

Elastic form factors of axial-vector mesons: A contact interaction exploration

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We employ a symmetry-preserving treatment of the contact interaction within the coupled formalism of Schwinger-Dyson and Bethe-Salpeter equations to calculate the elastic form factors of axial-vector mesons. In this study, we present the computation of the charge radii, magnetic moments, and quadrupole moments of axial-vector mesons, including those composed of light quarks, heavy quarks, or a light and a heavy quark. Our findings indicate that the electric form factor for axial-vector mesons, like that of vector mesons, crosses zero. Furthermore, this crossing occurs at a lower value for axial-vector mesons than for vector mesons. The results for vector-axial mesons follow a similar hierarchy in charge radii as observed for scalar, pseudoscalar, and vector mesons, with radii decreasing as the mass of the dressed quarks increases. We also include a term associated with the anomalous magnetic moment in the quark-photon vertex. This term has a noticeable impact on both the axial-vector magnetic moment and quadrupole moment, leading to significant percentage changes in their values. We compare our results with those obtained from other models whenever available.

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I. INTRODUCTION

The concept of axial-vector (AV) mesons was introduced early in the development of the quark model [1,2]. The study of AV mesons is essential for gaining deeper insights into quantum chromodynamics (QCD) and the nature of the strong interactions among quarks and gluons. AV mesons are characterized by quantum numbers $J^{\text{PC}} = 1^{++}$ and are the chiral partners of the vector (V) mesons. It implies that they transform into each other under the chiral transformations, forming pairs such as (ρ, a_1) and (σ, π) . The existence of the lightest AV meson, the a_1 meson, was first confirmed

by the ACCMOR Collaboration [3] through detailed partial-wave analyses of the $\pi^-\pi^-\pi^+$ system. Since this landmark discovery, several additional AV mesons have been observed over time [4–11], which have greatly enhanced our understanding of hadronic states in the framework of QCD. While many models have been successful in describing V and pseudoscalar (PS) mesons, scalar (S) mesons and AV mesons remain significant open questions in the field. One of the key puzzles is understanding the origin of the mass difference between V and AV mesons in the light meson sector. For instance, the mass of the ground state ρ_1 (770 MeV) is notably smaller than that of its chiral partner, the a_{11^+} (1260 MeV), see Fig. 1, with a mass gap of approximately 500 MeV. This puzzle was unveiled by understanding the interplay of dynamical chiral symmetry breaking and the consequent generation of a large dressed-quark anomalous chromomagnetic moment [12,13]. It results in the dramatic enhancement of the spin-orbit splitting between ground-state opposite-parity mesons.

Form factors of axial-vector mesons are relevant for the standard model phenomenology, for example, through contributing to the anomalous magnetic moment a_μ of

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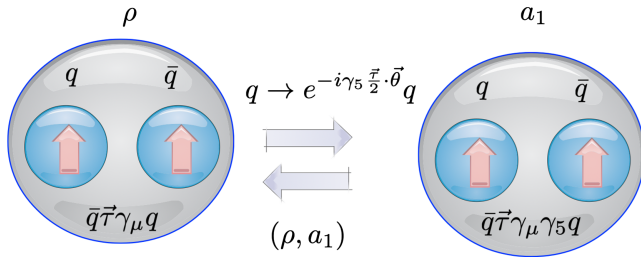


FIG. 1. The chiral partners. The ρ and a_1 mesons are rotated into each other under chiral transformation.

the muon [14–16]. The AV meson pole diagrams, arising from its transition to two virtual photons, contribute to the hadron light-by-light (HLbL) part of a_μ , see, for example, [17]. The AV contributions due to a_1 (1260), f_1 (1285), and f_1 (1420) are considered to correspond to about 20% of the total contribution of HLbL [14–19].

