study, we focus on the computation of matrix elements for hadrons undergoing a $b \to c$ transition ($H_b \to H_c$). The QCD matrix elements are denoted as $\langle H_c|\bar{c}\Gamma b|H_b\rangle$, where Γ represents a generic Dirac matrix. The states $|H_c\rangle$ and $|H_b\rangle$ correspond to the QCD baryon states and are normalized as:

$$\langle H_{b(c)}(p')|H_{b(c)}(p)\rangle = 2p^0(2\pi)^3\delta^{(3)}(\vec{p} - \vec{p'}). \tag{16}$$

The matching onto HQET up to second order is [16]

$$\begin{aligned}
\frac{\langle H_c|\bar{c}\Gamma b|H_b\rangle}{\sqrt{m_{H_c} m_{H_b}}} \simeq{}& \langle H_c^{v'}|\bar{c}_+^{v'}\Gamma b_+^v|H_b^v\rangle + \frac{1}{2m_c}\langle H_c^{v'}|(\bar{c}_+^{v'}\bar{\mathcal{J}}_1' + \mathcal{L}_1'\circ c_+^{v'})\Gamma b_+^v|H_b^v\rangle \\
&+ \frac{1}{2m_b}\langle H_c^{v'}|\bar{c}_+^{v'}\Gamma(\mathcal{J}_1 b_+^v + b_+^v\circ\mathcal{L}_1)|H_b^v\rangle \\
&+ \frac{1}{4m_c^2}\langle H_c^{v'}|\left(\bar{c}_+^{v'}\bar{\mathcal{J}}_2'\Pi_-' + \mathcal{L}_2'\circ\bar{c}_+^{v'} + \mathcal{L}_1'\circ\bar{c}_+^{v'}\bar{\mathcal{J}}_1'\Pi_-' + \frac{1}{2}\mathcal{L}_1'\circ\mathcal{L}_1'\circ\bar{c}_+^{v'}\right)\Gamma b_+^v|H_b^v\rangle \\
&+ \frac{1}{4m_b^2}\langle H_c^{v'}|\bar{c}_+^{v'}\Gamma\left(\Pi_-\mathcal{J}_2 b_+^v + b_+^v\circ\mathcal{L}_2 + \Pi_-\mathcal{J}_1 b_+^v\circ\mathcal{L}_1 + \frac{1}{2}b_+^v\circ\mathcal{L}_1\circ\mathcal{L}_1\right)|H_b^v\rangle \\
&+ \frac{1}{4m_c m_b}\langle H_c^{v'}|(\bar{c}_+^{v'}\bar{\mathcal{J}}_1' + \mathcal{L}_1'\circ\bar{c}_+^{v'})\Gamma(\mathcal{J}_1 b_+^v + b_+^v\circ\mathcal{L}_1)|H_b^v\rangle,
\end{aligned} \tag{17}$$

where b_+^v and $c_+^{v'}$ are the large components of the quark fields. We adopt the convention where terms involving the c-quark are denoted with primes, while those involving the b-quark remain unprimed. The matrix elements on the right-hand side are evaluated on the HQET states, which are defined as the eigenstates of $\mathcal{L}_0$ and normalized as follows:

$$\langle H^{v'}(p')|H^v(p)\rangle = 2v^0\delta_{vv'}(2\pi)^3\delta^{(3)}(\vec{p} - \vec{p'}). \tag{18}$$

Nonlocal terms, arising from the operator product with the HQET Lagrangian, emerge from the matching procedure, because the states in the full theory differ from those in the effective theory, as highlighted in [29]. Here, following [16] the $\circ$ symbol denotes such an operator product; for example, when we write above the term $\mathcal{L}_1'\circ\bar{c}_+^{v'}(z)$, this means

$$\mathcal{L}_1'\circ\bar{c}_+^{v'}(z) = i\int d^4x\,\mathcal{L}_1'(x)\bar{c}_+^{v'}(z).$$

III. NEXT-TO-LEADING ORDER CORRECTIONS TO $\Lambda_b \to \Lambda_c^*$ WARM-UP

In this section we rederive the baryon matrix elements for the transition $\Lambda_b \to \Lambda_c^*$ employing the HQE Eq. (17) up to $\mathcal{O}(\alpha_s, 1/m_{b,c})$.

Apart from computing the vector and axial current matrix elements that were already presented in [33], we also perform a determination of the tensor and pseudotensor current matrix elements. Furthermore, we consider the effects of the chromomagnetic operator $\mathcal{L}_{\mathrm{mag}}$ that were neglected in [33].

Starting from Eq. (17), the hadronic matrix in the HQE can be written at leading order (LO) as

$$\begin{aligned}
&\langle\Lambda_c^*(k,\eta,s_c)|\bar{c}_+^{v'}\Gamma b_+^v|\Lambda_b(p,s_b)\rangle \\
&\quad = \sqrt{4}\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\Gamma u(m_{\Lambda_b}v,s_b)\zeta^\alpha(w),
\end{aligned} \tag{19}$$

where $w \equiv v\cdot v' = (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)/(2m_{\Lambda_b}m_{\Lambda_c^*})$, v and v' are the four-velocities of the initial and final states, respectively, and Γ denotes a given Dirac structure. Following [43], the light-state transition amplitude $\zeta^\alpha(w)$ can be written as

$$\zeta^\alpha(w) = \zeta(w)(v - v')^\alpha. \tag{20}$$

Therefore, at leading order in the HQE all the form factors can be expressed in terms of the single amplitude $\zeta(w)$, independently from the Dirac structure of the current.

The local $1/m$ corrections to the current induce a shift that we can account for by operating the following substitution:

$$\Gamma^\mu \to \Gamma^\mu + \varepsilon_b\Delta J_\Gamma^\mu + \varepsilon_c\Delta\bar{J}_\Gamma^\mu, \tag{21}$$

where $\varepsilon_{b,c} = 1/(2m_{b,c})$ are the HQE parameters and

$$\Delta J_\Gamma^\mu = \bar{c}_+^{v'} \Gamma^\mu \mathcal{J}_1 b_+^v, \quad (22)$$

$$\Delta \bar{J}_\Gamma^\mu = \bar{c}_+^{v'} \bar{\mathcal{J}}_1 \Gamma^\mu b_+^v. \quad (23)$$

The hadronic matrix elements of ΔJ_Γ^μ and $\Delta \bar{J}_\Gamma^\mu$ can be parametrized as

$$\begin{aligned}&\langle \Lambda_c^*(k,\eta,s_c)|\Delta J_\Gamma^\mu|\Lambda_b(p,s_b)\rangle \\ &= \sqrt{4}\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\Gamma_\mu \gamma_\beta u(m_{\Lambda_b}v,s_b)\zeta_b^{\alpha\beta}(w), \quad (24)\end{aligned}$$

$$\begin{aligned}&\langle \Lambda_c^*(k,\eta,s_c)|\Delta \bar{J}_\Gamma^\mu|\Lambda_b(p,s_b)\rangle \\ &= \sqrt{4}\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma_\beta \Gamma_\mu u(m_{\Lambda_b}v,s_b)\zeta_c^{\alpha\beta}(w), \quad (25)\end{aligned}$$

where the most general decomposition of the light-state transition amplitude is

$$\zeta_{(q)}^{\alpha\beta}(w) = (v-v')^\alpha[\zeta_1^{(q)}(w)v^\beta + \zeta_2^{(q)}(w)v'^\beta] + g^{\alpha\beta}\zeta_3^{(q)}(w). \quad (26)$$

At this stage the $1/m$ corrections are described by six subleading Isgur-Wise (IW) functions; however, they can be related via the equations of motion. In particular, we have that $v_\beta \zeta_{(b)}^{\alpha\beta} = 0$ and $v'_\beta \zeta_{(c)}^{\alpha\beta} = 0$. This leads to the following relations:

$$\zeta_1^{(b)}(w) + w\zeta_2^{(b)}(w) + \zeta_3^{(b)}(w) = 0, \quad (27)$$

$$w\zeta_1^{(c)}(w) + \zeta_2^{(c)}(w) = 0. \quad (28)$$

Furthermore, from the modified Ward identity [16,33]

$$i\partial_\alpha[\bar{Q}_+^{v'}\Gamma Q_+^v] = \bar{Q}_+^{v'} i\overleftarrow{D}_\alpha \Gamma Q_+^v + \bar{Q}_+^{v'}\Gamma i D_\alpha Q_+^v, \quad (29)$$

we recover the following relations among leading and subleading IW functions:

$$\zeta_1^{(b)}(w) + \zeta_1^{(c)}(w) = \bar{\Lambda}\zeta(w), \quad (30)$$

$$\zeta_2^{(b)}(w) + \zeta_2^{(c)}(w) = -\bar{\Lambda}'\zeta(w), \quad (31)$$

$$\zeta_3^{(b)}(w) + \zeta_3^{(c)}(w) = 0, \quad (32)$$

where the important parameters $\bar{\Lambda}$ and $\bar{\Lambda}'$ represent the difference between the mass of the baryon states and that of the heavy quark at leading order in HQE:

$$\begin{aligned}\bar{\Lambda} &= m_{\Lambda_b} - m_b, \\ \bar{\Lambda}' &= m_{\Lambda_c^*} - m_c. \quad (33)\end{aligned}$$

Since the phase factor in Eq. (5) effectively removes the mass of the heavy quark m_Q from the states, these parameters control the spacetime dependence of the HQET states, as discussed in [29,30]. The relations above reduce the initial six subleading IW functions to one independent subleading IW function. Inspired by [33], we choose to express all in terms of ζ and $\zeta_{\rm SL} \equiv \zeta_3^{(b)} = -\zeta_3^{(c)}$:

$$\begin{aligned}\zeta_1^{(b)} &= -\frac{\zeta_{\rm SL}}{1-w^2} + \frac{w\zeta}{1-w^2}(\bar{\Lambda}' - \bar{\Lambda}w), & \zeta_2^{(b)} &= +\frac{w\zeta_{\rm SL}}{1-w^2} - \frac{\zeta}{1-w^2}(\bar{\Lambda}' - \bar{\Lambda}w), \\ \zeta_1^{(c)} &= +\frac{\zeta_{\rm SL}}{1-w^2} - \frac{\zeta}{1-w^2}(w\bar{\Lambda}' - \bar{\Lambda}), & \zeta_2^{(c)} &= -\frac{w\zeta_{\rm SL}}{1-w^2} + \frac{w\zeta}{1-w^2}(w\bar{\Lambda}' - \bar{\Lambda}). \quad (34)\end{aligned}$$

The relations among the IW functions, obtained via the equations of motions and the modified Ward identity, are singular at $w = 1$. In fact, for $w = 1$ we need to use, instead, the relation

$$\zeta_{\rm SL} + \zeta(\bar{\Lambda} - \bar{\Lambda}') = 0. \quad (35)$$

This equation permits one to verify that the HQE form factors obey, up to second order, the end-point relations reported in [44,45].

Before going into the details of the matrix element calculations, it is worth mentioning that we have cross-checked the outcomes presented in Ref. [33] pertaining to both the axial and vector form factors. Furthermore, our findings coincide with the results presented in [34], including the tensor and pseudotensor form factors up to the next-to-leading order in the HQE as well as the chromomagnetic contributions. We note that in [34] the authors employed the form factor basis introduced in [32] with ζ and $\zeta_1^{(c)}$ chosen to be independent IW functions.

We are now ready to investigate the implications stemming from the nonlocal $1/m$ corrections and the hard gluon exchange.

A. Vector and axial current matrix elements

To include both local $1/m$ and α_s corrections to the vector current matrix element, we use the approach introduced in Ref. [33], employing the following substitution:

$$\begin{aligned}\gamma^\mu \to J_V^\mu = C_1(w)\gamma^\mu + C_2(w)v^\mu + C_3(w)v'^\mu \\ + \Delta J_V^\mu + \Delta\bar{J}_V^\mu + \mathcal{O}(\alpha_s/m, 1/m^2). \quad (36)\end{aligned}$$

The corrections ΔJ_V^μ are given by eqs. (22) and (23), where $\Gamma^\mu = \gamma^\mu$ and C_i are the Wilson coefficients obtained by matching the HQET to QCD at the energy scale $\mu = \sqrt{m_c m_b}$ [34]. The Wilson coefficients depend on $w = v \cdot v'$, which is the recoil parameter. The expression for the Wilson coefficients C_i up to $\mathcal{O}(\alpha_s)$ can be found in [15]. In our notation, the Wilson coefficients are related to those in Ref. [15] by $C_i = \hat{\alpha}_s C_{V_i} + \delta_{i1}$, where $\hat{\alpha}_s = \alpha_s/\pi$.

In Eq. (36) we consider only the local power corrections ΔJ_V^μ and $\Delta \bar{J}_V^\mu$. Other $1/m$ local operators arise in the HQE from QCD hard corrections and then contribute at the order α_s/m. Since they are beyond the precision we aim for in the analysis proposed in this work, we neglect them.

From Eq. (24) we reobtain the following contributions already present in [33]:

$$
\begin{aligned}
\langle \Lambda_c^*(k,\eta,s_c)|\Delta J_{V\mu}|\Lambda_b(p,s_b)\rangle &= 2\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma^\mu u(m_{\Lambda_b}v,s_b)v^\alpha\big(\zeta_1^{(b)}(w)-\zeta_2^{(b)}(w)\big)\\
&\quad + 4\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)u(m_{\Lambda_b}v,s_b)v^\alpha v'^\mu\zeta_2^{(b)}(w)\\
&\quad + 2\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma^\mu\gamma^\alpha u(m_{\Lambda_b}v,s_b)\zeta_3^{(b)}(w),\\
\langle \Lambda_c^*(k,\eta,s_c)|\Delta \bar{J}_V^\mu|\Lambda_b(p,s_b)\rangle &= 2\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma^\mu u(m_{\Lambda_b}v,s_b)v^\alpha\big(\zeta_2^{(c)}(w)-\zeta_1^{(c)}(w)\big)\\
&\quad + 4\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)u(m_{\Lambda_b}v,s_b)v^\alpha v^\mu\zeta_1^{(c)}(w)\\
&\quad + 2\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma^\alpha\gamma^\mu u(m_{\Lambda_b}v,s_b)\zeta_3^{(c)}(w). \qquad (37)
\end{aligned}
$$

The same procedure is applied to the axial-vector current yielding [33]

$$
\gamma^\mu\gamma_5 \to J_A^\mu = C_1^{(5)}(w)\gamma^\mu\gamma^5 + C_2^{(5)}(w)v^\mu\gamma^5 + C_3^{(5)}(w)v'^\mu\gamma^5 + \Delta J_A^\mu + \Delta\bar{J}_A^\mu + \mathcal{O}(\alpha_s/m, 1/m^2). \qquad (38)
$$

The Wilson coefficients C_i^5 are related to those reported in [15] by $C_i^5 = \hat{\alpha}_s C_{A_i} + \delta_{i1}$. The $1/m$ pure current corrections ΔJ_A^μ and $\Delta \bar{J}_A^\mu$ can be computed from Eq. (24) with $\Gamma^\mu = \gamma^\mu\gamma_5$. We obtain

$$
\begin{aligned}
\langle \Lambda_c^*(k,\eta,s_c)|\Delta J_A^\mu|\Lambda_b(p,s_b)\rangle &= 2\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma^\mu\gamma^5 u(m_{\Lambda_b}v,s_b)v^\alpha\big(\zeta_1^{(b)}(w)+\zeta_2^{(b)}(w)\big)\\
&\quad - 4\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma^5 u(m_{\Lambda_b}v,s_b)v^\alpha v'_\mu\zeta_2^{(b)}(w)\\
&\quad + 2\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma^\mu\gamma^5\gamma^\alpha u(m_{\Lambda_b}v,s_b)\zeta_3^{(b)}(w),\\
\langle \Lambda_c^*(k,\eta,s_c)|\Delta \bar{J}_A^\mu|\Lambda_b(p,s_b)\rangle &= 2\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma^\mu\gamma^5 u(m_{\Lambda_b}v,s_b)v^\alpha\big(\zeta_1^{(c)}(w)+\zeta_2^{(c)}(w)\big)\\
&\quad + 4\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma^5 u(m_{\Lambda_b}v,s_b)v^\alpha v_\mu\zeta_1^{(c)}(w)\\
&\quad + 2\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\gamma^\alpha\gamma^\mu\gamma^5 u(m_{\Lambda_b}v,s_b)\zeta_3^{(c)}(w). \qquad (39)
\end{aligned}
$$

Besides the contributions from local operators describing the corrections to the infinite mass limit of the heavy quark (HQ) currents, also the effects from nonlocal insertions of the HQET Lagrangian at power $1/m$ in the HQ currents need to be included.

Nonlocal insertions of the kinetic operator can be parametrized as

$$
\begin{aligned}
&\langle \Lambda_c^*(k,\eta,s_c)|\mathcal{L}_{\rm kin}\circ\bar{c}_+^{v'}\Gamma b_+^v|\Lambda_b(p,s_b)\rangle\\
&\quad = \sqrt{4}\eta_{\rm kin}^{(b)}(w)v^\alpha\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\Gamma u(m_{\Lambda_b}v,s_b), \qquad (40)
\end{aligned}
$$

$$
\begin{aligned}
&\langle \Lambda_c^*(k,\eta,s_c)|\mathcal{L}'_{\rm kin}\circ\bar{c}_+^{v'}\Gamma b_+^v|\Lambda_b(p,s_b)\rangle\\
&\quad = \sqrt{4}\eta_{\rm kin}^{(c)}(w)v^\alpha\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\Gamma u(m_{\Lambda_b}v,s_b), \qquad (41)
\end{aligned}
$$

with $\Gamma = \gamma^\mu, \gamma^\mu\gamma_5$.

Clearly, they give rise to a w-dependent shift $\eta_{\rm kin}^{(b,c)}(w)$ to the leading-power IW function $\zeta(w)$. At order $\mathcal{O}(\alpha_s, 1/m)$ we can absorb this shift into the definition of ζ:

$$
\zeta(w) + \varepsilon_c\eta_{\rm kin}^{(c)}(w) + \varepsilon_b\eta_{\rm kin}^{(b)}(w) \to \zeta(w). \qquad (42)
$$

Nevertheless, as stressed in [15,32], the above redefinition leads to corrections of order $1/m^2$, which we need to take into account if we aim to explore the second order of the HQE.

Nonlocal insertion of the chromomagnetic operator gives two contributions which are

$$\langle \Lambda_c^*(k,\eta,s_c)|\mathcal{L}_{\rm mag}\circ\bar{c}_+^{v'}\Gamma b_+^{v}|\Lambda_b(p,s_b)\rangle = \eta_{\rm mag}^{(b)}(w) g_{\mu\alpha} v'_\nu \bar{u}^\alpha(m_{\Lambda_c^*}v',\eta,s_c)\Gamma\Pi_+ i\sigma^{\mu\nu}u(m_{\Lambda_b}v,s_b), \tag{43}$$

$$\langle \Lambda_c^*(k,\eta,s_c)|\mathcal{L}'_{\rm mag}\circ\bar{c}_+^{v'}\Gamma b_+^{v}|\Lambda_b(p,s_b)\rangle = \eta_{\rm mag}^{(c)}(w) g_{\mu\alpha} v_\nu \bar{u}^\alpha(m_{\Lambda_c^*}v',\eta,s_c) i\sigma^{\mu\nu}\Pi'_+\Gamma u(m_{\Lambda_b}v,s_b). \tag{44}$$

The chromomagnetic correction to the b vector current is given by

$$\varepsilon_b\eta_{\rm mag}^{(b)}(w)\big[2(w-1)\bar{u}_\alpha g^{\mu\alpha}u-(w-1)\bar{u}_\alpha\gamma^\alpha\gamma^\mu u+2\bar{u}_\alpha\gamma^\alpha v'^\mu u - 2\bar{u}_\alpha v^\alpha v'^\mu u+\bar{u}_{J\alpha}v^\alpha\gamma^\mu u\big]. \tag{45}$$

Analogously, the chromomagnetic correction to the c vector current is given by

$$\varepsilon_c\eta_{\rm mag}^{(c)}(w)\big[(1-w)\bar{u}_\alpha\gamma^\alpha\gamma^\mu u-2\bar{u}_\alpha\gamma^\alpha v^\mu u+\bar{u}_{J\alpha}v^\alpha\gamma^\mu u\big]. \tag{46}$$

The chromomagnetic correction to the b and c axial currents are, respectively,

$$\varepsilon_b\eta_{\rm mag}^{(b)}(w)\{-2(1+w)\bar{u}_\alpha g^{\mu\alpha}\gamma_5 u+(1+w)\bar{u}_\alpha\gamma^\alpha\gamma^\mu\gamma_5 u + 2\bar{u}_\alpha\gamma^\alpha v'^\mu\gamma_5 u+2\bar{u}_{J\alpha}v^\alpha v'^\mu\gamma_5 u-\bar{u}_{J\alpha}v^\alpha\gamma^\mu\gamma_5 u\}, \tag{47}$$

$$\varepsilon_c\eta_{\rm mag}^{(c)}(w)\big[-(w+1)\bar{u}_\alpha\gamma^\alpha\gamma^\mu\gamma_5 u-2\bar{u}_\alpha\gamma^\alpha v^\mu\gamma_5 u+\bar{u}_{J\alpha}v^\alpha\gamma^\mu\gamma_5 u\big]. \tag{48}$$

Here we went beyond the result of [33] with respect to the determination of the nonlocal magnetic contributions which, however, in another basis were determined in [34].

B. Vector and axial form factors in the VC limit

By virtue of the identity $v_\alpha(1+\not{v})\sigma^{\alpha\beta}(1+\not{v})=0$ the chromomagnetic correction is zero in the exact zero recoil limit ($w=1$) and, as argued in [46–48], is expected to be numerically small with respect to the local current corrections. Then, as a first approximation, the computation of the form factors can be performed by considering the VC limit (as also motivated in [16,31,32]) in which we set the field strength $G_{\alpha\beta}=0$ and the chromomagnetic correction results automatically to zero.

Furthermore, at order $\mathcal{O}(1/m)$, the correction to the leading-order HQ amplitude deriving from the insertion of the kinetic Lagrangian can be reabsorbed through a redefinition of the IW function ζ. Since we aim at extending the HQE to order $1/m_c^2$, we must take into account the contribution to $\mathcal{O}(1/m_c)$ of the kinetic operator, whereas the $\mathcal{O}(1/m_b)$ kinetic operator contribution can still be reabsorbed into the definition of the leading IW function ζ because otherwise it appears at order $1/m_b^2$ that is neglected here.

To the order we are working here theoretical consistency requires us to use directly the quark masses in the HQE for the form factors rather than approximate them by the baryon masses while still agreeing with the result of [33] valid to the next leading order. Nevertheless, we have also explicitly checked the results against the case in which the baryon masses are used also in the HQE as we shall discuss in the section about the results.

Concerning the final state $\Lambda_c(2595)^+$ for the vector current the form factors are

$$f_{1/2,0}=\frac{\zeta s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1+\frac{C_2 s_+}{2m_{\Lambda_b}(m_{\Lambda_b}+m_{\Lambda_c^*})}+\frac{C_3 s_+}{2m_{\Lambda_c^*}(m_{\Lambda_b}+m_{\Lambda_c^*})}\right) + \varepsilon_b\frac{\sqrt{s_+}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}'-2\zeta_{\rm SL}-\frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \varepsilon_c\frac{\sqrt{s_+}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}-2\zeta_{\rm SL}-\frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right)+\varepsilon_c\frac{\eta_{\rm kin}^{(c)}s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}, \tag{49}$$

$$f_{1/2,t}=\frac{\zeta s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1+\frac{C_2 s_+}{2m_{\Lambda_b}(m_{\Lambda_b}-m_{\Lambda_c^*})}+\frac{C_3 s_+}{2m_{\Lambda_c^*}(m_{\Lambda_b}-m_{\Lambda_c^*})}\right) + \varepsilon_b\frac{\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}'-2\zeta_{\rm SL}-\frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \varepsilon_c\frac{\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}-2\zeta_{\rm SL}-\frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right)+\varepsilon_c\frac{\eta_{\rm kin}^{(c)}s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}, \tag{50}$$

$$f_{1/2,\perp} = \frac{C_1 \zeta s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_b \frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\frac{\zeta \bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} - \bar{\Lambda}' \zeta \right) + \varepsilon_c \frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\bar{\Lambda}\zeta - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) + \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}}, \quad (51)$$

while for the axial form factors we obtain

$$g_{1/2,0} = \frac{\zeta s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1^5 - \frac{C_2^5 s_-}{2 m_{\Lambda_b}(m_{\Lambda_b} - m_{\Lambda_c^*})} - \frac{C_3^5 s_-}{2 m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})} \right) + \varepsilon_b \frac{\sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' + 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) + \varepsilon_c \frac{\sqrt{s_-}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) + \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}}, \quad (52)$$

$$g_{1/2,t} = \frac{\zeta s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1^5 + \frac{C_2^5 s_+}{2 m_{\Lambda_b}(m_{\Lambda_b} + m_{\Lambda_c^*})} + \frac{C_3^5 s_+}{2 m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*})} \right) + \varepsilon_b \frac{\sqrt{s_+}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' + 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) + \varepsilon_c \frac{\sqrt{s_+}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) + \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}}, \quad (53)$$

$$g_{1/2,\perp} = \frac{C_1^5 \zeta s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_b \frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\frac{\zeta \bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} - \zeta \bar{\Lambda}' \right) + \varepsilon_c \frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) + \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}}. \quad (54)$$

Considering the final state $\Lambda_c(2625)^+$, the vector form factors are

$$F_{1/2,0} = \frac{\zeta s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1 + \frac{C_2 s_+}{2 m_{\Lambda_b}(m_{\Lambda_b} + m_{\Lambda_c^*})} + \frac{C_3 s_+}{2 m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*})} \right) + \varepsilon_b \frac{\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' + \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) + \varepsilon_c \frac{\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} + \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) + \frac{\sqrt{s_+} s_-}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \varepsilon_c \eta_{\mathrm{kin}}^{(c)}, \quad (55)$$

$$F_{1/2,t} = \frac{\zeta s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1 + \frac{m_{\Lambda_c^*}(m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2 + q^2)}{2(m_{\Lambda_b} - m_{\Lambda_c^*}) m_{\Lambda_b} m_{\Lambda_c^*}} C_2 + \frac{m_{\Lambda_b}(m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2 - q^2)}{2(m_{\Lambda_b} - m_{\Lambda_c^*}) m_{\Lambda_b} m_{\Lambda_c^*}} C_3 \right) + \varepsilon_b \frac{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{s_-}}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' + \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) + \varepsilon_c \frac{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{s_-}}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} + \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) + \frac{\sqrt{s_-} s_+}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \varepsilon_c \eta_{\mathrm{kin}}^{(c)}, \quad (56)$$

$$F_{1/2,\perp} = \frac{\zeta\sqrt{s_+}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}C_1 + \varepsilon_b\zeta\frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{\bar\Lambda(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}} - \bar\Lambda'\right) + \varepsilon_c\frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda + \zeta_{\rm SL} - \zeta\frac{\bar\Lambda'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \frac{\sqrt{s_+}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\varepsilon_c\eta_{\rm kin}^{(c)}, \tag{57}$$

$$F_{3/2,\perp} = -\varepsilon_b\frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\zeta_{\rm SL}, \tag{58}$$

while the axial form factors read as

$$G_{1/2,0} = \frac{\zeta s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1^5 - \frac{C_2^5 s_-}{2m_{\Lambda_b}(m_{\Lambda_b}-m_{\Lambda_c^*})} - \frac{C_3^5 s_-}{2m_{\Lambda_c^*}(m_{\Lambda_b}-m_{\Lambda_c^*})}\right) + \varepsilon_b\frac{\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda' - \zeta_{\rm SL} - \frac{\zeta\bar\Lambda(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \varepsilon_c\frac{\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda + \zeta_{\rm SL} - \frac{\zeta\bar\Lambda'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \varepsilon_c\frac{\sqrt{s_-}s_+}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\rm kin}^{(c)}, \tag{59}$$

$$G_{1/2,t} = \frac{\zeta s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1^5 - \frac{(m_{\Lambda_b}^2-m_{\Lambda_c^*}^2+q^2)}{2(m_{\Lambda_b}+m_{\Lambda_c^*})m_{\Lambda_b}}C_2^5 - \frac{(m_{\Lambda_b}^2-m_{\Lambda_c^*}^2-q^2)}{2(m_{\Lambda_b}+m_{\Lambda_c^*})m_{\Lambda_c^*}}C_3^5\right) + \varepsilon_b\frac{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda' - \zeta_{\rm SL} - \frac{\zeta\bar\Lambda(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \varepsilon_c\frac{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda' + \zeta_{\rm SL} - \frac{\zeta\bar\Lambda(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \varepsilon_c\frac{\sqrt{s_+}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\rm kin}^{(c)}, \tag{60}$$

$$G_{1/2,\perp} = \frac{\zeta\sqrt{s_-}s_+}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}C_1^5 + \varepsilon_b\zeta\frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{\bar\Lambda(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}} - \bar\Lambda'\right) + \varepsilon_c\frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda + \zeta_{\rm SL} - \zeta\frac{\bar\Lambda'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \varepsilon_c\frac{\sqrt{s_-}s_+}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\rm kin}^{(c)}, \tag{61}$$

$$G_{3/2,\perp} = -\varepsilon_b\frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\zeta_{\rm SL}. \tag{62}$$

C. The chromomagnetic corrections for vector and axial form factors

The contributions of the chromomagnetic operators result in the following shifts to the form factors reported in Sec. III B:

$$f_{1/2,0}^{\rm mag} = \frac{s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(\varepsilon_b\eta_{\rm mag}^{(b)} - \varepsilon_c\eta_{\rm mag}^{(c)}\right), \tag{63}$$

$$f_{1/2,t}^{\rm mag} = \frac{s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(\varepsilon_b\eta_{\rm mag}^{(b)} - \varepsilon_c\eta_{\rm mag}^{(c)}\right), \tag{64}$$

$$f_{1/2,\perp}^{\rm mag} = -\frac{s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\varepsilon_c\eta_{\rm mag}^{(c)}, \tag{65}$$

for the vector form factors, while for the axial-vector form factors we obtain

$$g_{1/2,0}^{\rm mag} = \frac{s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(-\varepsilon_b\eta_{\rm mag}^{(b)} - \varepsilon_c\eta_{\rm mag}^{(c)}\right), \tag{66}$$

$$g_{1/2,t}^{\rm mag} = \frac{s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(-\varepsilon_b\eta_{\rm mag}^{(b)} - \varepsilon_c\eta_{\rm mag}^{(c)}\right), \tag{67}$$

$$g_{1/2,\perp}^{\rm mag} = -\frac{s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\varepsilon_c\eta_{\rm mag}^{(c)}. \tag{68}$$

Concerning the $\Lambda_c(2625)^+$ final state, the contributions of the chromomagnetic operator to the form factors are

$$F_{1/2,0}^{\rm mag} = \frac{s_-\sqrt{s_+}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(-\varepsilon_b\eta_{\rm mag}^{(b)} + \varepsilon_c\eta_{\rm mag}^{(c)}\right), \tag{69}$$

$$F^{\rm mag}_{1/2,t} = \frac{s_+\sqrt{s_-}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(-\varepsilon_b\eta^{(b)}_{\rm mag} + \varepsilon_c\eta^{(c)}_{\rm mag}\right), \quad (70)$$

$$F^{\rm mag}_{1/2,\perp} = \frac{s_-\sqrt{s_+}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\varepsilon_c\eta^{(c)}_{\rm mag}, \quad (71)$$

$$F^{\rm mag}_{3/2,\perp} = -\frac{s_-\sqrt{s_+}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\varepsilon_b\eta^{(b)}_{\rm mag}, \quad (72)$$

while for the axial-vector form factor we obtain

$$G^{\rm mag}_{1/2,0} = \frac{s_+\sqrt{s_-}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(\varepsilon_b\eta^{(b)}_{\rm mag} + \varepsilon_c\eta^{(c)}_{\rm mag}\right), \quad (73)$$

$$G^{\rm mag}_{1/2,t} = \frac{s_-\sqrt{s_+}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(\varepsilon_b\eta^{(b)}_{\rm mag} + \varepsilon_c\eta^{(c)}_{\rm mag}\right), \quad (74)$$

$$G^{\rm mag}_{1/2,\perp} = \frac{s_+\sqrt{s_-}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\varepsilon_c\eta^{(c)}_{\rm mag}, \quad (75)$$

$$G^{\rm mag}_{3/2,\perp} = -\frac{s_+\sqrt{s_-}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\varepsilon_b\eta^{(b)}_{\rm mag}. \quad (76)$$

D. Tensor and pseudotensor current matrix elements

We now obtain the tensor and pseudotensor current matrix elements by replacing Γ with $i\sigma_{\mu\nu}q^\nu, i\sigma_{\mu\nu}q^\nu\gamma_5$ in Eq. (19):

$$\sqrt{4}\zeta(w)\left\{-(m_{\Lambda_b}+m_{\Lambda_c^*})\bar{u}_\alpha\gamma^\mu v^\alpha u + m_{\Lambda_b}\bar{u}_\alpha v^\mu v^\alpha u + m_{\Lambda_c^*})\bar{u}_\alpha v'^\mu v^\alpha u\right\}, \quad (77)$$

$$\sqrt{4}\zeta(w)\left\{(m_{\Lambda_b}-m_{\Lambda_c^*})\bar{u}_\alpha\gamma^\mu v^\alpha\gamma_5 u + m_{\Lambda_b}\bar{u}_\alpha v^\mu v^\alpha\gamma_5 u + m_{\Lambda_c^*})\bar{u}_\alpha v'^\mu v^\alpha\gamma_5 u\right\}. \quad (78)$$

To include $1/m$ and α_s corrections to the tensor current matrix element, we consider the operator shift

$$\begin{aligned} i\sigma^{\mu\nu}q_\nu \to\ & C_{T_1}(w)i\sigma^{\mu\nu}q_\nu + C_{T_2}(w)(v\cdot q\gamma^\mu - v^\mu \not{q}) + C_{T_3}(w)(v'\cdot q\gamma^\mu - v'^\mu\not{q}) \\ & + C_{T_4}(w)(v'^\mu v\cdot q - v^\mu v'\cdot q) + \Delta J^\mu_T + \Delta\bar{J}^\mu_T + \mathcal{O}(\alpha_s/m, 1/m^2). \end{aligned} \quad (79)$$

Our definition of the C_{T_i} coefficients is related to the one given in [15] by the following substitutions: $\hat{\alpha}_s C_{T_i} + \delta_{i1} \to C_{T_i}$ and $i\hat{\alpha}_s C_{T_4} \to C_{T_4}$. From Eq. (19) we find the leading-order hadronic matrix element including the short-distance QCD corrections:

$$\begin{aligned} & 2\zeta(w)\bar{u}_\alpha v^\alpha\gamma^\mu u\left[-C_{T_1}(m_{\Lambda_b}+m_{\Lambda_c^*}) + C_{T_2}(m_{\Lambda_b}-m_{\Lambda_c^*}w) + C_{T_3}(wm_{\Lambda_b}-m_{\Lambda_c^*})\right] \\ & + 2\zeta(w)\bar{u}_\alpha v^\alpha v^\mu u\left[C_{T_1}m_{\Lambda_b} + C_{T_2}(m_{\Lambda_c^*}-m_{\Lambda_b}) + C_{T_4}(m_{\Lambda_c^*}-wm_{\Lambda_b})\right] \\ & + 2\zeta(w)\bar{u}_\alpha v^\alpha v'^\mu u\left[C_{T_1}m_{\Lambda_c^*} + C_{T_3}(m_{\Lambda_c^*}-m_{\Lambda_b}) + C_{T_4}(m_{\Lambda_b}-wm_{\Lambda_c^*})\right]. \end{aligned} \quad (80)$$

We consider only the local power corrections ΔJ^μ_T and $\Delta\bar{J}^\mu_T$ derived from Eq. (24) with $\Gamma^\mu = i\sigma^{\mu\nu}q_\nu$. The other local operators of the tensor current contribute at order α_s/m, which goes beyond the precision we are aiming to achieve here. The hadronic matrix elements of ΔJ^μ_T and $\Delta\bar{J}^\mu_T$ can be written as follows:

$$\begin{aligned} \langle\Lambda_c^*(k,\eta,s_c)|\Delta J^\mu_T|\Lambda_b(p,s_b)\rangle =\ & 4\bar{u}_\alpha g^{\mu\alpha}u(m_{\Lambda_b}-m_{\Lambda_c^*})\zeta_3^{(b)} + 2\bar{u}_\alpha\gamma^\alpha\gamma^\mu u(m_{\Lambda_c^*}-m_{\Lambda_b})\zeta_3^{(b)} \\ & + 2\bar{u}_\alpha\gamma^\alpha v^\mu u m_{\Lambda_b}\zeta_3^{(b)} + 2\bar{u}_\alpha\gamma^\alpha v'^\mu u m_{\Lambda_c^*}\zeta_3^{(b)} \\ & + \bar{u}_\alpha v^\alpha\gamma^\mu u\left[-4m_{\Lambda_b}\zeta_3^{(b)} - 2(m_{\Lambda_b}+m_{\Lambda_c^*})\zeta_1^{(b)} + 2\left(\frac{-m^2_{\Lambda_b}-m_{\Lambda_b}m_{\Lambda_c^*}+q^2}{m_{\Lambda_c^*}}\zeta_2^{(b)}\right)\right] \\ & + 2\bar{u}_\alpha v^\alpha v^\mu u m_{\Lambda_b}(\zeta_1^{(b)}+\zeta_2^{(b)}) + \bar{u}_\alpha v^\alpha v'^\mu u\left[2m_{\Lambda_c^*}\zeta_1^{(b)} + (4m_{\Lambda_b}-2m_{\Lambda_c^*})\zeta_2^{(b)}\right], \end{aligned} \quad (81)$$

$$\begin{aligned} \langle\Lambda_c^*(k,\eta,s_c)|\Delta\bar{J}^\mu_T|\Lambda_b(p,s_b)\rangle =\ & 2\bar{u}_\alpha\gamma^\alpha\gamma^\mu u(m_{\Lambda_c^*}-m_{\Lambda_b})\zeta_3^{(c)} + 2\bar{u}_\alpha\gamma^\alpha v^\mu u m_{\Lambda_b}\zeta_3^{(c)} \\ & + 2\bar{u}_\alpha\gamma^\alpha v'^\mu u m_{\Lambda_c^*}\zeta_3^{(c)} + \bar{u}_\alpha v^\alpha\gamma^\mu u\left[-2(m_{\Lambda_b}+m_{\Lambda_c^*})\zeta_2^{(c)} + 2\left(\frac{-m^2_{\Lambda_c^*}-m_{\Lambda_b}m_{\Lambda_c^*}+q^2}{m_{\Lambda_b}}\right)\zeta_1^{(c)}\right] \\ & + \bar{u}_\alpha v^\alpha v^\mu u\left[(4m_{\Lambda_c^*}-2m_{\Lambda_b})\zeta_1^{(c)} + 2m_{\Lambda_b}\zeta_2^{(c)}\right] + 2\bar{u}_\alpha v^\alpha v'^\mu u m_{\Lambda_c^*}(\zeta_1^{(c)}+\zeta_2^{(c)}). \end{aligned} \quad (82)$$

The short-distance corrections to the pseudotensor current are related to those of the tensor current via the identity

$$\sigma_{\mu\nu}\gamma_5 = \frac{i}{2}\varepsilon_{\mu\nu\rho\sigma}\sigma^{\rho\sigma}. \tag{83}$$

We get

$$\begin{aligned} i\sigma^{\mu\nu}q_\nu\gamma_5 \to C_{T_1}(w)i\sigma^{\mu\nu}q_\nu\gamma_5 - \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}q^\nu iC_{T_2}(w)(v^\rho\gamma^\sigma - v^\sigma\gamma^\rho) \\ - \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}q^\nu iC_{T_3}(w)(v'^\rho\gamma^\sigma - v'^\sigma\gamma^\rho) - \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}q^\nu C_{T_4}(w)(v'^\rho v^\sigma - v'^\sigma v^\rho). \end{aligned} \tag{84}$$

The hadronic matrix element of the short-distance corrections become

$$\begin{aligned} 2\zeta(w)C_{T_1}\left[(m_{\Lambda_b} - m_{\Lambda_c^*})\bar{u}_\alpha v^\alpha\gamma^\mu\gamma^5 u + m_{\Lambda_b}\bar{u}_\alpha v^\alpha v^\mu\gamma^5 u + m_{\Lambda_c^*}\bar{u}_\alpha v^\alpha v'^\mu\gamma^5 u\right] \\ + 2i\zeta(w)C_{T_2}\bar{u}_\alpha v^\alpha\varepsilon_{\mu\nu\rho\sigma}k^\nu v^\rho\gamma^\sigma u + 2i\zeta(w)C_{T_3}\bar{u}_\alpha v^\alpha\varepsilon_{\mu\nu\rho\sigma}p^\nu v'^\sigma\gamma^\rho u. \end{aligned} \tag{85}$$

From Eq. (24) with $\Gamma^\mu = i\sigma^{\mu\nu}q_\nu\gamma_5$ we obtain the hadronic matrix elements of ΔJ^μ_{T5} and $\Delta\bar{J}^\mu_{T5}$:

$$\begin{aligned} \langle\Lambda_c^*(k,\eta,s_c)|\Delta J^\mu_{T5}|\Lambda_b(p,s_b)\rangle &= 4\bar{u}_\alpha g^{\mu\alpha}\gamma^5 u(m_{\Lambda_b} + m_{\Lambda_c^*})\zeta_3^{(b)} - 2\bar{u}_\alpha\gamma^\alpha\gamma^\mu\gamma^5 u(m_{\Lambda_c^*} + m_{\Lambda_b})\zeta_3^{(b)} \\ &\quad - 2\bar{u}_\alpha\gamma^\alpha\gamma^5 v^\mu u m_{\Lambda_b}\zeta_3^{(b)} - 2\bar{u}_\alpha\gamma^\alpha\gamma^5 v'^\mu u m_{\Lambda_c^*}\zeta_3^{(b)} \\ &\quad + \bar{u}_\alpha v^\alpha\gamma^\mu\gamma^5 u\left[4m_{\Lambda_b}\zeta_3^{(b)} + 2(m_{\Lambda_b} - m_{\Lambda_c^*})\zeta_1^{(b)} + 2\left(\frac{m_{\Lambda_b}^2 - m_{\Lambda_b}m_{\Lambda_c^*} - q^2}{m_{\Lambda_c^*}}\zeta_2^{(b)}\right)\right] \\ &\quad + 2\bar{u}_\alpha v^\alpha v^\mu\gamma^5 u m_{\Lambda_b}(\zeta_1^{(b)} - \zeta_2^{(b)}) + \bar{u}_\alpha v^\alpha v'^\mu\gamma^5 u\left[2m_{\Lambda_c^*}\zeta_1^{(b)} + (4m_{\Lambda_b} + 2m_{\Lambda_c^*})\zeta_2^{(b)}\right], \end{aligned} \tag{86}$$

$$\begin{aligned} \langle\Lambda_c^*(k,\eta,s_c)|\Delta\bar{J}^\mu_{T5}|\Lambda_b(p,s_b)\rangle &= 2\bar{u}_\alpha\gamma^\alpha\gamma^\mu\gamma^5 u(m_{\Lambda_c^*} + m_{\Lambda_b})\zeta_3^{(c)} + 2\bar{u}_\alpha\gamma^\alpha v^\mu\gamma^5 u m_{\Lambda_b}\zeta_3^{(c)} \\ &\quad + 2\bar{u}_\alpha\gamma^\alpha v'^\mu\gamma^5 u m_{\Lambda_c^*}\zeta_3^{(c)} + \bar{u}_\alpha v^\alpha\gamma^\mu\gamma^5 u\left[2(m_{\Lambda_b} - m_{\Lambda_c^*})\zeta_2^{(c)} + 2\left(\frac{-m_{\Lambda_c^*}^2 + m_{\Lambda_b}m_{\Lambda_c^*} + q^2}{m_{\Lambda_b}}\right)\zeta_1^{(c)}\right] \\ &\quad + \bar{u}_\alpha v^\alpha v^\mu\gamma^5 u\left[(4m_{\Lambda_c^*} + 2m_{\Lambda_b})\zeta_1^{(c)} + 2m_{\Lambda_b}\zeta_2^{(c)}\right] + 2\bar{u}_\alpha v^\alpha v'^\mu\gamma^5 u m_{\Lambda_c^*}(\zeta_2^{(c)} - \zeta_1^{(c)}). \end{aligned} \tag{87}$$

Nonlocal insertions of the kinetic operator can be parametrized as

$$\langle\Lambda_c^*(k,\eta,s_c)|\mathcal{L}_{\rm kin}\circ\bar{c}_+^{v'}\Gamma b_+^v|\Lambda_b(p,s_b)\rangle = \sqrt{4}\eta_{\rm kin}^{(b)}(w)v^\alpha\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\Gamma u(m_{\Lambda_b}v,s_b), \tag{88}$$

$$\langle\Lambda_c^*(k,\eta,s_c)|\mathcal{L}'_{\rm kin}\circ\bar{c}_+^{v'}\Gamma b_+^v|\Lambda_b(p,s_b)\rangle = \sqrt{4}\eta_{\rm kin}^{(c)}(w)v^\alpha\bar{u}_\alpha(m_{\Lambda_c^*}v',\eta,s_c)\Gamma u(m_{\Lambda_b}v,s_b), \tag{89}$$

with $\Gamma = i\sigma^{\mu\nu}q_\nu, i\sigma^{\mu\nu}q_\nu\gamma_5$. The above corresponds to a w-dependent shift $\eta_{\rm kin}(w)$ with the same Dirac structure of the tree-level leading-order IW function $\zeta(w)$. At order $\mathcal{O}(1/m)$ we can again absorb it by redefining the leading-order IW function $\zeta(w)$, yet at $\mathcal{O}(1/m^2)$ we must retain it.

The chromomagnetic correction to the b tensor current can be parametrized as in Eq. (43) with $\Gamma = i\sigma^{\rho\sigma}q_\sigma$ and yields

$$\begin{aligned} &\varepsilon_b\eta_{\rm mag}^{(b)}(w)\{2(1-w)(m_{\Lambda_b} + m_{\Lambda_c^*})\bar{u}_\alpha g^{\alpha\rho}u + (1-w)(m_{\Lambda_b} + m_{\Lambda_c^*})\bar{u}_\alpha\gamma^\alpha\gamma^\rho u \\ &\quad - (m_{\Lambda_b} + m_{\Lambda_c^*})\bar{u}_\alpha v^\alpha\gamma^\rho u + m_{\Lambda_b}(w+1)\bar{u}_\alpha\gamma^\alpha v^\rho u \\ &\quad + \left[m_{\Lambda_c^*}(w-1) - 2m_{\Lambda_b}\right]\bar{u}_\alpha\gamma^\alpha v'^\rho u - m_{\Lambda_b}\bar{u}_\alpha v^\alpha v^\rho u + (2m_{\Lambda_b} + m_{\Lambda_c^*})\bar{u}_\alpha v^\alpha v'^\rho u\}. \end{aligned} \tag{90}$$

Analogously from Eq. (44) with $\Gamma = i\sigma^{\rho\sigma}q_\sigma$ we obtain the chromomagnetic correction to the c tensor current:

$$\begin{aligned} &\varepsilon_c\eta_{\rm mag}^{(c)}(w)\{(w-1)(m_{\Lambda_b}+m_{\Lambda_c^*})\bar{u}_\alpha\gamma^\alpha\gamma^\rho u - (m_{\Lambda_b}+m_{\Lambda_c^*})\bar{u}_\alpha v^\alpha\gamma^\rho u + [m_{\Lambda_b}(-w+1) + 2m_{\Lambda_c^*}]\bar{u}_\alpha\gamma^\alpha v^\rho u \\ &\quad - m_{\Lambda_c^*}(w+1)\bar{u}_\alpha\gamma^\alpha v'^\rho u + m_{\Lambda_b}\bar{u}_\alpha v^\alpha v^\rho u + m_{\Lambda_c^*}\bar{u}_\alpha v^\alpha v'^\rho u\}. \end{aligned} \tag{91}$$

By imposing $\Gamma = i\sigma^{\rho\sigma}\gamma_5 q_\sigma$ in Eqs. (43) and (44), we obtain that the chromomagnetic correction to the b and c pseudotensor currents is. respectively. given by

$$\varepsilon_b \eta^{(b)}_{\rm mag}(w)\big\{-2(w+1)(m_{\Lambda_b}-m_{\Lambda_c^*})\bar{u}_\alpha g^{\alpha\rho}\gamma_5 u + (w+1)(m_{\Lambda_b}-m_{\Lambda_c^*}),\bar{u}_\alpha\gamma^\alpha\gamma^\rho\gamma_5 u + (-m_{\Lambda_b}+m_{\Lambda_c^*})\bar{u}_\alpha v^\alpha\gamma^\rho\gamma_5 u + m_{\Lambda_b}(-w+1)\bar{u}_\alpha\gamma^\alpha v^\rho\gamma_5 u + \big[-m_{\Lambda_c^*}(w+1)+2m_{\Lambda_b}\big]\bar{u}_\alpha\gamma^\alpha v'^\rho\gamma_5 u + m_{\Lambda_b}\bar{u}_\alpha v^\alpha v^\rho\gamma_5 u + (2m_{\Lambda_b}-m_{\Lambda_c^*})\bar{u}_\alpha v^\alpha v'^\rho\gamma_5 u\big\}, \tag{92}$$

$$\varepsilon_c \eta^{(c)}_{\rm mag}(w)\big\{-(w+1)(m_{\Lambda_b}-m_{\Lambda_c^*})\bar{u}_\alpha\gamma^\alpha\gamma^\rho\gamma_5 u + (m_{\Lambda_b}-m_{\Lambda_c^*})\bar{u}_\alpha v^\alpha\gamma^\rho\gamma_5 u + \big[-m_{\Lambda_b}(w+1)+2m_{\Lambda_c^*}\big]\bar{u}_\alpha\gamma^\alpha v^\rho\gamma_5 u - m_{\Lambda_c^*}(w-1)\bar{u}_\alpha\gamma^\alpha v'^\rho\gamma_5 u + m_{\Lambda_b}\bar{u}_\alpha v^\alpha v^\rho\gamma_5 u + m_{\Lambda_c^*}\bar{u}_\alpha v^\alpha v'^\rho\gamma_5 u\big\}. \tag{93}$$

As expected, at zero recoil the chromomagnetic corrections vanish for each current.