Moreover, in the context of strong interactions, investigating the elastic form factors of AV mesons is expected to provide insights into how quarks and gluons interact through QCD to determine their internal structure, including charge distribution, charge radii, magnetic moments, and quadrupole moments. Notably, the electric charge, magnetic moment, and quadrupole moment correspond to the values of their respective form factors at zero momentum transfer. Despite the intriguing properties of AV mesons, experimental data on their masses, decay constants, and, in particular, their dynamic properties remain limited. We hope that our comprehensive analysis of these states will provide a valuable foundation for future experimental and theoretical investigations. This study is part of a broader effort to calculate the dynamic properties of all mesons within the framework of a contact interaction (CI) model [20–31]. In this context, we note that the multipole moments of AV mesons have been calculated using the light-cone sum rules method in [32] and within a holographic model in [33].

As previously established, dynamical chiral symmetry breaking induces an anomalous chromomagnetic moment in dressed light quarks. This emergent effect is particularly pronounced at infrared momenta, where its magnitude is comparable to the enhanced magnetic moment of these quarks, albeit with the opposite sign [12,34]. These intriguing features are crucial for various calculations involving hadronic properties, particularly in the infrared regime. To account for the spin-orbit repulsion, we introduce a phenomenological coupling, $g_{SO} = 0.25$, as a multiplicative factor in the Bethe-Salpeter kernel, see Refs. [29,34]. Furthermore, following Refs. [28,35,36], we incorporate a term associated with the anomalous magnetic moment in the quark-photon vertex, which can help capture the desirable features of form factors for low momentum transfer. The implications of introducing quark anomalous magnetic moment for the ρ -meson have been explored in [37–39], but this feature has not yet been

investigated in detail for AV mesons. This is one of the objectives of our study.

The article is organized as follows: In Sec. II, we outline the essential components required for the analysis within the CI model, including the dressed quark masses obtained by solving the gap equation. In Sec. III, we present the general expressions for the Bethe-Salpeter amplitudes (BSAs) of axial-vector mesons and their numerical results upon solving the corresponding Bethe-Salpeter equation (BSE). In Sec. IV, we examine the electromagnetic structure of AV mesons within the CI framework, define the symmetry-preserving quark-photon vertex, and emphasize the role of the anomalous magnetic moment contribution. We pay particular attention to the triangle diagram in the impulse approximation for the $M_\gamma M$ interaction, which constitutes the basic building block in the calculation of the elastic form factors of the mesons under study. The analytical and numerical results are provided in Secs. IVA and IVB, respectively. A concise summary and outlook for future research are presented in Sec. V. The Appendix tabulates mathematical expressions for the coefficients used in the computation of the electromagnetic form factors (EFFs).

II. THEORETICAL FOUNDATIONS OF THE CONTACT INTERACTION

In this section, we briefly review the essential aspects of the symmetry-preserving contact-interaction (CI) model [20], illustrated in Fig. 2, which provides the theoretical framework employed throughout this work. Although this discussion can be found in earlier works, it is useful to include it here to make the article self-contained. As a first step, we determine the gap equation of the model. To this end, we consider the dressed-quark propagator for a quark of flavor f , which satisfies

$$S^{-1}(p) = i\gamma \cdot p + m_f + \Sigma(p), \quad (1)$$

with the quark self-energy given by

$$\Sigma(p) = \frac{4}{3} \int \frac{d^4 q}{(2\pi)^4} g^2 D_{\mu\nu}(p-q) \gamma_\mu S(q) \Gamma_\nu(q,p), \quad (2)$$

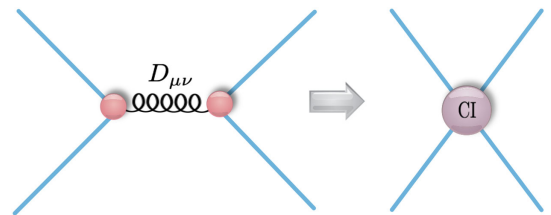


FIG. 2. Illustration of the CI framework. The left panel shows the full momentum-dependent gluon propagator, whereas the right panel displays the momentum-independent approximation defined in Eq. (3).