E. Tensor and pseudotensor form factors in the VC limit

In the following we list the expressions of the QCD form factors obtained from the matching on the HQE on-shell amplitudes in the VC limit. As we have already done for vector and axial current form factors, we explicitly report the kinetic operator contribution $\mathcal{O}(1/m_c)$.

Concerning the $\Lambda_c(2595)^+$ final state we find for the tensor form factors

$$t_{1/2,0} = \frac{\zeta m_{\Lambda_c^*} s_- \sqrt{s_+}}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}}\left(C_{T_1} - C_{T_2} + C_{T_3} - \frac{C_{T_4} s_+}{2m_{\Lambda_b} m_{\Lambda_c^*}}\right) + \varepsilon_b \frac{m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(\frac{\zeta\bar{\Lambda}(m^2_{\Lambda_b} + m^2_{\Lambda_c^*} - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}} - 2\zeta\bar{\Lambda}' + 4\zeta_{\rm SL}\right) + \varepsilon_c \frac{m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda} - 4\zeta_{\rm SL} - \frac{\zeta\bar{\Lambda}'(m^2_{\Lambda_b} + m^2_{\Lambda_c^*} - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}}\right) + \varepsilon_c \frac{\eta^{(c)}_{\rm kin} m_{\Lambda_c^*} s_- \sqrt{s_+}}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}}, \tag{94}$$

$$t_{1/2,\perp} = \frac{\zeta s_- \sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(\frac{C_{T_1} m_{\Lambda_c^*}}{m_{\Lambda_b} m_{\Lambda_c^*}} + \frac{C_{T_2}(-m^2_{\Lambda_b} + m^2_{\Lambda_c^*} - q^2)}{2m^2_{\Lambda_b}(m_{\Lambda_b} + m_{\Lambda_c^*})} - \frac{C_{T_3}(m^2_{\Lambda_b} - m^2_{\Lambda_c^*} - q^2)}{2(m_{\Lambda_b} + m_{\Lambda_c^*}) m_{\Lambda_b} m_{\Lambda_c^*}}\right) + \varepsilon_b \frac{m_{\Lambda_c^*}\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda}' - \frac{\zeta\bar{\Lambda}(m^2_{\Lambda_b} + m^2_{\Lambda_c^*} - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}}\right) + \varepsilon_c \frac{\sqrt{s_+} m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda} - 4\zeta_{\rm SL} - \frac{\bar{\Lambda}'\zeta(m^2_{\Lambda_b} + m^2_{\Lambda_c^*} - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}}\right) + \varepsilon_c \frac{\eta^{(c)}_{\rm kin} m_{\Lambda_c^*} s_- \sqrt{s_+}}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}}, \tag{95}$$

while for the pseudotensor form factors the matching gives

$$t^5_{1/2,0} = \frac{C_{T_1}\zeta m_{\Lambda_c^*}\sqrt{s_-} s_+}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_b \frac{m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(\frac{\zeta\bar{\Lambda}(m^2_{\Lambda_b} + m^2_{\Lambda_c^*} - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}} - 2\zeta\bar{\Lambda}' - 4\zeta_{\rm SL}\right) + \varepsilon_c \frac{m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda} - 4\zeta_{\rm SL} - \frac{\zeta\bar{\Lambda}'(m^2_{\Lambda_b} + m^2_{\Lambda_c^*} - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}}\right) + \varepsilon_c \frac{\eta^{(c)}_{\rm kin} m_{\Lambda_c^*}\sqrt{s_-} s_+}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}}, \tag{96}$$

$$t^5_{1/2,\perp} = \frac{\zeta\sqrt{s_-} s_+}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(\frac{C_{T_1} m_{\Lambda_c^*}}{m_{\Lambda_b} m_{\Lambda_c^*}} - \frac{C_{T_2} s_-}{2m^2_{\Lambda_b}(m_{\Lambda_b} - m_{\Lambda_c^*})} - \frac{C_{T_3} s_-}{2(m_{\Lambda_b} - m_{\Lambda_c^*}) m_{\Lambda_b} m_{\Lambda_c^*}}\right) + \varepsilon_b \frac{m_{\Lambda_c^*}\sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda}' - \frac{\zeta\bar{\Lambda}(m^2_{\Lambda_b} + m^2_{\Lambda_c^*} - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}}\right) + \varepsilon_c \frac{m_{\Lambda_c^*}\sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda} - 4\zeta_{\rm SL} - \frac{\zeta\bar{\Lambda}'(m^2_{\Lambda_b} + m^2_{\Lambda_c^*} - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}}\right) + \varepsilon_c \frac{\eta^{(c)}_{\rm kin} m_{\Lambda_c^*}\sqrt{s_-} s_+}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}}. \tag{97}$$

For the $\Lambda_c(2625)^+$ final state, the tensor form factors are

$$T_{1/2,0} = \zeta \frac{m_{\Lambda_c^*}\sqrt{s_+}s_-}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_{T_1} - C_{T_2} + C_{T_3} - \frac{s_+}{2m_{\Lambda_b}m_{\Lambda_c^*}}C_{T_4}\right) + \varepsilon_b \frac{2m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(-\zeta\bar{\Lambda}' - \zeta_{\rm SL} + \zeta\frac{m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2}{2m_{\Lambda_b}m_{\Lambda_c^*}}\bar{\Lambda}\right) + \varepsilon_c \frac{2m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda} + \zeta_{\rm SL} - \zeta\frac{m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2}{2m_{\Lambda_b}m_{\Lambda_c^*}}\bar{\Lambda}'\right) + \varepsilon_c \frac{m_{\Lambda_c^*}\sqrt{s_+}s_-}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\rm kin}^{(c)}, \tag{98}$$

$$T_{1/2,\perp} = \zeta \frac{\sqrt{s_+}s_-}{m_{\Lambda_b}\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(C_{T_1} - \frac{m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2 + q^2}{2m_{\Lambda_b}(m_{\Lambda_b} + m_{\Lambda_c^*})}C_{T_2} - \frac{m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2 - q^2}{2m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*})}C_{T_3}\right) + \varepsilon_b \frac{2m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}' - \zeta\frac{m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2}{2m_{\Lambda_b}m_{\Lambda_c^*}}\bar{\Lambda}\right) + \varepsilon_c \frac{2m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda} + \zeta_{\rm SL} - \zeta\frac{m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2}{2m_{\Lambda_b}m_{\Lambda_c^*}}\bar{\Lambda}'\right) + \varepsilon_c \frac{m_{\Lambda_c^*}\sqrt{s_+}s_-}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\rm kin}^{(c)}, \tag{99}$$

$$T_{3/2,\perp} = -\varepsilon_b \frac{2(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\zeta_{\rm SL}, \tag{100}$$

while for the pseudotensor form factor

$$T_{1/2,0}^5 = \frac{\zeta m_{\Lambda_c^*}s_+\sqrt{s_-}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}C_{T_1} + \varepsilon_b \frac{2m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}}{2m_{\Lambda_b}m_{\Lambda_c^*}} + \zeta_{\rm SL} - \zeta\bar{\Lambda}'\right) + \varepsilon_b \frac{2m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(-\zeta\frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}'}{2m_{\Lambda_b}m_{\Lambda_c^*}} + \zeta_{\rm SL} + \zeta\bar{\Lambda}\right) + \varepsilon_c \frac{m_{\Lambda_c^*}s_+\sqrt{s_-}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\rm kin}^{(c)}, \tag{101}$$

$$T_{1/2,\perp}^5 = \zeta \frac{s_+\sqrt{s_-}}{m_{\Lambda_b}\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(C_{T_1} - \frac{s_-}{2m_{\Lambda_b}(m_{\Lambda_b} - m_{\Lambda_c^*})}C_{T_2} - \frac{s_-}{2m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})}\right) + \varepsilon_b \frac{2m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{s_-}}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}' - \zeta\frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \varepsilon_c \frac{2m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{s_-}}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda} + \zeta_{\rm SL} - \zeta\frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}'}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \varepsilon_c \frac{m_{\Lambda_c^*}s_+\sqrt{s_-}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\rm kin}^{(c)}, \tag{102}$$

$$T_{3/2,\perp}^5 = -\varepsilon_b \frac{2(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\zeta_{\rm SL}. \tag{103}$$

F. The chromomagnetic correction for tensor and pseudotensor form factors

The contribution of the chromomagnetic operator results in a shift to the form factors defined in Sec. III E. Concerning the $\Lambda_c(2595)^+$ final state we find that the contributions of the chromomagnetic operator to the tensor form factors are

$$t_{1/2,0}^{\rm mag} = \frac{m_{\Lambda_c^*}s_-\sqrt{s_+}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(\varepsilon_b\eta_{\rm mag}^{(b)} - \varepsilon_c\eta_{\rm mag}^{(c)}), \tag{104}$$

$$t_{1/2,\perp}^{\rm mag} = -\frac{m_{\Lambda_c^*}s_-\sqrt{s_+}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\varepsilon_c\eta_{\rm mag}^{(c)}, \tag{105}$$

while for the pseudotensor form factors the matching gives

$$t_{1/2,0}^{\rm mag\,5} = -\frac{m_{\Lambda_c^*}s_+\sqrt{s_-}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(\varepsilon_b\eta_{\rm mag}^{(b)} + \varepsilon_c\eta_{\rm mag}^{(c)}), \tag{106}$$

$$t_{1/2,\perp}^{\rm mag\,5} = -\frac{m_{\Lambda_c^*}s_+\sqrt{s_-}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\varepsilon_c\eta_{\rm mag}^{(c)}. \tag{107}$$

For the $\Lambda_c(2625)^+$ final state, the contributions of the chromomagnetic operator to the tensor form factors are

$$T^{\rm mag}_{1/2,0} = \frac{m_{\Lambda_c^*} s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(-\varepsilon_b \eta^{(b)}_{\rm mag} + \varepsilon_c \eta^{(c)}_{\rm mag}\right), \quad (108)$$

$$T^{\rm mag}_{1/2,\perp} = \frac{m_{\Lambda_c^*} s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \varepsilon_c \eta^{(c)}_{\rm mag}, \quad (109)$$

$$T^{\rm mag}_{3/2,\perp} = \frac{(m_{\Lambda_b} + m_{\Lambda_c^*}) s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \varepsilon_b \eta^{(b)}_{\rm mag}, \quad (110)$$

while for the pseudotensor form factors we obtain

$$T^{\rm mag\,5}_{1/2,0} = \frac{m_{\Lambda_c^*} s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(\varepsilon_b \eta^{(b)}_{\rm mag} + \varepsilon_c \eta^{(c)}_{\rm mag}\right), \quad (111)$$

$$T^{\rm mag\,5}_{1/2,\perp} = \frac{m_{\Lambda_c^*} s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \varepsilon_c \eta^{(c)}_{\rm mag}, \quad (112)$$

$$T^{\rm mag\,5}_{3/2,\perp} = \frac{(m_{\Lambda_b} - m_{\Lambda_c^*}) s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \varepsilon_b \eta^{(b)}_{\rm mag}. \quad (113)$$

The proportionality of the chromomagnetic induced form factors with respect to s_- guarantees that the amplitudes vanish at zero recoil (e.g., $w = 1$).

Summarizing this section, we obtained nonlocal chromomagnetic and (pseudo)tensor form factor contributions that were absent in [33] but present in [34] expressed in a different basis. We explicitly checked that our results coincide with the ones of [34].

IV. NEXT-TO-NEXT-TO-LEADING ORDER CORRECTIONS

When delving into corrections at the next-to-next-to-leading order (NNLO) within the framework of HQET, it is necessary to turn our attention to all the $\mathcal{O}(1/m_{b,c}^2, 1/m_b m_c)$ terms. This is important to ensure a comprehensive and accurate computation of the matrix elements that contributes to the $\Lambda_b \to \Lambda_c^*$ transition.

However, since the $\mathcal{O}(1/m_c^2)$ terms are numerically favored with respect to $\mathcal{O}(1/m_b^2)$ and $\mathcal{O}(1/m_b m_c)$ ones, they are expected to give the major contribution to the amplitudes, as also underlined in [33,34].

Furthermore, a comprehensive study of the complete second-order correction would entail a larger number of independent IW unknown parameters. Therefore, to extend the analysis beyond the next-to-leading order while keeping as few unconstrained parameters as possible, we limit our calculations of the form factors to the $\mathcal{O}(1/m_c^2)$ terms. In addition, we further simplify our study by employing both the RC expansion and the VC limit. These two were introduced in [16] in the context of the computation of the second-order corrections to the mesonic $B \to D^{(*)}$ transitions.

We now proceed to parametrize the matrix elements at $\mathcal{O}(1/m_c^2)$ given in Eq. (17) which reads

$$\begin{aligned} &\langle \Lambda_c^*(k,\eta,s_c)|\bar c_+^{v'} \bar{\mathcal{J}}_2' \Pi_-' \Gamma b_+^v |\Lambda_b(p,s_b)\rangle \\ &\quad = \sqrt{4} \bar u_\mu \gamma_\alpha v'_\beta \Gamma u \psi^{\alpha\beta\mu}(v,v'), \end{aligned} \quad (114)$$

where

$$\begin{aligned} \psi^{\alpha\beta\mu}(v,v') = {}& \psi_1(w) v^\mu (v^\alpha v'^\beta - v^\beta v'^\alpha) \\ &+ \psi_2(w)(g^{\alpha\mu} v^\beta - g^{\beta\mu} v^\alpha) \\ &+ \psi_3(w)(g^{\alpha\mu} v'^\beta - g^{\beta\mu} v'^\alpha). \end{aligned} \quad (115)$$

To determine $\mathcal{L}_2' \circ \bar c_+^{v'} \Gamma b_+^v$ we observe that the associated terms given in Eq. (9) can be parametrized as the corresponding kinetic and chromomagnetic corrections at order $\mathcal{O}(1/m_c)$:

$$\begin{aligned} &\langle \Lambda_c^*(k,\eta,s_c)|\bar c_+^{v'} v_\beta D_\alpha G^{\alpha\beta} c_+^{v'} \circ \bar c_+^{v'} \Gamma b_+^v |\Lambda_b(p,s_b)\rangle = \bar u_\mu \Gamma u \lambda^\mu(v,v'), \\ &\langle \Lambda_c^*(k,\eta,s_c)| - i \bar c_+^{v'} v_\alpha \sigma_{\beta\gamma} D^\gamma G^{\alpha\beta} c_+^{v'} \circ \bar c_+^{v'} \Gamma b_+^v |\Lambda_b(p,s_b)\rangle = \eta(w) g^{\mu\alpha} v^\beta \bar u_\mu i \sigma_{\alpha\beta} \Pi_+' \Gamma u. \end{aligned} \quad (116)$$

We then consider two times the insertion of the first-order Lagrangian $\mathcal{L}_1' \circ \mathcal{L}_1' \circ \bar c_+^{v'} \Gamma b_+^v$ and find

$$\langle \Lambda_c^*(k,\eta,s_c)|\bar c_+^{v'} D^2 c_+^{v'} \circ \bar c_+^{v'} D^2 c_+^{v'} \circ \bar c_+^{v'} \Gamma b_+^v |\Lambda_b(p,s_b)\rangle = \bar u_\mu \Gamma u \alpha^\mu(v,v'), \quad (117)$$

where

$$\alpha^\mu(v,v') = \alpha(w)(v - v')^\mu. \quad (118)$$

Then

$$\langle \Lambda_c^*(k,\eta,s_c)|\bar c_+^{v'} \sigma_{\alpha\beta} G^{\alpha\beta} c_+^{v'} \circ \bar c_+^{v'} \sigma_{\gamma\delta} G^{\gamma\delta} c_+^{v'} \circ \bar c_+^{v'} \Gamma b_+^v |\Lambda_b(p,s_b)\rangle = \bar u_\mu \sigma_{\alpha\beta} \Pi_+' \sigma_{\gamma\delta} \Pi_+' \Gamma u \alpha'^{\alpha\beta\gamma\delta\mu}(v,v'), \quad (119)$$

where

$$\alpha'^{\alpha\beta\gamma\delta\mu}(v,v') = \alpha'_1(w)(g^{\alpha\gamma}g^{\beta\delta} - g^{\alpha\delta}g^{\beta\gamma})v^\mu + \alpha'_2(w)(g^{\alpha\gamma}v^\beta v^\delta - g^{\beta\gamma}v^\alpha v^\delta - g^{\alpha\delta}v^\beta v^\gamma + g^{\beta\delta}v^\alpha v^\gamma)v^\mu + \alpha'_3(w)(g^{\alpha\mu}g^{\beta\delta}v^\gamma - g^{\beta\mu}g^{\alpha\delta}v^\gamma + g^{\alpha\gamma}g^{\beta\mu}v^\delta - g^{\beta\gamma}g^{\alpha\mu}v^\delta + g^{\mu\gamma}g^{\beta\delta}v^\alpha - g^{\beta\gamma}g^{\mu\delta}v^\alpha + g^{\alpha\gamma}g^{\mu\delta}v^\beta - g^{\mu\gamma}g^{\alpha\delta}v^\beta). \quad (120)$$

We arrive at

$$\langle\Lambda_c^*(k,\eta,s_c)|\bar{c}_+^{v'}D^2c_+^{v'}\circ\bar{c}_+^{v'}\sigma_{\alpha\beta}G^{\alpha\beta}c_+^{v'}\circ\bar{c}_+^{v'}\Gamma b_+^v|\Lambda_b(p,s_b)\rangle = \alpha''(w)\bar{u}_\mu\sigma_{\alpha\beta}\Pi'_+\Gamma u g^{\alpha\mu}v^\beta. \quad (121)$$

Turning our attention to $\mathcal{L}'_1\circ\bar{c}_+^{v'}\bar{\mathcal{J}}'_1\Pi'_-\Gamma b_+^v$ we see that the first term in $\mathcal{L}'_1$ yields

$$\langle\Lambda_c^*(k,\eta,s_c)|\bar{c}_+^{v'}D^2c_+^{v'}\circ\bar{c}_+^{v'}\bar{\mathcal{J}}'_1\Pi'_-\Gamma b_+^v|\Lambda_b(p,s_b)\rangle = \bar{u}_\mu\gamma_\alpha\Pi'_-\Gamma u\beta^{\mu\alpha}(v,v'), \quad (122)$$

where

$$\beta^{\mu\alpha}(v,v') = v^\mu(\beta_1(w)v^\alpha + \beta_2 v'^\alpha) + \beta_3(w)g^{\mu\alpha}. \quad (123)$$

The second term in $\mathcal{L}'_1$ corresponds to

$$\langle\Lambda_c^*(k,\eta,s_c)|\bar{c}_+^{v'}\sigma_{\alpha\beta}G^{\alpha\beta}c_+^{v'}\circ\bar{c}_+^{v'}\bar{\mathcal{J}}'_1\Pi'_-\Gamma b_+^v|\Lambda_b(p,s_b)\rangle = \bar{u}_\mu\sigma_{\alpha\beta}\Pi'_+\gamma_\nu\Pi'_-\Gamma u\beta'^{\mu\alpha\beta\nu}(v,v'), \quad (124)$$

where

$$\beta'^{\mu\alpha\beta\nu}(v,v') = \beta'_1(g^{\alpha\mu}g^{\beta\nu} - g^{\alpha\nu}g^{\beta\mu}) + \beta'_2(g^{\alpha\mu}v^\beta - g^{\beta\mu}v^\alpha)v^\nu + \beta'_3(g^{\alpha\nu}v^\beta - g^{\beta\nu}v^\alpha)v^\mu + \beta'_4(g^{\alpha\mu}v^\beta - g^{\beta\mu}v^\alpha)v'^\nu. \quad (125)$$

We observe that there are initially 17 independent IW functions. Nevertheless, as we consider the constraints stemming from the equation of motion, as well as the modified Ward identities, this number reduces to 15. Moving forward, we now investigate the RC and VC limits, where the number of independent IW functions decreases to 3 and 2, respectively.

A. Residual chiral limit at $\mathcal{O}(1/m_c^2,\theta^2)$

The Residual chiral expansion, initially introduced in [16], aims at establishing an additional power counting besides the HQE one, identifying a subset of subdominant contributions that can be neglected. In fact, as detailed in [16], both experimental data and theoretical predictions derived within specific quark models suggest that there exists a hierarchy among the HQET matrix elements. This hierarchy depends on the number of insertions of the cross terms $\bar{Q}_+^v\not{D}_\perp Q_-^v$ and $\bar{Q}_-^v\not{D}_\perp Q_+^v$, which contain the transverse derivative. Specifically, matrix elements with more insertions of the transverse derivative are observed to be suppressed when compared to those with fewer insertions. Since the cross terms break the accidental $U(1)_+ \times U(1)_-$ symmetry of the kinetic Lagrangian $\mathcal{L} = \bar{Q}_+^v iv\cdot DQ_+^v + \bar{Q}_-^v iv\cdot DQ_-^v$ in Eq. (6) to a diagonal $U(1)$, we can systematically organize the perturbative HQ expansion by power counting the number of insertions of the cross operator, despite the absence of a small parameter for this symmetry breaking. This is achieved through the substitution $i\not{D}_\perp \to i\theta\not{D}_\perp$.

Building upon the insights presented in [16], the residual chiral expansion effectively introduces a power counting scheme where it is justified to retain $\mathcal{O}(\theta^2)$ terms. Thus, at $\mathcal{O}(1/m_c^2,\theta^2)$ Eq. (17) becomes

$$\frac{\langle H_c|\bar{c}\Gamma b|H_b\rangle}{\sqrt{m_{H_c}m_{H_b}}} \simeq \langle H_c^{v'}|\bar{c}_+^{v'}\Gamma b_+^v|H_b^v\rangle + \frac{1}{2m_c}\langle H_c^{v'}|(\bar{c}_+^{v'}\bar{\mathcal{J}}'_1 + \mathcal{L}'_1\circ\bar{c}_+^{v'})\Gamma b_+^v|H_b^v\rangle + \frac{1}{2m_b}\langle H_c^{v'}|\bar{c}_+^{v'}\Gamma(\mathcal{J}_1 b_+^v + b_+^v\circ\mathcal{L}_1)|H_b^v\rangle + \frac{1}{4m_c^2}\langle H_c^{v'}|(\bar{c}_+^{v'}\bar{\mathcal{J}}'_2\Pi'_- + \mathcal{L}'_2\circ\bar{c}_+^{v'})\Gamma b_+^v|H_b^v\rangle. \quad (126)$$

The second-order pure current correction can be written as

$$\langle\Lambda_c^*(k,\eta,s_c)|\bar{c}_+^{v'}\bar{\mathcal{J}}'_2\Pi'_-\Gamma b_+^v|\Lambda_b(p,s_b)\rangle = \langle\Lambda_c^*(k,\eta,s_c)|\bar{c}_+^{v'}\gamma_\alpha v'_\beta G^{\alpha\beta}b_+^v|\Lambda_b(p,s_b)\rangle = \sqrt{4}\bar{u}_\mu\gamma_\alpha v'_\beta\Gamma u\psi^{\alpha\beta\mu}(v,v'), \quad (127)$$

where the most general decomposition of the IW function $\psi^{\alpha\beta\mu}(v,v')$ is

$$\psi^{\alpha\beta\mu}(v,v') = \psi_1(w)v^\mu(v^\alpha v'^\beta - v^\beta v'^\alpha) + \psi_2(w)(g^{\alpha\mu}v^\beta - g^{\beta\mu}v^\alpha) + \psi_3(w)(g^{\alpha\mu}v'^\beta - g^{\beta\mu}v'^\alpha). \quad (128)$$

(i) For the vector current $\Gamma = \gamma_\mu$ Eq. (127) gives

$$4\psi_1 \bar{u}_\alpha v^\alpha v_\mu u - 2(1+w)\psi_1 \bar{u}_\alpha v^\alpha \gamma_\mu u + 2(\psi_3 + w\psi_2)\bar{u}_\alpha \gamma^\alpha \gamma_\mu u; \tag{129}$$

(ii) For the axial current $\Gamma = \gamma_\mu \gamma_5$ Eq. (127) gives

$$4\psi_1 \bar{u}_\alpha v^\alpha v_\mu \gamma_5 u + 2(1-w)\psi_1 \bar{u}_\alpha v^\alpha \gamma_\mu \gamma_5 u + 2(\psi_3 + w\psi_2)\bar{u}_\alpha \gamma^\alpha \gamma_\mu \gamma_5 u; \tag{130}$$

(iii) For the tensor current $\Gamma = i\sigma_{\mu\nu} q^\nu$ Eq. (127) gives

$$\begin{aligned} &2\psi_1(1+w)(m_{\Lambda_b} - m_{\Lambda_c^*})\bar{u}_\alpha v^\alpha \gamma_\mu u + \psi_1\left[4m_{\Lambda_c^*} - 2(1+w)m_{\Lambda_b}\right]\bar{u}_\alpha v^\alpha v_\mu u + 2\psi_1(1-w)m_{\Lambda_c^*}\bar{u}_\alpha v^\alpha v'_\mu u \\ &\quad + 2(\psi_3 + w\psi_2)\left[(m_{\Lambda_c^*} - m_{\Lambda_b})\bar{u}_\alpha \gamma^\alpha \gamma_\mu u + m_{\Lambda_b}\bar{u}_\alpha \gamma^\alpha v_\mu u + m_{\Lambda_c^*}\bar{u}_\alpha \gamma^\alpha v'_\mu u\right]; \end{aligned} \tag{131}$$

(iv) For the pseudotensor current $\Gamma = i\sigma_{\mu\nu}\gamma_5 q^\nu$ Eq. (127) gives

$$\begin{aligned} &2\psi_1(1-w)(m_{\Lambda_b} + m_{\Lambda_c^*})\bar{u}_\alpha v^\alpha \gamma_\mu \gamma_5 u + \psi_1(4m_{\Lambda_c^*} + 2m_{\Lambda_b}(1-w))\bar{u}_\alpha v^\alpha v_\mu \gamma_5 u - 2\psi_1(1+w)m_{\Lambda_c^*}\bar{u}_\alpha v^\alpha v'_\mu \gamma_5 u \\ &\quad + 2(\psi_3 + w\psi_2)\left[(m_{\Lambda_b} + m_{\Lambda_c^*})\bar{u}_\alpha \gamma^\alpha \gamma_\mu \gamma_5 u + m_{\Lambda_b}\bar{u}_\alpha \gamma^\alpha v_\mu \gamma_5 u + m_{\Lambda_c^*}\bar{u}_\alpha \gamma^\alpha v'_\mu \gamma_5 u\right]. \end{aligned} \tag{132}$$

The matrix elements of the insertion of second-order Lagrangian $\mathcal{L}'_2$ in the LO currents can easily be parametrized like the corresponding single insertions of the first-order Lagrangian [16]:

$$\begin{aligned} \langle \Lambda_c^*(k,\eta,s_c)|\bar{c}_+^{v'} v_\beta D_\alpha G^{\alpha\beta} c_+^{v'} \circ \bar{c}_+^{v'} \Gamma b_+^v |\Lambda_b(p,s_b)\rangle &= \sqrt{4}\bar{u}_\mu \Gamma u \lambda^\mu(v,v'), \\ \langle \Lambda_c^*(k,\eta,s_c)| - i\bar{c}_+^{v'} v_\alpha \sigma_{\beta\gamma} D^\gamma G^{\alpha\beta} c_+^{v'} \circ \bar{c}\Gamma b_+^v |\Lambda_b(p,s_b)\rangle &= \sqrt{4}\eta(w) g^{\mu\alpha} v^\beta \bar{u}_\mu i\sigma_{\alpha\beta}\Pi'_+ \Gamma u. \end{aligned} \tag{133}$$

At order $\mathcal{O}(1/m_c^2, \theta^2)$ they can be reabsorbed by redefining the IW functions $\eta_{\rm kin}^{(c)}$ and $\eta_{\rm mag}^{(c)}$ as follows:

$$\eta_{\rm kin}^{(c)} + \frac{1}{2m_c}\lambda(w) \to \eta_{\rm kin}^{(c)}, \tag{134}$$

$$\eta_{\rm mag}^{(c)}(w) + \frac{1}{2m_c}\eta(w) \to \eta_{\rm mag}^{(c)}(w). \tag{135}$$

B. Form factors at $\mathcal{O}(1/m_c^2, \theta^2)$

The NNLO contributions of the HQE for the matrix elements due to the current $\bar{\mathcal{J}}'_2$ in the RC limit induces a shift in the form factors reported in Sec. III, which for the $\Lambda_c(2595)^+$ vector current contribution reads

$$f_{1/2,0}^{\mathcal{J}'_2} = \varepsilon_c^2 \frac{\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \times \left(3(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right), \tag{136}$$

$$f_{1/2,t}^{\mathcal{J}'_2} = \varepsilon_c^2 \frac{\sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \times \left(3(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right), \tag{137}$$

$$f_{1/2,\perp}^{\mathcal{J}'_2} = \varepsilon_c^2 \frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right), \tag{138}$$

while for the axial-vector form factors we obtain

$$g_{1/2,0}^{\mathcal{J}'_2} = \varepsilon_c^2 \frac{\sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \times \left(3(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right), \tag{139}$$

$$g_{1/2,t}^{\mathcal{J}'_2} = \varepsilon_c^2 \frac{\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \times \left(3(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right), \tag{140}$$

$$g_{1/2,\perp}^{\mathcal{J}'_2} = \varepsilon_c^2 \frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right). \tag{141}$$

For the $\Lambda_c(2625)^+$ final state the vector current reads

$$F^{\mathcal{J}_2'}_{1/2,0} = -\frac{s_+^{3/2} s_-(m_{\Lambda_b} - m_{\Lambda_c^*})}{4(m_{\Lambda_b} + m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \varepsilon_c^2 \psi_1, \tag{142}$$

$$F^{\mathcal{J}_2'}_{1/2,t} = -\frac{s_+ s_-^{3/2}(m_{\Lambda_b} + m_{\Lambda_c^*})}{4(m_{\Lambda_b} - m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \varepsilon_c^2 \psi_1, \tag{143}$$

$$F^{\mathcal{J}_2'}_{1/2,\perp} = -\varepsilon_c^2 \frac{s_+^{3/2} s_-}{4(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \psi_1, \tag{144}$$

$$F^{\mathcal{J}_2'}_{3/2,\perp} = 0, \tag{145}$$

while for the axial vector

$$G^{\mathcal{J}_2'}_{1/2,0} = -\frac{s_+ s_-^{3/2}(m_{\Lambda_b} + m_{\Lambda_c^*})}{4(m_{\Lambda_b} - m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \varepsilon_c^2 \psi_1, \tag{146}$$

$$G^{\mathcal{J}_2'}_{1/2,t} = -\frac{s_+^{3/2} s_-(m_{\Lambda_b} - m_{\Lambda_c^*})}{4(m_{\Lambda_b} + m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \varepsilon_c^2 \psi_1, \tag{147}$$

$$G^{\mathcal{J}_2'}_{1/2,\perp} = -\frac{s_+ s_-^{3/2}}{4(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \varepsilon_c^2 \psi_1, \tag{148}$$

$$G^{\mathcal{J}_2'}_{3/2,\perp} = 0. \tag{149}$$

The tensor contributions for $\Lambda_c(2595)^+$ are

$$t^{\mathcal{J}_2'}_{1/2,0} = \varepsilon_c^2 \frac{m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(6(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{2(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right), \tag{150}$$

$$t^{\mathcal{J}_2'}_{1/2,\perp} = \varepsilon_c^2 \frac{m_{\Lambda_c^*}\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \times \left(6(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{2(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right), \tag{151}$$

while the pseudotensor induced form factors read

$$t^{5\mathcal{J}_2'}_{1/2,0} = \varepsilon_c^2 \frac{m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(6(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{2(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right), \tag{152}$$

$$t^{5\mathcal{J}_2'}_{1/2,\perp} = \varepsilon_c^2 \frac{m_{\Lambda_c^*}\sqrt{s_+}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \times \left(6(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{2(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right). \tag{153}$$

Similarly the tensor contributions for $\Lambda_c(2625)^+$ are

$$T^{\mathcal{J}_2'}_{1/2,0} = -\frac{m_{\Lambda_c^*} s_+^{3/2} s_-}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \varepsilon_c^2 \psi_1, \tag{154}$$

$$T^{\mathcal{J}_2'}_{1/2,\perp} = -\frac{m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*}) s_+^{3/2} s_-}{2(m_{\Lambda_b} + m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \varepsilon_c^2 \psi_1, \tag{155}$$

$$T^{\mathcal{J}_2'}_{3/2,\perp} = 0, \tag{156}$$

while the pseudotensor induced form factors are

$$T^{5\mathcal{J}_2'}_{1/2,0} = -\frac{m_{\Lambda_c^*} s_+ s_-^{3/2}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \varepsilon_c^2 \psi_1, \tag{157}$$

$$T^{5\mathcal{J}_2'}_{1/2,\perp} = -\frac{m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*}) s_+ s_-^{3/2}}{2(m_{\Lambda_b} - m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \varepsilon_c^2 \psi_1, \tag{158}$$

$$T^{5\mathcal{J}_2'}_{3/2,\perp} = 0. \tag{159}$$

C. Vanishing chromomagnetic limit at $\mathcal{O}(1/m_c^2)$

When taking the limit $G_{\alpha\beta} \to 0$ the number of matrix elements drastically reduces with the first- and second-order lagrangian correction simplifying to [16]

$$\mathcal{L}_1 = -\bar{Q}_+^v D^2 Q_+^v; \quad \mathcal{L}_2 = 0, \tag{160}$$

and Eq. (17) becomes

$$\frac{\langle H_c|\bar{c}\Gamma b|H_b\rangle}{\sqrt{m_{H_c} m_{H_b}}} \simeq \langle H_c^{v'}|\bar{c}_+^{v'}\Gamma b_+^v|H_b^v\rangle + \frac{1}{2m_c}\langle H_c^{v'}|(\bar{c}_+^{v'}\bar{\mathcal{J}}_1' - \bar{c}_+^{v'} D^2 c_+^{v'} \circ \bar{c}_+^{v'})\Gamma b_+^v|H_b^v\rangle + \frac{1}{2m_b}\langle H_c^{v'}|\bar{c}_+^{v'}\Gamma(\mathcal{J}_1 b_+^v - b_+^v \circ \bar{b}_+^v D^2 b_+^v)|H_b^v\rangle \\ + \frac{1}{4m_c^2}\langle H_c^{v'}|\left(-\bar{c}_+^{v'} D^2 c_+^{v'} \circ \bar{c}_+^{v'} \bar{\mathcal{J}}_1' \Pi_-' + \frac{1}{2}\bar{c}_+^{v'} D^2 c_+^{v'} \circ \bar{c}_+^{v'} D^2 c_+^{v'} \circ \bar{c}_+^{v'}\right)\Gamma b_+^v|H_b^v\rangle. \tag{161}$$

The second-order terms can be parametrized in the following way:

$$\langle \Lambda_c^*(k,\eta,s_c)| - \bar{c}_+^{v'} D^2 c_+^{v'} \circ \bar{c}_+^{v'} \bar{\mathcal{J}}_1' \Pi_-' \Gamma b_+^v|\Lambda_b(p,s_b)\rangle = \sqrt{4}\bar{u}_\mu \gamma_\alpha \Pi_-' \Gamma u \beta^{\mu\alpha}(v,v'), \tag{162}$$

$$\langle \Lambda_c^*(k,\eta,s_c)|\bar{c}_+^{v'} D^2 c_+^{v'} \circ \bar{c}_+^{v'} D^2 c_+^{v'} \circ \bar{c}_+^{v'} \Gamma b_+^v|\Lambda_b(p,s_b)\rangle = \sqrt{4}\bar{u}_\mu \Gamma u \alpha^\mu(v,v'), \tag{163}$$

where

$$\beta^{\mu\alpha}(v,v') = v^\mu(\beta_1(w)v^\alpha + \beta_2(w)v'^\alpha) + \beta_3(w)g^{\mu\alpha}, \quad (164)$$

$$\alpha^\mu(v,v') = \alpha(w)(v-v')^\mu. \quad (165)$$

The equations of motion imply that $v'_\alpha\beta^{\mu\alpha} = 0$ leading to the following relations between the IW functions entering in the definition of $\beta^{\mu\alpha}$:

$$\beta_1(w)w + \beta_2(w) = 0. \quad (166)$$

Moreover, things can be further simplified in Eq. (162) using that $\gamma_\alpha\Pi'_- = \Pi'_+\gamma_\alpha - v'_\alpha$ leading to

$$\langle\Lambda_c^*(k,\eta,s_c)| - \bar{c}_+^{v'}D^2c_+^{v'}\circ\bar{c}_+^{v'}\bar{\mathcal{J}}'_1\Pi'_-\Gamma b_+^v|\Lambda_b(p,s_b)\rangle$$
$$= \sqrt{4}\bar{u}_\mu\gamma_\alpha\Gamma u\beta^{\mu\alpha}(v,v') - \sqrt{4}\bar{u}_\mu\Gamma u v^\mu(\beta_1(w)w+\beta_2(w)). \quad (167)$$

We observe that $\sqrt{4}\bar{u}_\mu\gamma_\alpha\Gamma u\beta^{\mu\alpha}(v,v')$ assumes the same shape as the first-order pure current correction, while $\sqrt{4}\bar{u}_\mu\Gamma u v^\mu(\beta_1(w)w+\beta_2(w))$ vanishes due to Eq. (166).

The matrix element in Eq. (163) has the same parametrization of the LO order contribution to the matrix elements in HQE. Therefore, it shifts the form factors by a term proportional to the LO contribution that can be reabsorbed into the definition of the Isgur-Wise function $\eta_{\rm kin}^{(c)}$:

$$\eta_{\rm kin}^{(c)}(w) + \frac{1}{2m_c}\alpha(w) \to \eta_{\rm kin}^{(c)}(w). \quad (168)$$

D. Form factors in the VC limit: Including $\mathcal{O}(1/m_c^2)$ contributions

For the vector current contribution to $\Lambda_c(2595)^+$ the shifts produced by the insertion of the first-order pure current correction $\bar{\mathcal{J}}'_1$ read

$$f_{1/2,0}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = \varepsilon_c^2\frac{\sqrt{s_+}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(3\beta_3 - \frac{s_-s_+\beta_1}{4(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right), \quad (169)$$

$$f_{1/2,t}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = \varepsilon_c^2\frac{\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(3\beta_3 - \frac{s_-s_+\beta_1}{4(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right), \quad (170)$$

$$f_{1/2,\perp}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = \varepsilon_c^2\frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(3\beta_3 - \frac{s_-s_+\beta_1}{4(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right), \quad (171)$$

while for the axial-vector form factors we obtain

$$g_{1/2,0}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = \varepsilon_c^2\frac{\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(3\beta_3 - \frac{s_-s_+\beta_1}{4(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right), \quad (172)$$

$$g_{1/2,t}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = \varepsilon_c^2\frac{\sqrt{s_+}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(3\beta_3 - \frac{s_-s_+\beta_1}{4(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right), \quad (173)$$

$$g_{1/2,\perp}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = \varepsilon_c^2\frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(3\beta_3 - \frac{s_-s_+\beta_1}{4(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right). \quad (174)$$

Concerning the vector current contribution to $\Lambda_c(2625)^+$ the shifts produced by the insertion of the second-order pure current correction yield

$$F_{1/2,0}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = -\frac{(m_{\Lambda_b}-m_{\Lambda_c^*})s_+^{3/2}s_-}{4(m_{\Lambda_b}+m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\varepsilon_c^2\beta_1, \quad (175)$$

$$F_{1/2,t}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = -\frac{(m_{\Lambda_b}+m_{\Lambda_c^*})s_+s_-^{3/2}}{4(m_{\Lambda_b}-m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\varepsilon_c^2\beta_1, \quad (176)$$

$$F_{1/2,\perp}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = -\frac{s_+^{3/2}s_-}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\varepsilon_c^2\beta_1, \quad (177)$$

$$F_{3/2,\perp}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = 0, \quad (178)$$

while for the axial-vector form factors we obtain

$$G_{1/2,0}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = -\frac{(m_{\Lambda_b}+m_{\Lambda_c^*})s_+s_-^{3/2}}{4(m_{\Lambda_b}-m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\varepsilon_c^2\beta_1, \quad (179)$$

$$G_{1/2,t}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = -\frac{(m_{\Lambda_b}-m_{\Lambda_c^*})s_+^{3/2}s_-}{4(m_{\Lambda_b}+m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\varepsilon_c^2\beta_1, \quad (180)$$

$$G_{1/2,\perp}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = -\frac{s_+s_-^{3/2}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\varepsilon_c^2\beta_1, \quad (181)$$

$$G_{3/2,\perp}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = 0. \quad (182)$$

For the transition to $\Lambda_c(2595)^+$ mediated by the tensor current we have

$$t_{1/2,0}^{\mathcal{J}'_2} = \varepsilon_c^2\frac{m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(6\beta_3 - \frac{s_-s_+\beta_1}{2(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right), \quad (183)$$

$$t_{1/2,\perp}^{\mathcal{J}'_2} = \varepsilon_c^2\frac{m_{\Lambda_c^*}\sqrt{s_+}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(6\beta_3 - \frac{s_-s_+\beta_1}{2(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right), \quad (184)$$

while with the pseudotensor current we obtain

$$t_{1/2,0}^{5\mathcal{J}_2'} = \varepsilon_c^2 \frac{m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(6\beta_3 - \frac{s_- s_+ \beta_1}{2(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right), \tag{185}$$

$$t_{1/2,\perp}^{5\mathcal{J}_2'} = \varepsilon_c^2 \frac{m_{\Lambda_c^*}\sqrt{s_+}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}\left(6\beta_3 - \frac{s_- s_+ \beta_1}{2(m_{\Lambda_b} m_{\Lambda_c^*})^2}\right). \tag{186}$$

Concerning the $\Lambda_c(2625)^+$ final state, we obtain the following shifts for the tensor form factors:

$$T_{1/2,0}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = -\frac{m_{\Lambda_c^*} s_+^{3/2} s_-}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}}\varepsilon_c^2\beta_1, \tag{187}$$

$$T_{1/2,\perp}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = -\frac{m_{\Lambda_c^*}(m_{\Lambda_b}-m_{\Lambda_c^*}) s_+^{3/2} s_-}{2(m_{\Lambda_b}+m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}}\varepsilon_c^2\beta_1, \tag{188}$$

$$T_{3/2,\perp}^{\mathcal{L}'_1\circ\mathcal{J}'_1} = 0, \tag{189}$$

while for the pseudotensor form factors the shifts read as

$$T_{1/2,0}^{5\mathcal{L}'_1\circ\mathcal{J}'_1} = -\frac{m_{\Lambda_c^*} s_+ s_-^{3/2}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}}\varepsilon_c^2\beta_1, \tag{190}$$

$$T_{1/2,\perp}^{5\mathcal{L}'_1\circ\mathcal{J}'_1} = -\frac{m_{\Lambda_c^*}(m_{\Lambda_b}+m_{\Lambda_c^*}) s_+ s_-^{3/2}}{2(m_{\Lambda_b}-m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}}\varepsilon_c^2\beta_1, \tag{191}$$

$$T_{3/2,\perp}^{5\mathcal{L}'_1\circ\mathcal{J}'_1} = 0. \tag{192}$$

Remarkably, we observe that the form factors within the VC limit can be derived from their counterparts in the RC expansion, by making the following substitutions:

$$\psi_3 + w\psi_2 \to \beta_3, \qquad \psi_1 \to \beta_1. \tag{193}$$

V. FIT TO THE LQCD DATA

The form factors computed in the RC and VC limits depend on seven and five unknown IW functions, respectively. Although many models have been proposed in literature [49–58], it is not possible to determine the q^2-dependence of the IW functions from first principles in HQET [27,59].

Owing to the limited availability of measurements for the observables associated with the $\Lambda_b \to \Lambda_c^*$ transitions, the fitting of the IW parameters to experimental data remains unattainable. In fact, the measurements available to us pertain to the decay rate, which can be found in Ref. [60]. Fortunately, we can use the LQCD results to estimate these unknown terms following, e.g., Refs. [34,61,62].

For the transitions $\Lambda_b \to \Lambda_c^*(2595)$ and $\Lambda_b \to \Lambda_c^*(2625)$ we employ the recent data of [39], in which one finds updates of the early analysis presented in [38], obtained by imposing the relations among the form factors at zero recoil [44,45]. The lattice results provide a continuum extrapolation of the QCD form factors f_i in the low-recoil region assuming a linear dependence on the recoil parameter w:

$$f_i = F_i + A_i(w-1), \tag{194}$$

for vector, axial-vector, tensor, and pseudotensor currents. The best fit values of F_i and A_i and their covariance matrix are given in the ancillary files of [39]. Specifically, the LQCD results are valid only in the near zero-recoil regime ($w \lesssim 1.05$) and cannot be used to extrapolate the low q^2-dependence of the form factors. We stress that the relations between the form factors adopted in the LQCD computations and the ones used in this work are given in Appendix D.

We expand the IW functions to the first order in $(w-1)$ as follows:

$$\zeta \simeq \zeta^{(0)} + (w-1)\zeta^{(1)}. \tag{195}$$

We use the same parametrization for the subleading and the subsubleading IW functions. Then we further expand the QCD form factors computed in the previous sections and collected in Appendixes B 2 and B 3 to the first order in $(w-1)$, to be compared with the LQCD results. We follow the fitting procedure of [34] with the same input parameters summarized in Table I.

As noticed in [34], neglecting the order $1/m_c^2$ in the HQE, we achieve a poor fit to the data with a $\chi^2/\mathrm{d.o.f.} \sim 23$. This suggests that higher-order corrections are needed to accommodate the LQCD results.

We therefore start with examining the RC limit and notice that since the IW functions ψ_2 and ψ_3 always appear in the combination $\psi' = \psi_3 + w\psi_2$, we fit directly ψ'. After linearly expanding the IW functions as in Eq. (195) we further discover that the form factors are independent of

TABLE I. Values of the HQET input parameters from [34].

HQET parameters	
$\alpha_s(\sqrt{m_b m_c})$	0.26
m_b	4.78 GeV
m_c	1.38 GeV
ε_b	0.105 GeV^{-1}
ε_c	0.36 GeV^{-1}
m_{Λ_b}	5.61960 GeV
$m_{\Lambda_c(2595)^+}$	2.59225 GeV
$m_{\Lambda_c(2625)^+}$	2.62811 GeV
$\bar{\Lambda}$	0.81 GeV
$\bar{\Lambda}'$	1.10 GeV

TABLE II. Best fit points and uncertainties for the IW parameters in the RC limit.

Parameter	Best fit
$\zeta^{(0)}$	0.52 ± 0.16
$\zeta^{(1)}$	-6.11 ± 1.27
$\zeta^{(0)}_{\rm SL}$	0.15 ± 0.01
$\zeta^{(1)}_{\rm SL}$	-0.38 ± 0.11
$\eta^{(0)}_{{\rm kin},c}$	-0.26 ± 0.44
$\eta^{(1)}_{{\rm kin},c}$	9.77 ± 3.08
$\eta^{(0)}_{{\rm mag},c}$	0.01 ± 0.10
$\eta^{(1)}_{{\rm mag},c}$	-0.15 ± 1.44
$\eta^{(0)}_{{\rm mag},b}$	-0.08 ± 0.06
$\eta^{(1)}_{{\rm mag},b}$	0.25 ± 0.70
$\psi^{(0)}_1$	1.58 ± 0.72
$\psi'^{(0)}$	0.82 ± 0.05
$\psi'^{(1)}$	-1.13 ± 0.52

$\psi^{(1)}_1$ leaving us with 13 unknown IW parameters to fit to the lattice data. The χ^2 minimization yields an excellent fit with $\chi^2/\mathrm{d.o.f.} \sim 0.89$. The best fit and its uncertainties are summarized in Table II, and the correlation matrix is reported in Table V in Appendix E.