TABLE I. Ultraviolet regulator and coupling constant for different combinations of quarks in AV mesons. $\hat{\alpha}_{\text{IR}} = \hat{\alpha}_{\text{IRL}}/Z_H$, where $\hat{\alpha}_{\text{IRL}} = 4.57$. $\Lambda_{\text{IR}} = 0.24$ GeV is kept fixed.

	u, d, s	s	c, u	c, s	c	b, u	b, s	b, c	b
Z_H	1	1	0.590	0.912	1.401	13.686	0.592	30.972	1.426
Λ_{UV} [GeV]	1.215	1.580	2.791	3.895	7.270	9.378	11.688	12.610	13.876
$\hat{\alpha}_{\text{IR}}$ [GeV ⁻²]	4.57	4.57	7.74	5.01	3.26	0.33	7.72	0.15	3.20

where m_f is the current-quark mass, $D_{\mu\nu}(k)$ denotes the gluon propagator, and $\Gamma_\nu(q, p)$ is the quark-gluon interaction vertex. The defining feature of the CI model is the replacement of the dressed-gluon propagator by a momentum-independent vector $\times$ vector interaction,

$$g^2 D_{\mu\nu}(k) = 4\pi\hat{\alpha}_{\text{IR}}\delta_{\mu\nu}, \quad \hat{\alpha}_{\text{IR}} = \frac{\alpha_{\text{IR}}}{m_g^2}. \quad (3)$$

In this work, we use the standard value employed in the literature, i.e., $m_g = 500$ MeV, see Refs. [40–42], together with $\alpha_{\text{IR}}/\pi = 0.36$, yielding the value of $\hat{\alpha}_{\text{IR}}$. It is consistent with previous CI analyses [21–24,30]. Naturally, the physically relevant quantity is the effective interaction strength $\hat{\alpha}_{\text{IR}}$, rather than the individual parameters α_{IR} and m_g separately. All observables in the model depend on this combination together with the infrared and ultraviolet regulators. Infrared studies of QCD indicate that the Landau-gauge gluon propagator saturates at low momenta, dynamically generating an effective gluon mass scale and a finite infrared strong coupling [43–48]. Within this model, the quark-gluon vertex is approximated by its bare form,

$$\Gamma_\nu(q, p) = \gamma_\nu. \quad (4)$$

Therefore, the model should be considered as an effective infrared framework formulated in the Landau gauge rather than a fully gauge-covariant realization of QCD. More sophisticated gauge-covariant truncation schemes of the Schwinger–Dyson equations have been explored in Refs. [49,50]. In this CI model, the dressed-quark mass becomes momentum independent and satisfies

$$M_f = m_f + M_f \frac{4\hat{\alpha}_{\text{IR}}}{3\pi} \mathcal{C}(M_f^2), \quad (5)$$

where

TABLE II. Current (m_f) and dressed (M_f) quark masses employed as input in the Bethe-Salpeter equations and in the calculation of the electromagnetic form factors.

	u/d	s	c	b
Current mass m_f	0.007	0.170	1.080	3.920
Dressed mass M_f	0.367	0.530	1.520	4.750

$$\frac{\mathcal{C}(M^2)}{M^2} = \Gamma(-1, M^2\tau_{\text{UV}}^2) - \Gamma(-1, M^2\tau_{\text{IR}}^2), \quad (6)$$