It is time to consider the independent VC limit and notice that for the linearized IW functions the form factors are $\beta^{(1)}_1$ independent. Therefore, we are left with nine unknown IW parameters. Also in this case we find an excellent fit with $\chi^2/\mathrm{d.o.f.} \sim 0.84$ as summarized in Table III. The correlation matrix is reported in Table VII in Appendix E.

As a positive consistency check one observes that for the distinct RC and VC limits reported in Tables II and III the common IW form factors are compatible.

In an effort to be as complete as possible we follow the literature [61,62] and further investigate the possibility to use lattice data for the (axial) vector currents as input to predict the (pseudo)tensor contributions for both the RC and the VC limits. Subsequently, we compare these results again with the lattice one. In this case, the χ^2 minimization yields $\chi^2/\mathrm{d.o.f.} \sim 0.84$ for the RC limit and $\chi^2/\mathrm{d.o.f.} \sim 0.72$ for the VC limit. The results of our fit are shown in Table IV, and the corresponding correlation matrices are shown in Tables VI and VIII in Appendix E. In Fig. 1 we show the comparison between the LQCD results of [39] (orange band) with the predictions for tensor and pseudotensor form factors derived from fitting only the (axial) vector ones (Table IV). The RC and VC limits are illustrated as the blue and green bands, respectively. Our predictions for the form factors are compatible with the lattice results at the 1-σ level. The exception arises from the pseudotensor form factor $\tilde{h}^{(\frac{3}{2}^-)}_{\perp'}$ in the VC limit [see Fig. 1(h)]. The larger than one sigma deviation occurs because in the VC limit the $1/m_c^2$ corrections are not entirely captured.

Furthermore, we observe large uncertainties of the chromomagnetic IW functions in the RC limit, which are, in fact, compatible with zero. This arises because

TABLE III. Best fit points and uncertainties for the IW parameters in the VC limit.

Parameter	Best fit
$\zeta^{(0)}$	0.52 ± 0.16
$\zeta^{(1)}$	-5.97 ± 1.24
$\zeta^{(0)}_{\rm SL}$	0.15 ± 0.01
$\zeta^{(1)}_{\rm SL}$	-0.31 ± 0.10
$\eta^{(0)}_{{\rm kin},c}$	-0.24 ± 0.42
$\eta^{(1)}_{{\rm kin},c}$	9.48 ± 3.06
$\beta^{(0)}_1$	1.58 ± 0.71
$\beta^{(0)}_3$	0.81 ± 0.05
$\beta^{(1)}_3$	-0.96 ± 0.50

TABLE IV. Best fit points and uncertainties for the IW parameters in (a) the RC and (b) the VC limits.

Parameter	Best fit
$\zeta^{(0)}$	0.43 ± 0.50
$\zeta^{(1)}$	-6.59 ± 1.62
$\zeta^{(0)}_{\rm SL}$	0.16 ± 0.01
$\zeta^{(1)}_{\rm SL}$	-0.58 ± 0.17
$\eta^{(0)}_{{\rm kin},c}$	0.01 ± 1.30
$\eta^{(1)}_{{\rm kin},c}$	10.72 ± 4.01
$\eta^{(0)}_{{\rm mag},c}$	-0.04 ± 0.12
$\eta^{(1)}_{{\rm mag},c}$	-0.07 ± 1.61
$\eta^{(0)}_{{\rm mag},b}$	-0.01 ± 0.07
$\eta^{(1)}_{{\rm mag},b}$	-0.75 ± 0.93
$\psi^{(0)}_1$	1.48 ± 1.01
$\psi'^{(0)}$	0.83 ± 0.10
$\psi'^{(1)}$	-1.76 ± 0.68

Parameter	Best fit
$\zeta^{(0)}$	0.52 ± 0.43
$\zeta^{(1)}$	-6.49 ± 1.55
$\zeta^{(0)}_{\rm SL}$	0.16 ± 0.01
$\zeta^{(1)}_{\rm SL}$	-0.57 ± 0.17
$\eta^{(0)}_{{\rm kin},c}$	-0.21 ± 1.10
$\eta^{(1)}_{{\rm kin},c}$	10.56 ± 3.94
$\beta^{(0)}_1$	1.42 ± 0.96
$\beta^{(0)}_3$	0.84 ± 0.09
$\beta^{(1)}_3$	-1.69 ± 0.64

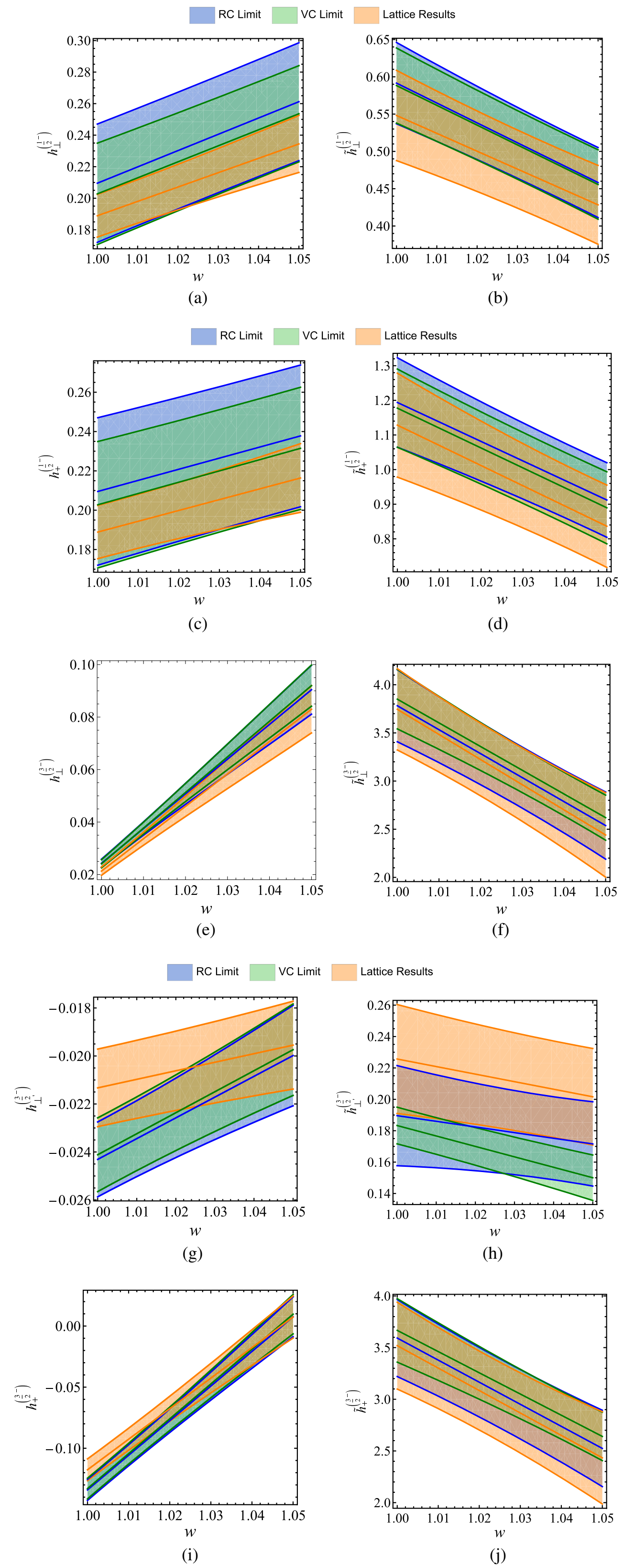

FIG. 1. Each subpanel, from (a) to (j), displays the LQCD results of [39] (depicted as the orange band) alongside the 1-σ level predictions for tensor and pseudotensor form factors coming from the independent RC (blue band) and VC (green band) limits in Table IV.

the available LQCD data are confined to the low-recoil region, while the chromomagnetic corrections are expected to be significant in the large-recoil region. As a result, it becomes meaningful to consider a scenario where we set the chromomagnetic IW functions to zero. It can be seen from Eq. (193) that this scenario corresponds exactly to the VC limit. Importantly, even in this case we obtain an excellent agreement with the lattice data.

For completeness, we have performed the same analysis above also using the baryon masses rather than the quark masses in the HQE. Here we observed that the overall qualitative picture remains unchanged with the second-order coefficients getting substantially larger and $\eta^{(1)}_{\mathrm{kin},c}$ getting roughly 2 times larger.

Our results clearly show that, in both the RC and the VC limits, $\mathcal{O}(1/m_c^2)$ corrections are essential to match the lattice data, corroborating and quantifying the expectations of [34].

VI. CONCLUSIONS

We presented the set of form factors for the $\Lambda_b \to \Lambda_c^*$ transitions, accounting for the next-to-next-to-leading $\mathcal{O}(1/m_c^2)$ corrections in the RC and VC limits. We determined the IW independent parameters via a fit to the lattice data from [39]. The latter compensate for the lack of experimental data for the $\Lambda_b \to \Lambda_c^* \ell \nu$ decay process. For the fits, we first enacted a χ^2 minimization procedure using the entire lattice dataset and then repeated the process using only the vector and axial form factors to generate predictions for the tensor and pseudotensor form factors. We discovered a notable agreement with the LQCD data, effectively resolving the previous tension underlined in [34].

Our results demonstrate that it is essential, to agree with the lattice data, to consider next-to-next-to-leading order power corrections $\mathcal{O}(1/m_c^2)$ for these processes. Furthermore, barring potential lattice issues, these corrections are large and indicate a slow convergence of the series. An independent test of both the effective approach and the lattice results will come from either more refined lattice simulations and/or future experiments. We further stress that our findings are applicable only close to the zero-recoil region. Future experimental measurements and theoretical efforts are needed to access the large-recoil regime which will allow us to fully describe the physics of the $\Lambda_b \to \Lambda_c^*$ decay processes.

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APPENDIX A: RARITA-SCHWINGER SPINOR

In the chiral representation, a spinor u with momentum

$$p^\mu = (p^0, |\vec{p}|\sin\theta\cos\phi, |\vec{p}|\sin\theta\sin\phi, |\vec{p}|\cos\theta), \qquad p^2 = m^2, \tag{A1}$$

and helicity $h = \pm 1/2$ in the rest frame, can be written as [33,63]

$$u(p, h = +1/2) = \frac{1}{\sqrt{2(p^0+m)}} \begin{bmatrix} +(p^0+m-|\vec{p}|) & \cos(\theta/2) & \\ +(p^0+m+|\vec{p}|) & \sin(\theta/2) & \exp(+i\phi) \\ +(p^0+m+|\vec{p}|) & \cos(\theta/2) & \\ +(p^0+m-|\vec{p}|) & \sin(\theta/2) & \exp(+i\phi) \end{bmatrix}, \tag{A2}$$

$$u(p, h = -1/2) = \frac{1}{\sqrt{2(p^0+m)}} \begin{bmatrix} -(p^0+m-|\vec{p}|) & \sin(\theta/2) & \exp(-i\phi) \\ +(p^0+m+|\vec{p}|) & \cos(\theta/2) & \\ -(p^0+m+|\vec{p}|) & \sin(\theta/2) & \exp(-i\phi) \\ +(p^0+m-|\vec{p}|) & \cos(\theta/2) & \end{bmatrix}. \tag{A3}$$

We characterize a state with quantum numbers $J^P = 3/2^-$ using the spin-3/2 component $u^\alpha_{(3/2)}$ stemming from the projection of a general Rarita-Schwinger object $u^\alpha_{\mathrm{RS}}(k,\eta) = \eta^\alpha u(k)$,

$$\begin{aligned} u^\alpha_{(3/2)}(k,\eta,s_c) &= \left[\eta^\alpha - \frac{1}{3}\left(\gamma^\alpha + \frac{k^\alpha}{m_{\Lambda_c^*}}\right)\not\eta\right] u(k,s_c) \\ &= \left[g^\alpha{}_\beta - \frac{1}{3}\left(\gamma^\alpha + \frac{k^\alpha}{m_{\Lambda_c^*}}\right)\gamma_\beta\right] u^\beta_{\mathrm{RS}}(k,\eta(\lambda),s_c) \\ &\equiv [P_{3/2}]^\alpha{}_\beta u^\beta_{\mathrm{RS}}(k,\eta(\lambda),s_c). \end{aligned} \tag{A4}$$

Here, $u(k,s_c)$ denotes the spin-$1/2^+$ spinor of four momentum k and rest-frame helicity $s_c = \pm 1/2$, as explicitly presented above. The vector η is a polarization vector with $J^P = 1^-$. Similarly, we can describe the state with spin-parity $J^P = 1/2^-$, by means of the projection onto the spin-1/2 component, as follows:

$$u^\alpha_{(1/2)}(k,\eta,s_c) = \frac{1}{3}\left[\gamma^\alpha + \frac{k^\alpha}{m_{\Lambda_c^*}}\right]\not\eta u(k,s_c) \tag{A5}$$

$$= \frac{1}{3}\left[\gamma^\alpha + \frac{k^\alpha}{m_{\Lambda_c^*}}\right]\gamma_\beta u^\beta_{\mathrm{RS}}(k,\eta(\lambda),s_c) \tag{A6}$$

$$\equiv [P_{1/2}]^\alpha{}_\beta u^\beta_{\mathrm{RS}}(k,\eta(\lambda),s_c). \tag{A7}$$

The Rarita-Schwinger fields satisfy the following useful identities:

$$k_\alpha u^\alpha_{(3/2)}(k,\eta,s_c) = 0 = k_\alpha u^\alpha_{(1/2)}(k,\eta,s_c), \tag{A8}$$

$$\gamma_\alpha u^\alpha_{(3/2)}(k,\eta,s_c) = 0, \tag{A9}$$

$$-i\sigma_{\alpha\beta} u^\alpha_{(3/2)}(k,\eta,s_c) = u^\beta_{(3/2)}(k,\eta,s_c). \tag{A10}$$

APPENDIX B: FORM FACTOR BASIS

Here, we present the spin structures $\Gamma^{\alpha\mu}_{J,i}$ that contribute to the transition $\Lambda_b \to \Lambda_c^*$. For the vector and axial currents we follow the notation given in [33], while for the tensor and pseudotensor currents we use the parametrization of Ref. [61]. For the vector current ($J = V$) mediating the transition to $\Lambda_c(2595)^+$ we find

$$\begin{aligned} \Gamma^{\alpha\mu}_{V,(1/2,t)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}} \frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}} p^\alpha \frac{m_{\Lambda_b} - m_{\Lambda_c^*}}{\sqrt{q^2}} \frac{q^\mu}{\sqrt{q^2}}, \\ \Gamma^{\alpha\mu}_{V,(1/2,0)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}} \frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}} p^\alpha \frac{m_{\Lambda_b} + m_{\Lambda_c^*}}{s_+}\left[(p+k)^\mu - \frac{m^2_{\Lambda_b} - m^2_{\Lambda_c^*}}{q^2} q^\mu\right], \\ \Gamma^{\alpha\mu}_{V,(1/2,\perp)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}} \frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}} p^\alpha \left[\gamma^\mu - \frac{2m_{\Lambda_c^*}}{s_+} p^\mu - \frac{2m_{\Lambda_b}}{s_+} k^\mu\right]; \end{aligned} \tag{B1}$$

for the axial current ($J = A$) we have

$$\begin{aligned}
\Gamma^{\alpha\mu}_{A,(1/2,t)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}}\frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}}p^\alpha\frac{m_{\Lambda_b}+m_{\Lambda_c^*}}{\sqrt{q^2}}\frac{q^\mu}{\sqrt{q^2}},\\
\Gamma^{\alpha\mu}_{A,(1/2,0)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}}p^\alpha\frac{m_{\Lambda_b}-m_{\Lambda_c^*}}{s_-}\left[(p+k)^\mu-\frac{m^2_{\Lambda_b}-m^2_{\Lambda_c^*}}{q^2}q^\mu\right],\\
\Gamma^{\alpha\mu}_{A,(1/2,\perp)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}}p^\alpha\left[\gamma^\mu+\frac{2m_{\Lambda_c^*}}{s_-}p^\mu-\frac{2m_{\Lambda_b}}{s_-}k^\mu\right].
\end{aligned} \tag{B2}$$

For the tensor current ($J = T$) we find

$$\Gamma^{\alpha\mu}_{T,(1/2,0)} = \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\frac{q^2}{s_+s_-}p^\alpha\left[(p+k)^\mu-\frac{m^2_{\Lambda_b}-m^2_{\Lambda_c^*}}{q^2}q^\mu\right], \tag{B3}$$

$$\Gamma^{\alpha\mu}_{T,(1/2,\perp)} = \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\frac{m_{\Lambda_b}+m_{\Lambda_c^*}}{s_-}p^\alpha\left[\gamma^\mu-2\frac{m_{\Lambda_c^*}}{s_+}p^\mu-2\frac{m_{\Lambda_b}}{s_+}k^\mu\right], \tag{B4}$$

while for the pseudotensor current ($J = T5$) we obtain

$$\Gamma^{\alpha\mu}_{T5,(1/2,0)} = \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}}\frac{q^2}{s_+s_-}p^\alpha\left[(p+k)^\mu-\frac{m^2_{\Lambda_b}-m^2_{\Lambda_c^*}}{q^2}q^\mu\right], \tag{B5}$$

$$\Gamma^{\alpha\mu}_{T5,(1/2,\perp)} = \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}}\frac{m_{\Lambda_b}-m_{\Lambda_c^*}}{s_+}p^\alpha\left[\gamma^\mu+2\frac{m_{\Lambda_c^*}}{s_-}p^\mu-2\frac{m_{\Lambda_b}}{s_-}k^\mu\right]. \tag{B6}$$

When we consider the final state $\Lambda_c(2625)^+$, for the vector current ($J = V$) we get

$$\begin{aligned}
\Gamma^{\alpha\mu}_{V,(1/2,t)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}}p^\alpha\frac{m_{\Lambda_b}-m_{\Lambda_c^*}}{\sqrt{q^2}}\frac{q^\mu}{\sqrt{q^2}},\\
\Gamma^{\alpha\mu}_{V,(1/2,0)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}}\frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}}p^\alpha\frac{m_{\Lambda_b}+m_{\Lambda_c^*}}{s_+}\left[(p+k)^\mu-\frac{m^2_{\Lambda_b}-m^2_{\Lambda_c^*}}{q^2}q^\mu\right],\\
\Gamma^{\alpha\mu}_{V,(1/2,\perp)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}}\frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}}p^\alpha\left[\gamma^\mu-\frac{2m_{\Lambda_c^*}}{s_+}p^\mu-\frac{2m_{\Lambda_b}}{s_+}k^\mu\right],\\
\Gamma^{\alpha\mu}_{V,(3/2,\perp)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}}\frac{-4i\varepsilon^{\alpha\mu pk}}{\sqrt{s_+s_-}}\gamma_5+\Gamma_{V,(1/2,\perp)},
\end{aligned} \tag{B7}$$

while for the axial current ($J = A$) we use

$$\begin{aligned}
\Gamma^{\alpha\mu}_{A,(1/2,t)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}}\frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}}p^\alpha\frac{m_{\Lambda_b}+m_{\Lambda_c^*}}{\sqrt{q^2}}\frac{q^\mu}{\sqrt{q^2}},\\
\Gamma^{\alpha\mu}_{A,(1/2,0)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}}p^\alpha\frac{m_{\Lambda_b}-m_{\Lambda_c^*}}{s_-}\left[(p+k)^\mu-\frac{m^2_{\Lambda_b}-m^2_{\Lambda_c^*}}{q^2}q^\mu\right],\\
\Gamma^{\alpha\mu}_{A,(1/2,\perp)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\frac{2m_{\Lambda_c^*}}{\sqrt{s_+s_-}}p^\alpha\left[\gamma^\mu+\frac{2m_{\Lambda_c^*}}{s_-}p^\mu-\frac{2m_{\Lambda_b}}{s_-}k^\mu\right],\\
\Gamma^{\alpha\mu}_{A,(3/2,\perp)} &= \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\frac{-4i\varepsilon^{\alpha\mu pk}}{\sqrt{s_+s_-}}\gamma_5-\Gamma_{A,(1/2,\perp)}.
\end{aligned} \tag{B8}$$

For the tensor current ($J = T$) we find

$$\Gamma^{\alpha\mu}_{T,(1/2,0)} = \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\frac{q^2}{s_+s_-}p^\alpha\left[(p+k)^\mu - \frac{m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2}{q^2}q^\mu\right], \tag{B9}$$

$$\Gamma^{\alpha\mu}_{T,(1/2,\perp)} = \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\frac{m_{\Lambda_b}+m_{\Lambda_c^*}}{s_-}p^\alpha\left[\gamma^\mu - 2\frac{m_{\Lambda_c^*}}{s_+}p^\mu - 2\frac{m_{\Lambda_b}}{s_+}k^\mu\right], \tag{B10}$$

$$\Gamma^{\alpha\mu}_{T,(3/2,\perp)} = \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_+}}\left[g^{\alpha\mu} + \frac{m_{\Lambda_c^*}}{s_-}p^\alpha\left(\gamma^\mu - 2\frac{1}{m_{\Lambda_c^*}}k^\mu + 2\frac{m_{\Lambda_c^*}}{s_+}p^\mu + 2\frac{m_{\Lambda_b}}{s_+}k^\mu\right)\right], \tag{B11}$$

and for the pseudotensor current ($J = T5$) we obtain

$$\Gamma^{\alpha\mu}_{T5,(1/2,0)} = \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}}\frac{q^2}{s_+s_-}p^\alpha\left[(p+k)^\mu - \frac{m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2}{q^2}q^\mu\right], \tag{B12}$$

$$\Gamma^{\alpha\mu}_{T5,(1/2,\perp)} = \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}}\frac{m_{\Lambda_b}-m_{\Lambda_c^*}}{s_+}p^\alpha\left[\gamma^\mu + 2\frac{m_{\Lambda_c^*}}{s_-}p^\mu - 2\frac{m_{\Lambda_b}}{s_-}k^\mu\right], \tag{B13}$$

$$\Gamma^{\alpha\mu}_{T5,(3/2,\perp)} = \frac{\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}}{\sqrt{s_-}}\left[g^{\alpha\mu} - \frac{m_{\Lambda_c^*}}{s_+}p^\alpha\left(\gamma^\mu + 2\frac{1}{m_{\Lambda_c^*}}k^\mu - 2\frac{m_{\Lambda_c^*}}{s_-}p^\mu + 2\frac{m_{\Lambda_b}}{s_-}k^\mu\right)\right]. \tag{B14}$$

In the equations presented above, we have used the convention $\epsilon^{0123} = -\epsilon_{0123} = +1$ for the Levi-Civita tensor.

1. Helicity amplitudes

By applying the principles of angular momentum composition, the allowed on-shell amplitudes for the final state with a total angular momentum $J = 1/2$ are [33]

$$\begin{aligned}
\mathcal{A}_\Gamma^{(1/2)}(+1/2,+1/2,0) &\equiv -\sqrt{\frac{1}{3}}\mathcal{A}_\Gamma(+1/2,+1/2,0,0) + \sqrt{\frac{2}{3}}\mathcal{A}_\Gamma(+1/2,-1/2,+1,0),\\
\mathcal{A}_\Gamma^{(1/2)}(+1/2,+1/2,t) &\equiv -\sqrt{\frac{1}{3}}\mathcal{A}_\Gamma(+1/2,+1/2,0,t) + \sqrt{\frac{2}{3}}\mathcal{A}_\Gamma(+1/2,-1/2,+1,t),\\
\mathcal{A}_\Gamma^{(1/2)}(+1/2,-1/2,-1) &\equiv \sqrt{\frac{1}{3}}\mathcal{A}_\Gamma(+1/2,-1/2,0,-1) - \sqrt{\frac{2}{3}}\mathcal{A}_\Gamma(+1/2,+1/2,-1,-1).
\end{aligned} \tag{B15}$$

On the other hand, the complementary set of $J = 3/2$ amplitudes reads as

$$\begin{aligned}
\mathcal{A}_\Gamma^{(3/2)}(+1/2,+3/2,+1) &\equiv \mathcal{A}_\Gamma(+1/2,+1/2,+1,+1),\\
\mathcal{A}_\Gamma^{(3/2)}(+1/2,+1/2,0) &\equiv \sqrt{\frac{2}{3}}\mathcal{A}_\Gamma(+1/2,+1/2,0,0) + \sqrt{\frac{1}{3}}\mathcal{A}_\Gamma(+1/2,-1/2,+1,0),\\
\mathcal{A}_\Gamma^{(3/2)}(+1/2,+1/2,t) &\equiv \sqrt{\frac{2}{3}}\mathcal{A}_\Gamma(+1/2,+1/2,0,t) + \sqrt{\frac{1}{3}}\mathcal{A}_\Gamma(+1/2,-1/2,+1,t),\\
\mathcal{A}_\Gamma^{(3/2)}(+1/2,-1/2,-1) &\equiv \sqrt{\frac{2}{3}}\mathcal{A}_\Gamma(+1/2,-1/2,0,-1) + \sqrt{\frac{1}{3}}\mathcal{A}_\Gamma(+1/2,+1/2,-1,-1).
\end{aligned} \tag{B16}$$

For the transitions to $J = 1/2$ the set of amplitudes in Eq. (B16) vanishes identically. Similarly for transitions to $J = 3/2$ the equations in Eq. (B15) are zero.

We list the on-shell amplitudes for the transition $\Lambda_b \to \Lambda_c(2595)^+$. For the vector current we find the following nonzero amplitudes:

$$\mathcal{A}_V^{(1/2)}(+1/2,+1/2,0) = \mathcal{A}_V^{(1/2)}(-1/2,-1/2,0) = -\sqrt{\frac{1}{3}} f_{1/2,0} \frac{m_{\Lambda_b} + m_{\Lambda_c^*}}{\sqrt{q^2}} \sqrt{4 m_{\Lambda_b} m_{\Lambda_c^*}}, \tag{B17}$$

$$\mathcal{A}_V^{(1/2)}(+1/2,+1/2,t) = \mathcal{A}_V^{(1/2)}(-1/2,-1/2,t) = -\sqrt{\frac{1}{3}} f_{1/2,t} \frac{m_{\Lambda_b} - m_{\Lambda_c^*}}{\sqrt{q^2}} \sqrt{4 m_{\Lambda_b} m_{\Lambda_c^*}}, \tag{B18}$$

$$\mathcal{A}_V^{(1/2)}(+1/2,-1/2,-1) = \mathcal{A}_V^{(1/2)}(-1/2,+1/2,+1) = -\sqrt{\frac{2}{3}} f_{1/2,\perp} \sqrt{4 m_{\Lambda_b} m_{\Lambda_c^*}}. \tag{B19}$$

For the axial-vector current we find similarly

$$\mathcal{A}_A^{(1/2)}(+1/2,+1/2,0) = -\mathcal{A}_A^{(1/2)}(-1/2,-1/2,0) = -\sqrt{\frac{1}{3}} g_{1/2,0} \frac{m_{\Lambda_b} - m_{\Lambda_c^*}}{\sqrt{q^2}} \sqrt{4 m_{\Lambda_b} m_{\Lambda_c^*}}, \tag{B20}$$

$$\mathcal{A}_A^{(1/2)}(+1/2,+1/2,t) = -\mathcal{A}_A^{(1/2)}(-1/2,-1/2,t) = -\sqrt{\frac{1}{3}} g_{1/2,t} \frac{m_{\Lambda_b} + m_{\Lambda_c^*}}{\sqrt{q^2}} \sqrt{4 m_{\Lambda_b} m_{\Lambda_c^*}}, \tag{B21}$$

$$\mathcal{A}_A^{(1/2)}(+1/2,-1/2,-1) = -\mathcal{A}_A^{(1/2)}(-1/2,+1/2,+1) = +\sqrt{\frac{2}{3}} g_{1/2,\perp} \sqrt{4 m_{\Lambda_b} m_{\Lambda_c^*}}. \tag{B22}$$

For the tensor current we find the following nonzero amplitude:

$$\mathcal{A}_T^{(1/2)}(+1/2,+1/2,0) = \mathcal{A}_T^{(1/2)}(-1/2,-1/2,0) = -\sqrt{\frac{1}{3}} t_{1/2,0} \frac{m_{\Lambda_b} \sqrt{q^2}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}, \tag{B23}$$

$$\mathcal{A}_T^{(1/2)}(+1/2,-1/2,-1) = \mathcal{A}_T^{(1/2)}(-1/2,+1/2,+1) = +\sqrt{\frac{2}{3}} t_{1/2,\perp} \frac{m_{\Lambda_b} (m_{\Lambda_b} + m_{\Lambda_c^*})}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}. \tag{B24}$$

For the pseudotensor current we find similarly

$$\mathcal{A}_{T5}^{(1/2)}(+1/2,+1/2,0) = -\mathcal{A}_{T5}^{(1/2)}(-1/2,-1/2,0) = -\sqrt{\frac{1}{3}} t^5_{1/2,0} \frac{m_{\Lambda_b} \sqrt{q^2}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}, \tag{B25}$$

$$\mathcal{A}_{T5}^{(1/2)}(+1/2,-1/2,-1) = -\mathcal{A}_{T5}^{(1/2)}(-1/2,+1/2,+1) = +\sqrt{\frac{2}{3}} t^5_{1/2,\perp} \frac{m_{\Lambda_b} (m_{\Lambda_b} - m_{\Lambda_c^*})}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}}. \tag{B26}$$

We list the on-shell amplitudes for the transition $\Lambda_b \to \Lambda_c(2625)^+$.

For the vector current we find the following nonzero amplitudes:

$$\begin{aligned}\mathcal{A}_V^{(3/2)}(+1/2,+3/2,+1) &= \mathcal{A}_V^{(3/2)}(-1/2,-3/2,-1) \\ &= -2 F_{3/2,\perp} \sqrt{4 m_{\Lambda_b} m_{\Lambda_c^*}},\end{aligned} \tag{B27}$$

$$\mathcal{A}_V^{(3/2)}(+1/2,+1/2,0) = \mathcal{A}_V^{(3/2)}(-1/2,-1/2,0) = +\sqrt{\frac{2}{3}} F_{1/2,0} \frac{m_{\Lambda_b} + m_{\Lambda_c^*}}{\sqrt{q^2}} \sqrt{4 m_{\Lambda_b} m_{\Lambda_c^*}}, \tag{B28}$$

$$\mathcal{A}_V^{(3/2)}(+1/2,+1/2,t)=\mathcal{A}_V^{(3/2)}(-1/2,-1/2,t)=+\sqrt{\frac{2}{3}}F_{1/2,t}\frac{m_{\Lambda_b}-m_{\Lambda_c^*}}{\sqrt{q^2}}\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}, \tag{B29}$$

$$\mathcal{A}_V^{(3/2)}(+1/2,-1/2,-1)=\mathcal{A}_V^{(3/2)}(-1/2,+1/2,+1)=-\frac{2}{\sqrt{3}}F_{1/2,\perp}\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}. \tag{B30}$$

For the axial-vector current we find similarly

$$\mathcal{A}_A^{(3/2)}(+1/2,+3/2,+1)=-\mathcal{A}_A^{(3/2)}(-1/2,-3/2,-1)=-2G_{3/2,\perp}\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}, \tag{B31}$$

$$\mathcal{A}_A^{(3/2)}(+1/2,+1/2,0)=-\mathcal{A}_A^{(3/2)}(-1/2,-1/2,0)=+\sqrt{\frac{2}{3}}G_{1/2,0}\frac{m_{\Lambda_b}-m_{\Lambda_c^*}}{\sqrt{q^2}}\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}, \tag{B32}$$

$$\mathcal{A}_A^{(3/2)}(+1/2,+1/2,t)=-\mathcal{A}_A^{(3/2)}(-1/2,-1/2,t)=+\sqrt{\frac{2}{3}}G_{1/2,t}\frac{m_{\Lambda_b}+m_{\Lambda_c^*}}{\sqrt{q^2}}\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}, \tag{B33}$$

$$\mathcal{A}_A^{(3/2)}(+1/2,-1/2,-1)=-\mathcal{A}_A^{(3/2)}(-1/2,+1/2,+1)=+\frac{2}{\sqrt{3}}G_{1/2,\perp}\sqrt{4m_{\Lambda_b}m_{\Lambda_c^*}}. \tag{B34}$$

For the tensor current we find the following nonzero amplitudes:

$$\mathcal{A}_T^{(3/2)}(+1/2,+3/2,+1)=\mathcal{A}_T^{(3/2)}(-1/2,-3/2,-1)=-2T_{3/2,\perp}\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}, \tag{B35}$$

$$\mathcal{A}_T^{(3/2)}(+1/2,+1/2,0)=\mathcal{A}_T^{(3/2)}(-1/2,-1/2,0)=-\sqrt{\frac{2}{3}}T_{1/2,0}\frac{m_{\Lambda_b}\sqrt{q^2}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}, \tag{B36}$$

$$\mathcal{A}_T^{(3/2)}(+1/2,-1/2,-1)=\mathcal{A}_T^{(3/2)}(-1/2,+1/2,+1)=\frac{2}{\sqrt{3}}T_{1/2,\perp}\frac{m_{\Lambda_b}(m_{\Lambda_b}+m_{\Lambda_c^*})}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}. \tag{B37}$$

For the pseudotensor current we find similarly

$$\mathcal{A}_{T5}^{(3/2)}(+1/2,+3/2,+1)=-\mathcal{A}_{T5}^{(3/2)}(-1/2,-3/2,-1)=2T^5_{3/2,\perp}\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}, \tag{B38}$$

$$\mathcal{A}_{T5}^{(3/2)}(+1/2,+1/2,0)=-\mathcal{A}_{T5}^{(3/2)}(-1/2,-1/2,0)=\sqrt{\frac{2}{3}}T^5_{1/2,0}\frac{m_{\Lambda_b}\sqrt{q^2}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}, \tag{B39}$$

$$\mathcal{A}_{T5}^{(3/2)}(+1/2,-1/2,-1)=-\mathcal{A}_{T5}^{(3/2)}(-1/2,+1/2,+1)=\frac{2}{\sqrt{3}}T^5_{1/2,\perp}\frac{m_{\Lambda_b}(m_{\Lambda_b}-m_{\Lambda_c^*})}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}. \tag{B40}$$

We do not report the expressions of the on-shell amplitudes within the HQET framework. Nevertheless, one can readily reconstruct them by substituting the form factors provided in Appendixes B 2 and B 3 into the equations given above.

2. Form factors at $\mathcal{O}(1/m_c^2)$ in the RC limit

Here we list the full set of form factors up to $\mathcal{O}(1/m_c^2, \theta^2)$. For the final state $\Lambda_c(2595)^+$ the form factors are

$$\begin{aligned} f_{1/2,0} = {} & \frac{\zeta s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1 + \frac{C_2 s_+}{2m_{\Lambda_b}(m_{\Lambda_b} + m_{\Lambda_c^*})} + \frac{C_3 s_+}{2m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*})} \right) \\ & + \varepsilon_b \frac{\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\ & + \varepsilon_c \frac{\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\ & + \frac{s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} (\varepsilon_c \eta_{\mathrm{kin}}^{(c)} + \varepsilon_b \eta_{\mathrm{mag}}^{(b)} - \varepsilon_c \eta_{\mathrm{mag}}^{(c)}) \\ & + \varepsilon_c^2 \frac{\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right), \end{aligned} \tag{B41}$$

$$\begin{aligned} f_{1/2,t} = {} & \frac{\zeta s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1 + \frac{C_2 s_+}{2m_{\Lambda_b}(m_{\Lambda_b} - m_{\Lambda_c^*})} + \frac{C_3 s_+}{2m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})} \right) \\ & + \varepsilon_b \frac{\sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\ & + \varepsilon_c \frac{\sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\ & + \frac{s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} (\varepsilon_c \eta_{\mathrm{kin}}^{(c)} + \varepsilon_b \eta_{\mathrm{mag}}^{(b)} - \varepsilon_c \eta_{\mathrm{mag}}^{(c)}) \\ & + \varepsilon_c^2 \frac{\sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right), \end{aligned} \tag{B42}$$

$$\begin{aligned} f_{1/2,\perp} = {} & \frac{C_1 \zeta s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_b \frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\frac{\zeta \bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b} m_{\Lambda_c^*}} - \bar{\Lambda}' \zeta \right) \\ & + \varepsilon_c \frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\bar{\Lambda} \zeta - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\ & + \frac{s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} (\varepsilon_c \eta_{\mathrm{kin}}^{(c)} - \varepsilon_c \eta_{\mathrm{mag}}^{(c)}) + \varepsilon_c^2 \frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right), \end{aligned} \tag{B43}$$

$$\begin{aligned} g_{1/2,0} = {} & \frac{\zeta s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1^5 - \frac{C_2^5 s_-}{2m_{\Lambda_b}(m_{\Lambda_b} - m_{\Lambda_c^*})} - \frac{C_3^5 s_-}{2m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})} \right) \\ & + \varepsilon_b \frac{\sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' + 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\ & + \varepsilon_c \frac{\sqrt{s_-}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\ & + \frac{s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} (\varepsilon_c \eta_{\mathrm{kin}}^{(c)} - \varepsilon_b \eta_{\mathrm{mag}}^{(b)} - \varepsilon_c \eta_{\mathrm{mag}}^{(c)}) \\ & + \varepsilon_c^2 \frac{\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3(\psi_3 + w\psi_2) - \frac{s_- s_+ \psi_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right), \end{aligned} \tag{B44}$$

$$
\begin{aligned}
g_{1/2,t} = {} & \frac{\zeta s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1^5 + \frac{C_2^5 s_+}{2m_{\Lambda_b}(m_{\Lambda_b}+m_{\Lambda_c^*})} + \frac{C_3^5 s_+}{2m_{\Lambda_c^*}(m_{\Lambda_b}+m_{\Lambda_c^*})}\right) \\
& + \varepsilon_b \frac{\sqrt{s_+}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}' + 2\zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \varepsilon_c \frac{\sqrt{s_+}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda} - 2\zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \frac{s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(\varepsilon_c\eta_{\mathrm{kin}}^{(c)} - \varepsilon_b\eta_{\mathrm{mag}}^{(b)} - \varepsilon_c\eta_{\mathrm{mag}}^{(c)}) \\
& + \varepsilon_c^2 \frac{\sqrt{s_+}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(3(\psi_3 + w\psi_2) - \frac{s_-s_+\psi_1}{4(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right),
\end{aligned}
\tag{B45}
$$

$$
\begin{aligned}
g_{1/2,\perp} = {} & \frac{C_1^5\zeta s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}} + \varepsilon_b \frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}} - \zeta\bar{\Lambda}'\right) \\
& + \varepsilon_c \frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda} - 2\zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \frac{s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(\varepsilon_c\eta_{\mathrm{kin}}^{(c)} - \varepsilon_c\eta_{\mathrm{mag}}^{(c)}) + \varepsilon_c^2 \frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(3(\psi_3 + w\psi_2) - \frac{s_-s_+\psi_1}{4(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right),
\end{aligned}
\tag{B46}
$$

$$
\begin{aligned}
t_{1/2,0} = {} & \frac{\zeta m_{\Lambda_c^*}s_-\sqrt{s_+}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_{T_1} - C_{T_2} + C_{T_3} - \frac{C_{T_4}s_+}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \varepsilon_b \frac{m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b}m_{\Lambda_c^*}} - 2\zeta\bar{\Lambda}' + 4\zeta_{\mathrm{SL}}\right) \\
& + \varepsilon_c \frac{m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda} - 4\zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \frac{m_{\Lambda_c^*}s_-\sqrt{s_+}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(\varepsilon_c\eta_{\mathrm{kin}}^{(c)} + \varepsilon_b\eta_{\mathrm{mag}}^{(b)} - \varepsilon_c\eta_{\mathrm{mag}}^{(c)}) \\
& + \varepsilon_c^2 \frac{m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(6(\psi_3 + w\psi_2) - \frac{s_-s_+\psi_1}{2(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right),
\end{aligned}
\tag{B47}
$$

$$
\begin{aligned}
t_{1/2,\perp} = {} & \frac{\zeta s_-\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{C_{T_1}m_{\Lambda_c^*}}{m_{\Lambda_b}m_{\Lambda_c^*}} + \frac{C_{T_2}(-m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b}^2(m_{\Lambda_b}+m_{\Lambda_c^*})} - \frac{C_{T_3}(m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2 - q^2)}{2(m_{\Lambda_b}+m_{\Lambda_c^*})m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \varepsilon_b \frac{m_{\Lambda_c^*}\sqrt{s_+}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda}' - \frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \varepsilon_c \frac{\sqrt{s_+}m_{\Lambda_c^*}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda} - 4\zeta_{\mathrm{SL}} - \frac{\bar{\Lambda}'\zeta(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \frac{m_{\Lambda_c^*}s_-\sqrt{s_+}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(\varepsilon_c\eta_{\mathrm{kin}}^{(c)} - \varepsilon_c\eta_{\mathrm{mag}}^{(c)}) \\
& + \varepsilon_c^2 \frac{m_{\Lambda_c^*}\sqrt{s_+}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(6(\psi_3 + w\psi_2) - \frac{s_-s_+\psi_1}{2(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right),
\end{aligned}
\tag{B48}
$$

$$
\begin{aligned}
t_{1/2,0}^5 = {} & \frac{C_{T_1}\zeta m_{\Lambda_c^*}\sqrt{s_-}s_+}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}} + \varepsilon_b \frac{m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b}m_{\Lambda_c^*}} - 2\zeta\bar{\Lambda}' - 4\zeta_{\mathrm{SL}}\right) \\
& + \varepsilon_c \frac{m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda} - 4\zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \frac{m_{\Lambda_c^*}s_+\sqrt{s_-}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(\varepsilon_c\eta_{\mathrm{kin}}^{(c)} - \varepsilon_b\eta_{\mathrm{mag}}^{(b)} - \varepsilon_c\eta_{\mathrm{mag}}^{(c)}) \\
& + \varepsilon_c^2 \frac{m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(6(\psi_3 + w\psi_2) - \frac{s_-s_+\psi_1}{2(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right),
\end{aligned}
\tag{B49}
$$

$$
\begin{aligned}
t^5_{1/2,\perp} = {}& \frac{\zeta\sqrt{s_-}s_+}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{C_{T_1}m_{\Lambda_c^*}}{m_{\Lambda_b}m_{\Lambda_c^*}} - \frac{C_{T_2}s_-}{2m^2_{\Lambda_b}(m_{\Lambda_b}-m_{\Lambda_c^*})} - \frac{C_{T_3}s_-}{2(m_{\Lambda_b}-m_{\Lambda_c^*})m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \varepsilon_b \frac{m_{\Lambda_c^*}\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda}' - \frac{\zeta\bar{\Lambda}(m^2_{\Lambda_b}+m^2_{\Lambda_c^*}-q^2)}{m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \varepsilon_c \frac{m_{\Lambda_c^*}\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(2\zeta\bar{\Lambda} - 4\zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}'(m^2_{\Lambda_b}+m^2_{\Lambda_c^*}-q^2)}{m_{\Lambda_b}m_{\Lambda_c^*}}\right) + \frac{m_{\Lambda_c^*}s_+\sqrt{s_-}}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(\varepsilon_c\eta^{(c)}_{\mathrm{kin}} - \varepsilon_c\eta^{(c)}_{\mathrm{mag}}) \\
& + \varepsilon_c^2 \frac{m_{\Lambda_c^*}\sqrt{s_+}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(6(\psi_3+w\psi_2) - \frac{s_-s_+\psi_1}{2(m_{\Lambda_b}m_{\Lambda_c^*})^2}\right). \qquad \text{(B50)}
\end{aligned}
$$

For the final state $\Lambda_c(2625)^+$ the form factors are

$$
\begin{aligned}
F_{1/2,0} = {}& \frac{\zeta s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1 + \frac{C_2 s_+}{2m_{\Lambda_b}(m_{\Lambda_b}+m_{\Lambda_c^*})} + \frac{C_3 s_+}{2m_{\Lambda_c^*}(m_{\Lambda_b}+m_{\Lambda_c^*})}\right) \\
& + \varepsilon_b \frac{\sqrt{s_+}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}' + \zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}(m^2_{\Lambda_b}+m^2_{\Lambda_c^*}-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \varepsilon_c \frac{\sqrt{s_+}(m_{\Lambda_b}-m_{\Lambda_c^*})}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda} + \zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}'(m^2_{\Lambda_b}+m^2_{\Lambda_c^*}-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \frac{\sqrt{s_+}s_-}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(2\varepsilon_c\eta^{(c)}_{\mathrm{kin}} - \varepsilon_b\eta^{(b)}_{\mathrm{mag}} + \varepsilon_c\eta^{(c)}_{\mathrm{mag}}) - \varepsilon_c^2\frac{s_+^{3/2}s_-(m_{\Lambda_b}-m_{\Lambda_c^*})}{4(m_{\Lambda_b}+m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\psi_1, \qquad \text{(B51)}
\end{aligned}
$$

$$
\begin{aligned}
F_{1/2,t} = {}& \frac{\zeta s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1 + \frac{m_{\Lambda_c^*}(m^2_{\Lambda_b}-m^2_{\Lambda_c^*}+q^2)}{2(m_{\Lambda_b}-m_{\Lambda_c^*})m_{\Lambda_b}m_{\Lambda_c^*}}C_2 + \frac{m_{\Lambda_b}(m^2_{\Lambda_b}-m^2_{\Lambda_c^*}-q^2)}{2(m_{\Lambda_b}-m_{\Lambda_c^*})m_{\Lambda_b}m_{\Lambda_c^*}}C_3\right) \\
& + \varepsilon_b \frac{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{s_-}}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}' + \zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}(m^2_{\Lambda_b}+m^2_{\Lambda_c^*}-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \varepsilon_c \frac{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{s_-}}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda} + \zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}'(m^2_{\Lambda_b}+m^2_{\Lambda_c^*}-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \frac{s_+\sqrt{s_-}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(2\varepsilon_c\eta^{(c)}_{\mathrm{kin}} - \varepsilon_b\eta^{(b)}_{\mathrm{mag}} + \varepsilon_c\eta^{(c)}_{\mathrm{mag}}) - \varepsilon_c^2\frac{s_+s_-^{3/2}(m_{\Lambda_b}+m_{\Lambda_c^*})}{4(m_{\Lambda_b}-m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\psi_1, \qquad \text{(B52)}
\end{aligned}
$$

$$
\begin{aligned}
F_{1/2,\perp} = {}& \frac{\zeta\sqrt{s_+}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}C_1 + \varepsilon_b\zeta\frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{\bar{\Lambda}(m^2_{\Lambda_b}+m^2_{\Lambda_c^*}-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}} - \bar{\Lambda}'\right) \\
& + \varepsilon_c\frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda} + \zeta_{\mathrm{SL}} - \zeta\frac{\bar{\Lambda}'(m^2_{\Lambda_b}+m^2_{\Lambda_c^*}-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\
& + \frac{\sqrt{s_+}s_-}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(2\varepsilon_c\eta^{(c)}_{\mathrm{kin}} + \varepsilon_c\eta^{(c)}_{\mathrm{mag}}) - \varepsilon_c^2\frac{s_+^{3/2}s_-}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\psi_1, \\
F_{3/2,\perp} = {}& -\varepsilon_b\frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\zeta_{\mathrm{SL}} - \varepsilon_b\frac{s_-\sqrt{s_+}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta^{(b)}_{\mathrm{mag}}, \qquad \text{(B53)}
\end{aligned}
$$

$$
\begin{aligned}
G_{1/2,0} = {} & \frac{\zeta s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1^5 - \frac{C_2^5 s_-}{2m_{\Lambda_b}(m_{\Lambda_b}-m_{\Lambda_c^*})} - \frac{C_3^5 s_-}{2m_{\Lambda_c^*}(m_{\Lambda_b}-m_{\Lambda_c^*})}\right)\\
& + \varepsilon_b\frac{\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda' - \zeta_{\rm SL} - \frac{\zeta\bar\Lambda(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right)\\
& + \varepsilon_c\frac{\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda + \zeta_{\rm SL} - \frac{\zeta\bar\Lambda'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right)\\
& + \frac{s_+\sqrt{s_-}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(2\varepsilon_c\eta_{\rm kin}^{(c)} + \varepsilon_b\eta_{\rm mag}^{(b)} + \varepsilon_c\eta_{\rm mag}^{(c)}) - \varepsilon_c^2\frac{s_+ s_-^{3/2}(m_{\Lambda_b}+m_{\Lambda_c^*})}{4(m_{\Lambda_b}-m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\psi_1,
\end{aligned}
\tag{B54}
$$

$$
\begin{aligned}
G_{1/2,t} = {} & \frac{\zeta s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1^5 - \frac{(m_{\Lambda_b}^2-m_{\Lambda_c^*}^2+q^2)}{2(m_{\Lambda_b}+m_{\Lambda_c^*})m_{\Lambda_b}}C_2^5 - \frac{(m_{\Lambda_b}^2-m_{\Lambda_c^*}^2-q^2)}{2(m_{\Lambda_b}+m_{\Lambda_c^*})m_{\Lambda_c^*}}C_3^5\right)\\
& + \varepsilon_b\frac{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda' - \zeta_{\rm SL} - \frac{\zeta\bar\Lambda(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right)\\
& + \varepsilon_c\frac{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda' + \zeta_{\rm SL} - \frac{\zeta\bar\Lambda(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right)\\
& + \frac{\sqrt{s_+}s_-}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(2\varepsilon_c\eta_{\rm kin}^{(c)} + \varepsilon_b\eta_{\rm mag}^{(b)} + \varepsilon_c\eta_{\rm mag}^{(c)}) - \varepsilon_c^2\frac{s_+^{3/2}s_-(m_{\Lambda_b}-m_{\Lambda_c^*})}{4(m_{\Lambda_b}+m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\psi_1,
\end{aligned}
\tag{B55}
$$