with $\Gamma(\alpha, x)$ denoting the incomplete gamma function. Using the parameter sets listed in Tables I and II, we compute the masses and FF of AV mesons considered in this work. The parameters collected in Table I indicate that $\hat{\alpha}_{\text{IR}}$ varies with the mass scale Λ_{UV} , see Fig. 3, as described in Ref. [34]. It effectively captures the behavior of the effective strong coupling, which should decrease as the energy scale (Λ_{UV}) increases. Moreover, as quark masses grow, so does Λ_{UV} , representing the highest energy scale of the system under consideration. The red dashed-dotted curve in Fig. 3 serves as a guide for choosing Z_H to ensure a smaller effective $\hat{\alpha}_{\text{IR}}$ at higher Λ_{UV} . This strategy was adopted in several subsequent works [21,24,30,51,52]. For the AV mesons, which are the heaviest among all the mesons studied previously [25,27,53], these parameters have been adjusted according to the equation (a and k have appropriate dimensions in GeV units),

$$\frac{\hat{\alpha}_{\text{IR}}}{M_M^4} = ae^{-k\Lambda_{\text{UV}}}, \quad a = 4.50, \quad k = 1.06. \quad (7)$$

Nevertheless, the behavior of $\hat{\alpha}_{\text{IR}}$ and Λ_{UV} remains consistent with that observed in previous studies: the coupling diminishes (which is in keeping with the fact their electromagnetic sizes reduce), and the ultraviolet cutoff increases as the studied meson is heavier, meaning that the coupling constant and the ultraviolet regulator vary as a function of the meson mass. Table II presents the current quark masses m_f used here and the dynamically generated dressed masses M_f of u, s, c , and b computed from the gap equation, Eq. (5).¹ As a result of Eq. (5), the generated dressed-quark masses remain constant through the whole energy range. This behavior is shown in Fig. 4 where we compare the theoretical predictions from lattice-QCD [54,55] and the contact interaction approach. In addition, the dressed quark mass generated in the chiral limit is also presented. As can be seen in the figure, the masses computed with the CI model approach the running masses at $Q^2 \rightarrow 0$. This is the main reason to use it to estimate static properties such as masses and charge radii.

¹We assume isospin symmetry throughout this work.

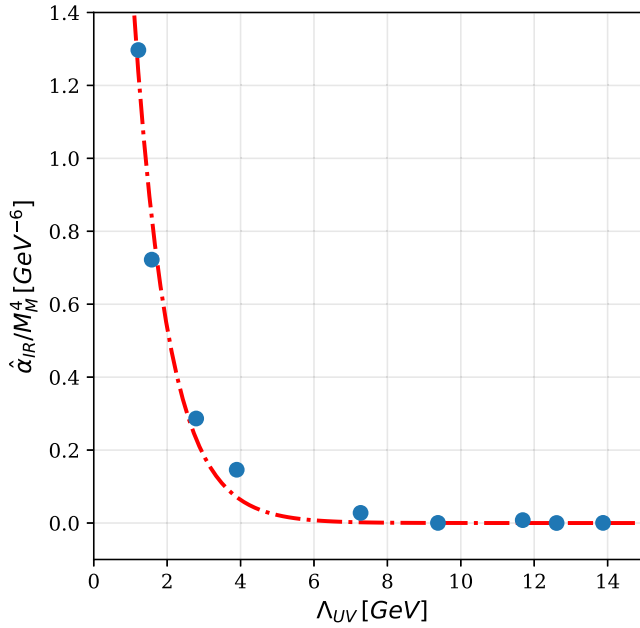


FIG. 3. The ratio of the effective coupling to the meson mass is shown as a function of the ultraviolet regulator. The data points correspond to the parameters listed in Table I, while the dashed line represents the fit described by Eq. (7).

In this work, we investigate light, heavy-light, and heavy AV mesons within the CI framework through the BSE presented in the next section. The interaction kernel is

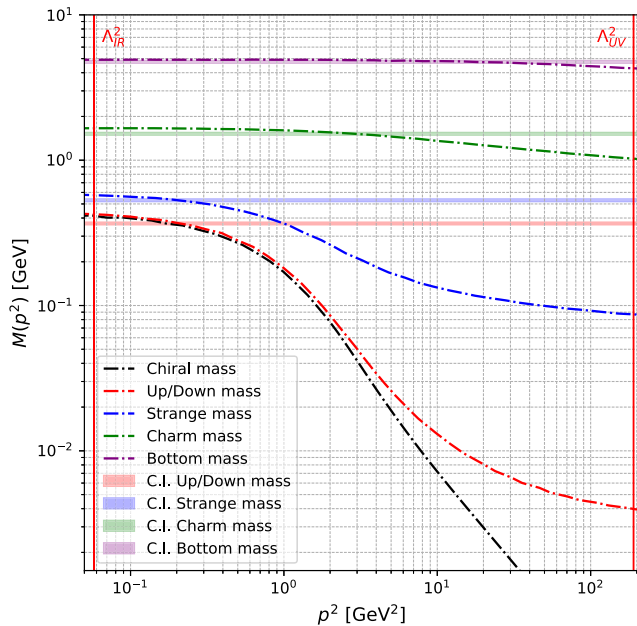


FIG. 4. Running dressed quark masses. Dot-dashed lines represents QCD-akin results for the Landau-gauge mass function, see, for example, [54,55], while horizontal lines are the constant quark masses generated through the CI approach. Λ_{UV} corresponds to the b -quark value in Table I.

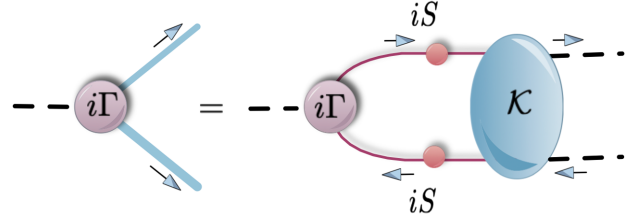


FIG. 5. Diagrammatic representation of the homogeneous BSE. The purple blob denotes the meson Bethe-Salpeter amplitude Γ , the solid black lines correspond to dressed quark propagators S , and the shaded green oval represents the dressed quark-antiquark interaction kernel $\mathcal{K}$.

constructed consistently with the gap equation, following the CI formulation of Refs. [25,27].

III. BETHE-SALPETER EQUATION

Mesons are quark-antiquark bound states described by the homogeneous BSE [56], illustrated in Fig. 5. Solving the BSE yields the masses and BSAs of the AV mesons,

$$[\Gamma(k; P)]_{tu} = \int \frac{d^4 q}{(2\pi)^4} [\chi(q; P)]_{sr} \mathcal{K}_{tu}^{rs}(q, k; P), \quad (8)$$

where $[\Gamma(k; P)]_{tu}$ represents the bound state's BSA, and $\chi(q; P) = S(q+P)\Gamma S(q)$ is the BS wave function; r, s, t, u represent color, flavor, and spinor indices; and $\mathcal{K}$ is the relevant quark-antiquark scattering kernel. This equation possesses solutions on that discrete set of P^2 values for which bound states exist.

The quantum numbers of AV mesons are $J^{PC} = 1^{++}$. Within the CI, the general Lorentz-Dirac structure of the AV BSA for a meson composed of quarks $f_1 \bar{f}_2$ is uniquely fixed to be

$$\Gamma_\mu^{AV}(P) = \gamma_5 \gamma_\mu^\perp E^{AV}(P), \quad (9)$$

with the transverse projector,

$$\gamma_\mu^\perp = \gamma_\mu - \frac{\gamma \cdot P}{P^2} P_\mu. \quad (10)$$

The γ_5 factor encodes the positive parity of AV mesons and distinguishes their BSA from that of vector (V) mesons, $\Gamma_\mu^V = \gamma_\mu^\perp E^V$, under a parity transformation. Recall that the bound-state solutions exist at discrete values $P^2 = -M_A^2$, where M_A is the AV meson mass. The resulting masses and BSA normalization constants E^{AV} are presented in Table III for all ten AV mesons investigated. The errors relative to experimental values are at the level of 1–11%, comparable in magnitude to those found for the V meson sector [25]. With all the essential elements of the CI framework now established, including the model parameters and the Bethe-Salpeter description of AV mesons, we proceed to

TABLE III. Calculated values of the BSAs and the masses of the AV mesons by using the parameters in Tables I and II (compare the parameters with the ones in Ref. [21]).