$$
\begin{aligned}
G_{1/2,\perp} = {} & \frac{\zeta\sqrt{s_-}s_+}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}C_1^5 + \varepsilon_b\zeta\frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{\bar\Lambda(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}} - \bar\Lambda'\right) + \varepsilon_c\frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda + \zeta_{\rm SL} - \zeta\frac{\bar\Lambda'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right)\\
& + \frac{s_+\sqrt{s_-}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(2\varepsilon_c\eta_{\rm kin}^{(c)} + \varepsilon_c\eta_{\rm mag}^{(c)}) - \varepsilon_c^2\frac{s_+ s_-^{3/2}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\psi_1,
\end{aligned}
\tag{B56}
$$

$$
G_{3/2,\perp} = -\varepsilon_b\frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\zeta_{\rm SL} - \varepsilon_b\frac{s_+\sqrt{s_-}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\rm mag}^{(b)},
\tag{B57}
$$

$$
\begin{aligned}
T_{1/2,0} = {} & \zeta\frac{m_{\Lambda_c^*}\sqrt{s_+}s_-}{(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_{T_1} - C_{T_2} + C_{T_3} - \frac{s_+}{2m_{\Lambda_b}m_{\Lambda_c^*}}C_{T_4}\right) + \varepsilon_b\frac{2m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(-\zeta\bar\Lambda' - \zeta_{\rm SL} + \zeta\frac{m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2}{2m_{\Lambda_b}m_{\Lambda_c^*}}\bar\Lambda\right)\\
& + \varepsilon_c\frac{2m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda + \zeta_{\rm SL} - \zeta\frac{m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2}{2m_{\Lambda_b}m_{\Lambda_c^*}}\bar\Lambda'\right) + \frac{m_{\Lambda_c^*}\sqrt{s_+}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(2\varepsilon_c\eta_{\rm kin}^{(c)} - \varepsilon_b\eta_{\rm mag}^{(b)} + \varepsilon_c\eta_{\rm mag}^{(c)}) - \varepsilon_c^2\frac{m_{\Lambda_c^*}s_+^{3/2}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\psi_1,
\end{aligned}
\tag{B58}
$$

$$
\begin{aligned}
T_{1/2,\perp} = {} & \zeta\frac{\sqrt{s_+}s_-}{m_{\Lambda_b}\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(C_{T_1} - \frac{m_{\Lambda_b}^2-m_{\Lambda_c^*}^2+q^2}{2m_{\Lambda_b}(m_{\Lambda_b}+m_{\Lambda_c^*})}C_{T_2} - \frac{m_{\Lambda_b}^2-m_{\Lambda_c^*}^2-q^2}{2m_{\Lambda_c^*}(m_{\Lambda_b}+m_{\Lambda_c^*})}C_{T_3}\right)\\
& + \varepsilon_b\frac{2m_{\Lambda_c^*}(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda' - \zeta\frac{m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2}{2m_{\Lambda_b}m_{\Lambda_c^*}}\bar\Lambda\right)\\
& + \varepsilon_c\frac{2m_{\Lambda_c^*}(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar\Lambda + \zeta_{\rm SL} - \zeta\frac{m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2}{2m_{\Lambda_b}m_{\Lambda_c^*}}\bar\Lambda'\right)\\
& + \frac{m_{\Lambda_c^*}\sqrt{s_+}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}(2\varepsilon_c\eta_{\rm kin}^{(c)} + \varepsilon_c\eta_{\rm mag}^{(c)}) - \varepsilon_c^2\frac{m_{\Lambda_c^*}(m_{\Lambda_b}-m_{\Lambda_c^*})s_+^{3/2}s_-}{2(m_{\Lambda_b}+m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\psi_1,
\end{aligned}
\tag{B59}
$$

$$
T_{3/2,\perp} = -\varepsilon_b\frac{2(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\zeta_{\rm SL} + \varepsilon_b\frac{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{s_+}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\rm mag}^{(b)},
\tag{B60}
$$

$$
\begin{aligned}
T^5_{1/2,0} = &\frac{\zeta m_{\Lambda_c^*} s_+ \sqrt{s_-}}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} C_{T_1} + \varepsilon_b \frac{2 m_{\Lambda_c^*} \sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}}{2 m_{\Lambda_b} m_{\Lambda_c^*}} + \zeta_{\mathrm{SL}} - \zeta \bar{\Lambda}' \right) \\
&+ \varepsilon_b \frac{2 m_{\Lambda_c^*} \sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(-\zeta \frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}'}{2 m_{\Lambda_b} m_{\Lambda_c^*}} + \zeta_{\mathrm{SL}} + \zeta \bar{\Lambda} \right) \\
&+ \frac{m_{\Lambda_c^*} s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} (2\varepsilon_c \eta_{\mathrm{kin}}^{(c)} + \varepsilon_b \eta_{\mathrm{mag}}^{(b)} + \varepsilon_c \eta_{\mathrm{mag}}^{(c)}) - \varepsilon_c^2 \frac{m_{\Lambda_c^*} s_+ s_-^{3/2}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \psi_1,
\end{aligned} \tag{B61}
$$

$$
\begin{aligned}
T^5_{1/2,\perp} = &\zeta \frac{s_+ \sqrt{s_-}}{m_{\Lambda_b} \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(C_{T_1} - \frac{s_-}{2 m_{\Lambda_b} (m_{\Lambda_b} - m_{\Lambda_c^*})} C_{T_2} - \frac{s_-}{2 m_{\Lambda_c^*} (m_{\Lambda_b} - m_{\Lambda_c^*})} \right) \\
&+ \varepsilon_b \frac{2 m_{\Lambda_c^*} (m_{\Lambda_b} + m_{\Lambda_c^*}) \sqrt{s_-}}{(m_{\Lambda_b} - m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' - \zeta \frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
&+ \varepsilon_c \frac{2 m_{\Lambda_c^*} (m_{\Lambda_b} + m_{\Lambda_c^*}) \sqrt{s_-}}{(m_{\Lambda_b} - m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} + \zeta_{\mathrm{SL}} - \zeta \frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}'}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
&+ \frac{m_{\Lambda_c^*} s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} (2\varepsilon_c \eta_{\mathrm{kin}}^{(c)} + \varepsilon_c \eta_{\mathrm{mag}}^{(c)}) - \varepsilon_c^2 \frac{m_{\Lambda_c^*} (m_{\Lambda_b} + m_{\Lambda_c^*}) s_+ s_-^{3/2}}{2(m_{\Lambda_b} - m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \psi_1,
\end{aligned} \tag{B62}
$$

$$
T^5_{3/2,\perp} = -\varepsilon_b \frac{2(m_{\Lambda_b} + m_{\Lambda_c^*}) \sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \zeta_{\mathrm{SL}} + \varepsilon_b \frac{(m_{\Lambda_b} - m_{\Lambda_c^*}) s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \eta_{\mathrm{mag}}^{(b)}. \tag{B63}
$$

3. Form factors at $\mathcal{O}(1/m_c^2)$ in the VC limit

Here we list the full set of form factors up to $\mathcal{O}(1/m_c^2)$ in the VC limit. For the final state $\Lambda_c(2595)^+$ the form factors are

$$
\begin{aligned}
f_{1/2,0} = &\frac{\zeta s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1 + \frac{C_2 s_+}{2 m_{\Lambda_b} (m_{\Lambda_b} + m_{\Lambda_c^*})} + \frac{C_3 s_+}{2 m_{\Lambda_c^*} (m_{\Lambda_b} + m_{\Lambda_c^*})} \right) \\
&+ \varepsilon_b \frac{\sqrt{s_+} (m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda} (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
&+ \varepsilon_c \frac{\sqrt{s_+} (m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}' (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
&+ \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_c^2 \frac{\sqrt{s_+} (m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3\beta_3 - \frac{s_- s_+ \beta_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right),
\end{aligned} \tag{B64}
$$

$$
\begin{aligned}
f_{1/2,t} = &\frac{\zeta s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1 + \frac{C_2 s_+}{2 m_{\Lambda_b} (m_{\Lambda_b} - m_{\Lambda_c^*})} + \frac{C_3 s_+}{2 m_{\Lambda_c^*} (m_{\Lambda_b} - m_{\Lambda_c^*})} \right) \\
&+ \varepsilon_b \frac{\sqrt{s_-} (m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda} (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
&+ \varepsilon_c \frac{\sqrt{s_-} (m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2\zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}' (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
&+ \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_c^2 \frac{\sqrt{s_-} (m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3\beta_3 - \frac{s_- s_+ \beta_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right),
\end{aligned} \tag{B65}
$$

$$
\begin{aligned}
f_{1/2,\perp} = {} & \frac{C_1 \zeta s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_b \frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\frac{\zeta \bar{\Lambda} (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} - \bar{\Lambda}' \zeta \right) \\
& + \varepsilon_c \frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\bar{\Lambda} \zeta - 2 \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}' (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
& + \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_c^2 \frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3\beta_3 - \frac{s_- s_+ \beta_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right),
\end{aligned} \tag{B66}
$$

$$
\begin{aligned}
g_{1/2,0} = {} & \frac{\zeta s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1^5 - \frac{C_2^5 s_-}{2 m_{\Lambda_b} (m_{\Lambda_b} - m_{\Lambda_c^*})} - \frac{C_3^5 s_-}{2 m_{\Lambda_c^*} (m_{\Lambda_b} - m_{\Lambda_c^*})} \right) \\
& + \varepsilon_b \frac{\sqrt{s_-} (m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' + 2 \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda} (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
& + \varepsilon_c \frac{\sqrt{s_-} (m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2 \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}' (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
& + \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_c^2 \frac{\sqrt{s_-} (m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3\beta_3 - \frac{s_- s_+ \beta_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right),
\end{aligned} \tag{B67}
$$

$$
\begin{aligned}
g_{1/2,t} = {} & \frac{\zeta s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1^5 + \frac{C_2^5 s_+}{2 m_{\Lambda_b} (m_{\Lambda_b} + m_{\Lambda_c^*})} + \frac{C_3^5 s_+}{2 m_{\Lambda_c^*} (m_{\Lambda_b} + m_{\Lambda_c^*})} \right) \\
& + \varepsilon_b \frac{\sqrt{s_+} (m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda}' + 2 \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda} (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
& + \varepsilon_c \frac{\sqrt{s_+} (m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2 \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}' (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
& + \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_c^2 \frac{\sqrt{s_+} (m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*}) \sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3\beta_3 - \frac{s_- s_+ \beta_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right),
\end{aligned} \tag{B68}
$$

$$
\begin{aligned}
g_{1/2,\perp} = {} & \frac{C_1^5 \zeta s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_b \frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\frac{\zeta \bar{\Lambda} (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} - \zeta \bar{\Lambda}' \right) \\
& + \varepsilon_c \frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \bar{\Lambda} - 2 \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}' (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
& + \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} s_+ \sqrt{s_-}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_c^2 \frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(3\beta_3 - \frac{s_- s_+ \beta_1}{4(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right),
\end{aligned} \tag{B69}
$$

$$
\begin{aligned}
t_{1/2,0} = {} & \frac{\zeta m_{\Lambda_c^*} s_- \sqrt{s_+}}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_{T_1} - C_{T_2} + C_{T_3} - \frac{C_{T_4} s_+}{2 m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
& + \varepsilon_b \frac{m_{\Lambda_c^*} \sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\frac{\zeta \bar{\Lambda} (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}} - 2 \zeta \bar{\Lambda}' + 4 \zeta_{\mathrm{SL}} \right) \\
& + \varepsilon_c \frac{m_{\Lambda_c^*} \sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(2 \zeta \bar{\Lambda} - 4 \zeta_{\mathrm{SL}} - \frac{\zeta \bar{\Lambda}' (m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\
& + \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} m_{\Lambda_c^*} s_- \sqrt{s_+}}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_c^2 \frac{m_{\Lambda_c^*} \sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(6\beta_3 - \frac{s_- s_+ \beta_1}{2(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right),
\end{aligned} \tag{B70}
$$

$$t_{1/2,\perp} = \frac{\zeta s_- \sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\frac{C_{T_1} m_{\Lambda_c^*}}{m_{\Lambda_b} m_{\Lambda_c^*}} + \frac{C_{T_2}(-m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b}^2 (m_{\Lambda_b} + m_{\Lambda_c^*})} - \frac{C_{T_3}(m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2 - q^2)}{2(m_{\Lambda_b} + m_{\Lambda_c^*}) m_{\Lambda_b} m_{\Lambda_c^*}} \right)$$
$$+ \varepsilon_b \frac{m_{\Lambda_c^*} \sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(2\zeta\bar{\Lambda}' - \frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}} \right)$$
$$+ \varepsilon_c \frac{\sqrt{s_+} m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(2\zeta\bar{\Lambda} - 4\zeta_{\mathrm{SL}} - \frac{\bar{\Lambda}'\zeta(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}} \right)$$
$$+ \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} m_{\Lambda_c^*} s_- \sqrt{s_+}}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_c^2 \frac{m_{\Lambda_c^*} \sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(6\beta_3 - \frac{s_- s_+ \beta_1}{2(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right), \tag{B71}$$

$$t_{1/2,0}^5 = \frac{C_{T_1} \zeta m_{\Lambda_c^*} \sqrt{s_-} s_+}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_b \frac{m_{\Lambda_c^*} \sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}} - 2\zeta\bar{\Lambda}' - 4\zeta_{\mathrm{SL}} \right)$$
$$+ \varepsilon_c \frac{m_{\Lambda_c^*} \sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(2\zeta\bar{\Lambda} - 4\zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}} \right)$$
$$+ \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} m_{\Lambda_c^*} \sqrt{s_-} s_+}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_c^2 \frac{m_{\Lambda_c^*} \sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(6\beta_3 - \frac{s_- s_+ \beta_1}{2(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right), \tag{B72}$$

$$t_{1/2,\perp}^5 = \frac{\zeta \sqrt{s_-} s_+}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\frac{C_{T_1} m_{\Lambda_c^*}}{m_{\Lambda_b} m_{\Lambda_c^*}} - \frac{C_{T_2} s_-}{2m_{\Lambda_b}^2 (m_{\Lambda_b} - m_{\Lambda_c^*})} - \frac{C_{T_3} s_-}{2(m_{\Lambda_b} - m_{\Lambda_c^*}) m_{\Lambda_b} m_{\Lambda_c^*}} \right)$$
$$+ \varepsilon_b \frac{m_{\Lambda_c^*} \sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(2\zeta\bar{\Lambda}' - \frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}} \right)$$
$$+ \varepsilon_c \frac{m_{\Lambda_c^*} \sqrt{s_-}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(2\zeta\bar{\Lambda} - 4\zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{m_{\Lambda_b} m_{\Lambda_c^*}} \right)$$
$$+ \varepsilon_c \frac{\eta_{\mathrm{kin}}^{(c)} m_{\Lambda_c^*} \sqrt{s_-} s_+}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} + \varepsilon_c^2 \frac{m_{\Lambda_c^*} \sqrt{s_+}(m_{\Lambda_b} + m_{\Lambda_c^*})}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(6\beta_3 - \frac{s_- s_+ \beta_1}{2(m_{\Lambda_b} m_{\Lambda_c^*})^2} \right). \tag{B73}$$

For the final state $\Lambda_c(2625)^+$ the form factors are

$$F_{1/2,0} = \frac{\zeta s_- \sqrt{s_+}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_1 + \frac{C_2 s_+}{2m_{\Lambda_b}(m_{\Lambda_b} + m_{\Lambda_c^*})} + \frac{C_3 s_+}{2m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*})} \right)$$
$$+ \varepsilon_b \frac{\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta\bar{\Lambda}' + \zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right)$$
$$+ \varepsilon_c \frac{\sqrt{s_+}(m_{\Lambda_b} - m_{\Lambda_c^*})}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta\bar{\Lambda} + \zeta_{\mathrm{SL}} - \frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right)$$
$$+ \varepsilon_c \frac{\sqrt{s_+} s_-}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \eta_{\mathrm{kin}}^{(c)} - \varepsilon_c^2 \frac{(m_{\Lambda_b} - m_{\Lambda_c^*}) s_+^{3/2} s_-}{4(m_{\Lambda_b} + m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \beta_1, \tag{B74}$$

$$\begin{aligned} F_{1/2,t} = {} & \frac{\zeta s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1+\frac{m_{\Lambda_c^*}(m_{\Lambda_b}^2-m_{\Lambda_c^*}^2+q^2)}{2(m_{\Lambda_b}-m_{\Lambda_c^*})m_{\Lambda_b}m_{\Lambda_c^*}}C_2+\frac{m_{\Lambda_b}(m_{\Lambda_b}^2-m_{\Lambda_c^*}^2-q^2)}{2(m_{\Lambda_b}-m_{\Lambda_c^*})m_{\Lambda_b}m_{\Lambda_c^*}}C_3\right) \\ & +\varepsilon_b\frac{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{s_-}}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}'+\zeta_{\mathrm{SL}}-\frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\ & +\varepsilon_c\frac{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{s_-}}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}+\zeta_{\mathrm{SL}}-\frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\ & +\varepsilon_c\frac{s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\mathrm{kin}}^{(c)}-\varepsilon_c^2\frac{(m_{\Lambda_b}+m_{\Lambda_c^*})s_+s_-^{3/2}}{4(m_{\Lambda_b}-m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\beta_1, \end{aligned} \tag{B75}$$

$$\begin{aligned} F_{1/2,\perp} = {} & \frac{\zeta\sqrt{s_+}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}C_1+\varepsilon_b\zeta\frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{\bar{\Lambda}(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}-\bar{\Lambda}'\right)+\varepsilon_c\frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}+\zeta_{\mathrm{SL}}-\zeta\frac{\bar{\Lambda}'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\ & +\varepsilon_c\frac{\sqrt{s_+}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\mathrm{kin}}^{(c)}-\varepsilon_c^2\frac{s_+^{3/2}s_-}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\beta_1, \end{aligned} \tag{B76}$$

$$F_{3/2,\perp} = -\varepsilon_b\frac{\sqrt{s_+}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\zeta_{\mathrm{SL}}. \tag{B77}$$

$$\begin{aligned} G_{1/2,0} = {} & \frac{\zeta s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1^5-\frac{C_2^5s_-}{2m_{\Lambda_b}(m_{\Lambda_b}-m_{\Lambda_c^*})}-\frac{C_3^5s_-}{2m_{\Lambda_c^*}(m_{\Lambda_b}-m_{\Lambda_c^*})}\right) \\ & +\varepsilon_b\frac{\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}'-\zeta_{\mathrm{SL}}-\frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\ & +\varepsilon_c\frac{\sqrt{s_-}(m_{\Lambda_b}+m_{\Lambda_c^*})}{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}+\zeta_{\mathrm{SL}}-\frac{\zeta\bar{\Lambda}'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\ & +\varepsilon_c\frac{s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\mathrm{kin}}^{(c)}-\varepsilon_c^2\frac{(m_{\Lambda_b}+m_{\Lambda_c^*})s_+s_-^{3/2}}{4(m_{\Lambda_b}-m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\beta_1, \end{aligned} \tag{B78}$$

$$\begin{aligned} G_{1/2,t} = {} & \frac{\zeta s_-\sqrt{s_+}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\left(C_1^5-\frac{(m_{\Lambda_b}^2-m_{\Lambda_c^*}^2+q^2)}{2(m_{\Lambda_b}+m_{\Lambda_c^*})m_{\Lambda_b}}C_2^5-\frac{(m_{\Lambda_b}^2-m_{\Lambda_c^*}^2-q^2)}{2(m_{\Lambda_b}+m_{\Lambda_c^*})m_{\Lambda_c^*}}C_3^5\right) \\ & +\varepsilon_b\frac{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}'-\zeta_{\mathrm{SL}}-\frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\ & +\varepsilon_c\frac{(m_{\Lambda_b}-m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b}+m_{\Lambda_c^*})\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}'+\zeta_{\mathrm{SL}}-\frac{\zeta\bar{\Lambda}(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\ & +\varepsilon_c\frac{\sqrt{s_+}s_-}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\mathrm{kin}}^{(c)}-\varepsilon_c^2\frac{(m_{\Lambda_b}-m_{\Lambda_c^*})s_+^{3/2}s_-}{4(m_{\Lambda_b}+m_{\Lambda_c^*})(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\beta_1, \end{aligned} \tag{B79}$$

$$\begin{aligned} G_{1/2,\perp} = {} & \frac{\zeta\sqrt{s_-}s_+}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}C_1^5+\varepsilon_b\zeta\frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\frac{\bar{\Lambda}(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}-\bar{\Lambda}'\right) \\ & +\varepsilon_c\frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b}m_{\Lambda_c^*}}}\left(\zeta\bar{\Lambda}+\zeta_{\mathrm{SL}}-\zeta\frac{\bar{\Lambda}'(m_{\Lambda_b}^2+m_{\Lambda_c^*}^2-q^2)}{2m_{\Lambda_b}m_{\Lambda_c^*}}\right) \\ & +\varepsilon_c\frac{s_+\sqrt{s_-}}{2(m_{\Lambda_b}m_{\Lambda_c^*})^{3/2}}\eta_{\mathrm{kin}}^{(c)}-\varepsilon_c^2\frac{s_+s_-^{3/2}}{4(m_{\Lambda_b}m_{\Lambda_c^*})^{5/2}}\beta_1, \end{aligned} \tag{B80}$$

$$G_{3/2,\perp} = -\varepsilon_b \frac{\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \zeta_{\mathrm{SL}}, \tag{B81}$$

$$\begin{aligned} T_{1/2,0} = {} & \zeta \frac{m_{\Lambda_c^*}\sqrt{s_+} s_-}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \left(C_{T_1} - C_{T_2} + C_{T_3} - \frac{s_+}{2m_{\Lambda_b} m_{\Lambda_c^*}} C_{T_4} \right) \\ & + \varepsilon_b \frac{2m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(-\zeta\bar{\Lambda}' - \zeta_{\mathrm{SL}} + \zeta \frac{m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2}{2m_{\Lambda_b} m_{\Lambda_c^*}} \bar{\Lambda} \right) \\ & + \varepsilon_c \frac{2m_{\Lambda_c^*}\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta\bar{\Lambda} + \zeta_{\mathrm{SL}} - \zeta \frac{m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2}{2m_{\Lambda_b} m_{\Lambda_c^*}} \bar{\Lambda}' \right) \\ & + \varepsilon_c \frac{m_{\Lambda_c^*}\sqrt{s_+} s_-}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \eta_{\mathrm{kin}}^{(c)} - \varepsilon_c^2 \frac{m_{\Lambda_c^*} s_+^{3/2} s_-}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \beta_1, \end{aligned} \tag{B82}$$

$$\begin{aligned} T_{1/2,\perp} = {} & \zeta \frac{\sqrt{s_+} s_-}{m_{\Lambda_b}\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(C_{T_1} - \frac{m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2 + q^2}{2m_{\Lambda_b}(m_{\Lambda_b} + m_{\Lambda_c^*})} C_{T_2} - \frac{m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2 - q^2}{2m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*})} C_{T_3} \right) \\ & + \varepsilon_b \frac{2m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta\bar{\Lambda}' - \zeta \frac{m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2}{2m_{\Lambda_b} m_{\Lambda_c^*}} \bar{\Lambda} \right) \\ & + \varepsilon_c \frac{2m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{s_+}}{(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta\bar{\Lambda} + \zeta_{\mathrm{SL}} - \zeta \frac{m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2}{2m_{\Lambda_b} m_{\Lambda_c^*}} \bar{\Lambda}' \right) \\ & + \varepsilon_c \frac{m_{\Lambda_c^*}\sqrt{s_+} s_-}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \eta_{\mathrm{kin}}^{(c)} - \varepsilon_c^2 \frac{m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*}) s_+^{3/2} s_-}{2(m_{\Lambda_b} + m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \beta_1, \end{aligned} \tag{B83}$$

$$\begin{aligned} T_{3/2,\perp} = {} & -\varepsilon_b \frac{2(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{s_+}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \zeta_{\mathrm{SL}}, \\ T_{1/2,0}^5 = {} & \frac{\zeta m_{\Lambda_c^*} s_+ \sqrt{s_-}}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} C_{T_1} + \varepsilon_b \frac{2m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta \frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}}{2m_{\Lambda_b} m_{\Lambda_c^*}} + \zeta_{\mathrm{SL}} - \zeta\bar{\Lambda}' \right) \\ & + \varepsilon_b \frac{2m_{\Lambda_c^*}\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(-\zeta \frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}'}{2m_{\Lambda_b} m_{\Lambda_c^*}} + \zeta_{\mathrm{SL}} + \zeta\bar{\Lambda} \right) + \varepsilon_c \frac{m_{\Lambda_c^*} s_+ \sqrt{s_-}}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \eta_{\mathrm{kin}}^{(c)} - \varepsilon_c^2 \frac{m_{\Lambda_c^*} s_+ s_-^{3/2}}{2(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \beta_1, \end{aligned} \tag{B84}$$

$$\begin{aligned} T_{1/2,\perp}^5 = {} & \zeta \frac{s_+\sqrt{s_-}}{m_{\Lambda_b}\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(C_{T_1} - \frac{s_-}{2m_{\Lambda_b}(m_{\Lambda_b} - m_{\Lambda_c^*})} C_{T_2} - \frac{s_-}{2m_{\Lambda_c^*}(m_{\Lambda_b} - m_{\Lambda_c^*})} \right) \\ & + \varepsilon_b \frac{2m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{s_-}}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta\bar{\Lambda}' - \zeta \frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\ & + \varepsilon_c \frac{2m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{s_-}}{(m_{\Lambda_b} - m_{\Lambda_c^*})\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \left(\zeta\bar{\Lambda} + \zeta_{\mathrm{SL}} - \zeta \frac{(m_{\Lambda_b}^2 + m_{\Lambda_c^*}^2 - q^2)\bar{\Lambda}'}{2m_{\Lambda_b} m_{\Lambda_c^*}} \right) \\ & + \varepsilon_c \frac{m_{\Lambda_c^*} s_+ \sqrt{s_-}}{(m_{\Lambda_b} m_{\Lambda_c^*})^{3/2}} \eta_{\mathrm{kin}}^{(c)} - \varepsilon_c^2 \frac{m_{\Lambda_c^*}(m_{\Lambda_b} + m_{\Lambda_c^*}) s_+ s_-^{3/2}}{2(m_{\Lambda_b} - m_{\Lambda_c^*})(m_{\Lambda_b} m_{\Lambda_c^*})^{5/2}} \beta_1, \\ T_{3/2,\perp}^5 = {} & -\varepsilon_b \frac{2(m_{\Lambda_b} + m_{\Lambda_c^*})\sqrt{s_-}}{\sqrt{m_{\Lambda_b} m_{\Lambda_c^*}}} \zeta_{\mathrm{SL}}. \end{aligned} \tag{B85}$$

APPENDIX C: POLARIZATION VECTORS

In this section, we present the definitions of the polarization vectors that have been employed in the determination of the on-shell amplitude, according to the procedure outlined in Ref. [33]. We have selected the z axis to align with the flight direction of the Λ_c^*. Consequently, within the rest frame of the Λ_b ($\Lambda_b-\mathrm{RF}$), we find

$$p^\mu|_{\Lambda b\text{-RF}} = (m_{\Lambda_b}, 0, 0, 0), \tag{C1}$$

$$q^\mu|_{\Lambda b\text{-RF}} = (q^0, 0, 0, -|\vec{q}|), \tag{C2}$$

$$k^\mu|_{\Lambda b\text{-RF}} = (m_{\Lambda_b} - q^0, 0, 0, +|\vec{q}|). \tag{C3}$$

Expressed in terms of the invariant q^2, we obtain

$$q^0|_{\Lambda_b-\mathrm{RF}} = \frac{m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2 + q^2}{2m_{\Lambda_b}}, \quad |\vec{q}||_{\Lambda_b-\mathrm{RF}} = \frac{\sqrt{\lambda(m_{\Lambda_b}^2, m_{\Lambda_c^*}^2, q^2)}}{2m_{\Lambda_b}}, \tag{C4}$$

where λ is the Källén function

$$\lambda(a,b,c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ac. \tag{C5}$$

The definition of the Rarita-Schwinger spinor involves a spin-1 polarization vector denoted as $\eta(m)$. Following Refs. [33,63] we have

$$\eta(\pm)|_{\Lambda_b-\mathrm{RF}} = (0, \mp 1, -i, 0)/\sqrt{2}, \tag{C6}$$

$$\eta(0)|_{\Lambda_b-\mathrm{RF}} = (|\vec{q}|, 0, 0, m_{\Lambda_b} - q^0)/m_{\Lambda_c^*}. \tag{C7}$$

For the exchange of the virtual W we use the following polarization vectors [33,63]:

$$\varepsilon^\mu(t)|_{\Lambda_b-\mathrm{RF}} = (q^0, 0, 0, -|\vec{q}|)/\sqrt{q^2} = q^\mu/\sqrt{q^2}, \tag{C8}$$

$$\varepsilon^\mu(\pm)|_{\Lambda_b-\mathrm{RF}} = (0, \pm 1, -i, 0)/\sqrt{2}, \tag{C9}$$

$$\varepsilon^\mu(0)|_{\Lambda_b-\mathrm{RF}} = (+|\vec{q}|, 0, 0, -q_0)/\sqrt{q^2}. \tag{C10}$$

APPENDIX D: RELATIONS WITH LATTICE FORM FACTORS

Our definitions of form factors are related to the lattice one in Refs. [38,39] by the following relations:

$$F_{1/2,t} = \frac{1}{2}\sqrt{\frac{s_-}{4m_{\Lambda_b}m_{\Lambda_c^*}}} f_0^{(\frac{3}{2}^-)}, \qquad F_{1/2,0} = \frac{1}{2}\sqrt{\frac{s_+}{4m_{\Lambda_b}m_{\Lambda_c^*}}} f_+^{(\frac{3}{2}^-)},$$

$$F_{1/2,\perp} = \frac{1}{2}\sqrt{\frac{s_+}{4m_{\Lambda_b}m_{\Lambda_c^*}}} f_\perp^{(\frac{3}{2}^-)}, \qquad F_{3/2,\perp} = -\frac{1}{2}\sqrt{\frac{s_+}{4m_{\Lambda_b}m_{\Lambda_c^*}}} f_{\perp'}^{(\frac{3}{2}^-)},$$

$$G_{1/2,t} = \frac{1}{2}\sqrt{\frac{s_+}{4m_{\Lambda_b}m_{\Lambda_c^*}}} g_0^{(\frac{3}{2}^-)}, \qquad G_{1/2,0} = \frac{1}{2}\sqrt{\frac{s_-}{4m_{\Lambda_b}m_{\Lambda_c^*}}} g_+^{(\frac{3}{2}^-)},$$

$$G_{1/2,\perp} = \frac{1}{2}\sqrt{\frac{s_-}{4m_{\Lambda_b}m_{\Lambda_c^*}}} g_\perp^{(\frac{3}{2}^-)}, \qquad G_{3/2,\perp} = \frac{1}{2}\sqrt{\frac{s_-}{4m_{\Lambda_b}m_{\Lambda_c^*}}} g_{\perp'}^{(\frac{3}{2}^-)},$$

$$f_{1/2,t} = \frac{1}{2}\sqrt{\frac{3s_-}{m_{\Lambda_b}m_{\Lambda_c^*}}} \frac{m_{\Lambda_b} + m_{\Lambda_c^*}}{m_{\Lambda_b} - m_{\Lambda_c^*}} f_0^{(\frac{1}{2}^-)}, \qquad f_{1/2,0} = \frac{1}{2}\sqrt{\frac{3s_+}{m_{\Lambda_b}m_{\Lambda_c^*}}} \frac{m_{\Lambda_b} - m_{\Lambda_c^*}}{m_{\Lambda_b} + m_{\Lambda_c^*}} f_+^{(\frac{1}{2}^-)},$$

$$f_{1/2,\perp} = \frac{1}{2}\sqrt{\frac{3s_+}{m_{\Lambda_b}m_{\Lambda_c^*}}} f_\perp^{(\frac{1}{2}^-)},$$

$$g_{1/2,t} = \frac{1}{2}\sqrt{\frac{3s_+}{m_{\Lambda_b}m_{\Lambda_c^*}}} \frac{m_{\Lambda_b} - m_{\Lambda_c^*}}{m_{\Lambda_b} + m_{\Lambda_c^*}} g_0^{(\frac{1}{2}^-)}, \qquad g_{1/2,0} = \frac{1}{2}\sqrt{\frac{3s_-}{m_{\Lambda_b}m_{\Lambda_c^*}}} \frac{m_{\Lambda_b} + m_{\Lambda_c^*}}{m_{\Lambda_b} - m_{\Lambda_c^*}} g_+^{(\frac{1}{2}^-)},$$

$$g_{1/2,\perp} = \frac{1}{2}\sqrt{\frac{3s_-}{m_{\Lambda_b}m_{\Lambda_c^*}}} g_\perp^{(\frac{1}{2}^-)},$$

$$T_{1/2,0} = s_+^{1/2}\sqrt{\frac{m_{\Lambda_c^*}}{4m_{\Lambda_b}}} h_+^{(\frac{3}{2}^-)},$$

$$
\begin{aligned}
T_{1/2,\perp} &= s_+^{1/2}\sqrt{\frac{m_{\Lambda_c^*}}{4m_{\Lambda_b}}}h_\perp^{\left(\frac{3}{2}^-\right)}, \qquad T_{3/2,\perp} = \sqrt{\frac{s_+}{4m_{\Lambda_b}m_{\Lambda_c^*}}}(m_{\Lambda_b}+m_{\Lambda_c^*})h_{\perp'}^{\left(\frac{3}{2}^-\right)}, \\
T^5_{1/2,0} &= s_-^{1/2}\sqrt{\frac{m_{\Lambda_c^*}}{4m_{\Lambda_b}}}\tilde{h}_+^{\left(\frac{3}{2}^-\right)}, \\
T^5_{1/2,\perp} &= s_-^{1/2}\sqrt{\frac{m_{\Lambda_c^*}}{4m_{\Lambda_b}}}\tilde{h}_\perp^{\left(\frac{3}{2}^-\right)}, \qquad T^5_{3/2,\perp} = -\sqrt{\frac{s_-}{4m_{\Lambda_b}m_{\Lambda_c^*}}}(m_{\Lambda_b}-m_{\Lambda_c^*})\tilde{h}_{\perp'}^{\left(\frac{3}{2}^-\right)}, \\
t_{1/2,0} &= \sqrt{\frac{3s_+m_{\Lambda_c^*}}{m_{\Lambda_b}}}h_+^{\left(\frac{1}{2}^-\right)}, \qquad t_{1/2,\perp} = \sqrt{\frac{3s_+m_{\Lambda_c^*}}{m_{\Lambda_b}}}\frac{m_{\Lambda_b}-m_{\Lambda_c^*}}{m_{\Lambda_b}+m_{\Lambda_c^*}}h_\perp^{\left(\frac{1}{2}^-\right)}, \\
t^5_{1/2,0} &= \sqrt{\frac{3s_-m_{\Lambda_c^*}}{m_{\Lambda_b}}}\tilde{h}_+^{\left(\frac{1}{2}^-\right)}, \qquad t^5_{1/2,\perp} = \sqrt{\frac{3s_-m_{\Lambda_c^*}}{m_{\Lambda_b}}}\frac{m_{\Lambda_b}+m_{\Lambda_c^*}}{m_{\Lambda_b}-m_{\Lambda_c^*}}\tilde{h}_\perp^{\left(\frac{1}{2}^-\right)}.
\end{aligned}
\tag{D1}
$$

APPENDIX E: CORRELATION MATRICES FROM LQCD FIT

In this section, we provide the correlation matrices that correspond to the fitting results within the RC and VC limits. Our analysis produces the outcomes presented in Tables V and VII when considering the complete lattice dataset. When focusing solely on the vector and axial lattice form factors, we observe the results outlined in Tables VI and VIII.

TABLE V. Correlation matrix for the IW parameters in the RC limit, when using the full lattice dataset.

1	0.211	0.195	0.011	−0.972	−0.214	0.204	0.075	−0.025	0.004	−0.298	0.825	0.103
0.211	1	−0.055	0.201	−0.316	−0.891	−0.022	0.174	0.104	−0.097	−0.907	0.132	0.047
0.195	−0.055	1	−0.072	−0.176	0.064	0.097	−0.005	−0.141	0.012	−0.030	0.540	−0.054
0.011	0.201	−0.072	1	0.005	−0.141	0.052	0.175	0.428	−0.270	0.004	−0.023	0.629
−0.972	−0.316	−0.176	0.005	1	0.256	−0.176	−0.085	0.022	0.003	0.423	−0.793	−0.058
−0.214	−0.891	0.064	−0.141	0.256	1	0.008	−0.032	−0.080	0.067	0.752	−0.133	−0.038
0.204	−0.022	0.097	0.052	−0.176	0.008	1	−0.525	−0.032	0.033	0.109	0.154	0.173
0.075	0.174	−0.005	0.175	−0.085	−0.032	−0.525	1	0.073	−0.076	−0.209	0.068	−0.027
−0.025	0.104	−0.141	0.428	0.022	−0.080	−0.032	0.073	1	−0.592	−0.020	−0.077	0.224
0.004	−0.097	0.012	−0.270	0.003	0.067	0.033	−0.076	−0.592	1	0.052	0.009	−0.118
−0.298	−0.907	−0.030	0.004	0.423	0.752	0.109	−0.209	−0.020	0.052	1	−0.232	0.172
0.825	0.132	0.540	−0.023	−0.793	−0.133	0.154	0.068	−0.077	0.009	−0.232	1	0.060
0.103	0.047	−0.054	0.629	−0.058	−0.038	0.173	−0.027	0.224	−0.118	0.172	0.060	1

TABLE VI. Correlation matrix for the IW parameters in the RC limit, when using only the vector and axial lattice form factors.

1	0.483	0.014	0.084	−0.997	−0.464	0.423	0.136	−0.007	−0.019	−0.639	0.942	0.247
0.483	1	−0.066	0.196	−0.515	−0.924	0.137	0.183	0.068	−0.075	−0.899	0.436	0.173
0.014	−0.066	1	−0.086	−0.013	0.074	0.046	−0.016	−0.142	0.029	−0.008	0.268	−0.080
0.084	0.196	−0.086	1	−0.077	−0.160	0.142	0.143	0.129	−0.123	0.045	0.057	0.757
−0.997	−0.515	−0.013	−0.077	1	0.478	−0.413	−0.139	0.006	0.020	0.674	−0.938	−0.232
−0.464	−0.924	0.074	−0.160	0.478	1	−0.139	−0.048	−0.056	0.062	0.796	−0.417	−0.163
0.423	0.137	0.046	0.142	−0.413	−0.139	1	−0.389	−0.045	0.028	−0.114	0.395	0.290
0.136	0.183	−0.016	0.143	−0.139	−0.048	−0.389	1	0.074	−0.069	−0.212	0.132	0.034
−0.007	0.068	−0.142	0.129	0.006	−0.056	−0.045	0.074	1	−0.679	−0.032	−0.047	0.081
−0.019	−0.075	0.029	−0.123	0.020	0.062	0.028	−0.069	−0.679	1	0.045	−0.005	−0.076
−0.639	−0.899	−0.008	0.045	0.674	0.796	−0.114	−0.212	−0.032	0.045	1	−0.601	0.041
0.942	0.436	0.268	0.057	−0.937	−0.417	0.395	0.131	−0.046	−0.005	−0.601	1	0.214
0.247	0.173	−0.080	0.757	−0.232	−0.163	0.290	0.034	0.081	−0.076	0.041	0.214	1

TABLE VII. Correlation matrix for the IW parameters in the VC limit, when using the full lattice dataset.

1	0.190	0.170	−0.044	−0.970	−0.222	−0.302	0.815	0.065
0.190	1	−0.056	0.138	−0.301	−0.902	−0.910	0.114	0.018
0.170	−0.056	1	−0.037	−0.151	0.058	−0.030	0.527	−0.044
−0.044	0.138	−0.037	1	0.061	−0.115	0.051	−0.045	0.607
−0.970	−0.301	−0.151	0.061	1	0.263	0.431	−0.780	−0.021
−0.222	−0.902	0.058	−0.115	0.263	1	0.764	−0.139	−0.021
−0.302	−0.910	−0.030	0.051	0.431	0.764	1	−0.229	0.179
0.815	0.114	0.527	−0.045	−0.780	−0.139	−0.229	1	0.043
0.065	0.018	−0.044	0.607	−0.021	−0.021	0.179	0.043	1

TABLE VIII. Correlation matrix for the IW parameters in the RC limit, when using only the vector and axial lattice form factors.

1	0.423	−0.011	−0.056	−0.995	−0.445	−0.620	0.923	0.091
0.423	1	−0.072	0.123	−0.461	−0.930	−0.890	0.369	0.096
−0.011	−0.072	1	−0.085	0.012	0.078	−0.003	0.281	−0.091
−0.056	0.123	−0.085	1	0.063	−0.116	0.137	−0.075	0.745
−0.995	−0.461	0.012	0.063	1	0.461	0.661	−0.917	−0.075
−0.445	−0.930	0.078	−0.116	0.461	1	0.799	−0.389	−0.109
−0.620	−0.890	−0.003	0.137	0.661	0.799	1	−0.571	0.136
0.923	0.369	0.281	−0.075	−0.917	−0.389	−0.571	1	0.065
0.091	0.096	−0.091	0.745	−0.075	−0.109	0.136	0.065	1

[1] W. Detmold, C. Lehner, and S. Meinel, Phys. Rev. D **92**, 034503 (2015).
[2] D. Bigi and P. Gambino, Phys. Rev. D **94**, 094008 (2016).
[3] D. Bigi, P. Gambino, and S. Schacht, J. High Energy Phys. 11 (2017) 061.
[4] P. Gambino, M. Jung, and S. Schacht, Phys. Lett. B **795**, 386 (2019).
[5] P. Gambino, A. S. Kronfeld, M. Rotondo, C. Schwanda, F. Bernlochner, A. Bharucha, C. Bozzi, M. Calvi, L. Cao, G. Ciezarek *et al.*, Eur. Phys. J. C **80**, 966 (2020).
[6] S. Simula, G. Martinelli, M. Naviglio, and L. Vittorio, Proc. Sci. CKM2021 (**2021**) 045.
[7] G. Martinelli, S. Simula, and L. Vittorio, Phys. Rev. D **105**, 034503 (2022).
[8] M. Bordone, B. Capdevila, and P. Gambino, Phys. Lett. B **822**, 136679 (2021).
[9] G. Martinelli, S. Simula, and L. Vittorio, Eur. Phys. J. C **82**, 1083 (2022).
[10] G. Martinelli, S. Simula, and L. Vittorio, Proc. Sci. LATTICE2021 (**2022**) 365.
[11] G. Martinelli, M. Naviglio, S. Simula, and L. Vittorio, Phys. Rev. D **106**, 093002 (2022).
[12] G. Martinelli, M. Naviglio, S. Simula, and L. Vittorio, arXiv:2205.09742.
[13] G. Martinelli, M. Naviglio, S. Simula, and L. Vittorio, EPJ Web Conf. **270**, 00015 (2022).
[14] M. Naviglio, G. Martinelli, S. Simula, and L. Vittorio, Proc. Sci. ICHEP2022 (**2022**) 755.
[15] F. U. Bernlochner, Z. Ligeti, M. Papucci, and D. J. Robinson, Phys. Rev. D **95**, 115008 (2017); **97**, 059902 (E) (2018).
[16] F. U. Bernlochner, Z. Ligeti, M. Papucci, M. T. Prim, D. J. Robinson, and C. Xiong, Phys. Rev. D **106**, 096015 (2022).
[17] M. Bordone, M. Jung, and D. van Dyk, Eur. Phys. J. C **80**, 74 (2020).
[18] Y. S. Amhis *et al.* (Heavy Flavor Averaging Group and HFLAV Collaborations), Phys. Rev. D **107**, 052008 (2023).
[19] C. Murgui, A. Peñuelas, M. Jung, and A. Pich, J. High Energy Phys. 09 (2019) 103.
[20] D. Bardhan, P. Byakti, and D. Ghosh, J. High Energy Phys. 01 (2017) 125.
[21] R. Dutta, Phys. Rev. D **93**, 054003 (2016).
[22] A. Datta, S. Kamali, S. Meinel, and A. Rashed, J. High Energy Phys. 08 (2017) 131.
[23] A. Ray, S. Sahoo, and R. Mohanta, Phys. Rev. D **99**, 015015 (2019).
[24] N. Penalva, E. Hernández, and J. Nieves, Phys. Rev. D **100**, 113007 (2019).

[25] M. Ferrillo, A. Mathad, P. Owen, and N. Serra, J. High Energy Phys. 12 (2019) 148.
[26] X. L. Mu, Y. Li, Z. T. Zou, and B. Zhu, Phys. Rev. D **100**, 113004 (2019).
[27] N. Isgur and M. B. Wise, Phys. Lett. B **232**, 113 (1989).
[28] H. Georgi, Phys. Lett. B **240**, 447 (1990).
[29] M. Neubert, Phys. Rep. **245**, 259 (1994).
[30] A. F. Falk and M. Neubert, Phys. Rev. D **47**, 2982 (1993).
[31] A. F. Falk and M. Neubert, Phys. Rev. D **47**, 2965 (1993).
[32] A. K. Leibovich and I. W. Stewart, Phys. Rev. D **57**, 5620 (1998).
[33] P. Böer, M. Bordone, E. Graverini, P. Owen, M. Rotondo, and D. Van Dyk, J. High Energy Phys. 06 (2018) 155.
[34] M. Papucci and D. J. Robinson, Phys. Rev. D **105**, 016027 (2022).
[35] J. Nieves, R. Pavao, and S. Sakai, Eur. Phys. J. C **79**, 417 (2019).
[36] J. Nieves and R. Pavao, Phys. Rev. D **101**, 014018 (2020).
[37] M. L. Du, E. Hernández, and J. Nieves, Phys. Rev. D **106**, 114020 (2022).
[38] S. Meinel and G. Rendon, Phys. Rev. D **103**, 094516 (2021).
[39] S. Meinel and G. Rendon, Phys. Rev. D **105**, 054511 (2022).
[40] M. E. Luke and A. V. Manohar, Phys. Lett. B **286**, 348 (1992).
[41] E. Eichten and B. R. Hill, Phys. Lett. B **243**, 427 (1990).
[42] A. F. Falk, B. Grinstein, and M. E. Luke, Nucl. Phys. **B357**, 185 (1991).
[43] A. F. Falk, Nucl. Phys. **B378**, 79 (1992).
[44] G. Hiller and R. Zwicky, J. High Energy Phys. 03 (2014) 042.
[45] G. Hiller and R. Zwicky, J. High Energy Phys. 11 (2021) 073.
[46] M. Neubert, Phys. Rev. D **46**, 3914 (1992).
[47] M. Neubert, Z. Ligeti, and Y. Nir, Phys. Lett. B **301**, 101 (1993).
[48] M. Neubert, Z. Ligeti, and Y. Nir, Phys. Rev. D **47**, 5060 (1993).
[49] N. Isgur, D. Scora, B. Grinstein, and M. B. Wise, Phys. Rev. D **39**, 799 (1989).
[50] D. Scora and N. Isgur, Phys. Rev. D **52**, 2783 (1995).
[51] E. E. Jenkins, A. V. Manohar, and M. B. Wise, Nucl. Phys. **B396**, 27 (1993).
[52] E. E. Jenkins, A. V. Manohar, and M. B. Wise, Nucl. Phys. **B396**, 38 (1993).
[53] M. Wirbel, B. Stech, and M. Bauer, Z. Phys. C **29**, 637 (1985).
[54] J. G. Korner and G. A. Schuler, Z. Phys. C **46**, 93 (1990).
[55] M. Pervin, W. Roberts, and S. Capstick, Phys. Rev. C **72**, 035201 (2005).
[56] T. Gutsche, M. A. Ivanov, J. G. Korner, V. E. Lyubovitskij, and P. Santorelli, Phys. Rev. D **86**, 074013 (2012).
[57] T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij, P. Santorelli, and C. T. Tran, Phys. Rev. D **98**, 053003 (2018).
[58] D. Bečirević, A. Le Yaouanc, V. Morénas, and L. Oliver, Phys. Rev. D **102**, 094023 (2020).
[59] N. Isgur and M. B. Wise, Phys. Lett. B **237**, 527 (1990).
[60] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D **96**, 112005 (2017).
[61] M. Bordone, Symmetry **13**, 531 (2021).
[62] F. U. Bernlochner, Z. Ligeti, D. J. Robinson, and W. L. Sutcliffe, Phys. Rev. Lett. **121**, 202001 (2018).
[63] H. E. Haber, arXiv:hep-ph/9405376.