	Mass [GeV]	E_{AV}	m_{AV}^{exp} [GeV]	Error [%]
$a_1(u\bar{d})$	1.373	0.32	1.260	8.96
$K_1(u\bar{s})$	1.479	0.32	1.340	10.37
$f_1(s\bar{s})$	1.586	0.32	1.430	10.90
$D_1(c\bar{u})$	2.285	0.46	2.420	5.57
$D_{s1}(c\bar{s})$	2.427	0.35	2.460	1.34
$\chi_{c1}(c\bar{c})$	3.297	0.24	3.510	6.06
$B_1(u\bar{b})$	5.612	0.12	5.721	1.90
$B_{s1}(s\bar{b})$	5.583	0.50	5.830	4.23
$B_{cb}(c\bar{b})$	6.521	0.06	...	...
$\chi_{b1}(b\bar{b})$	9.608	0.16	9.892	2.87

investigate their electromagnetic form factors within a symmetry-preserving treatment.

IV. FORM FACTORS

Electromagnetic form factors (EFFs) encode essential information about the internal structure of mesons across different momentum scales. In the nonperturbative regime, they provide insight into confinement, dynamical chiral symmetry breaking, and the role of dressed quarks, while at large momentum transfer they are expected to approach the behavior dictated by perturbative QCD. In the intermediate region, EFFs interpolate smoothly between these two dynamical domains. Although the electromagnetic structure of vector mesons has been widely explored, analogous studies for axial-vector mesons remain comparatively limited. In this section, we investigate the EFFs of AV mesons within the CI framework. The interaction of an external photon with the quark constituents of the meson is described by the dressed quark-photon vertex, $\Gamma_\mu^\gamma(k_+, k_-, M_{f_1})$, which satisfies the vector Ward-Takahashi identity,

$$iP_\mu \Gamma_\mu^\gamma(k_+, k_-, M_{f_1}) = S^{-1}(k_+, M_{f_1}) - S^{-1}(k_-, M_{f_1}). \quad (11)$$

Preserving this identity is essential for a consistent description of meson electromagnetic properties. Within the CI framework, the quark-photon vertex is obtained from the inhomogeneous Bethe-Salpeter equation,

$$\Gamma_\mu^\gamma(Q, M_{f_1}) = \gamma_\mu - \frac{16\pi\hat{\alpha}_{\text{IR}}}{3} \int \frac{d^4 q}{(2\pi)^4} \gamma_\alpha \chi_\mu(q_+, q, M_{f_1}) \gamma_\alpha, \quad (12)$$

where

$$\chi_\mu(q_+, q, M_{f_1}) = S(q + P, M_{f_1}) \Gamma_\mu(Q) S(q, M_{f_1}). \quad (13)$$

Because the interaction kernel is momentum independent, the vertex admits the decomposition,

$$\Gamma_\mu^\gamma(Q, M_{f_1}) = \gamma_\mu^L(Q) P_L(Q^2, M_{f_1}) + \gamma_\mu^\perp(Q) P_T(Q^2, M_{f_1}), \quad (14)$$

with

$$\gamma_\mu = \gamma_\mu^L + \gamma_\mu^\perp, \quad (15)$$

and

$$\gamma_\mu^\perp(Q) = \gamma_\mu - \frac{\gamma \cdot Q}{Q^2} Q_\mu. \quad (16)$$

Substituting this form into Eq. (12) leads to

$$P_L(Q^2) = 1, \quad P_T(Q^2) = \frac{1}{1 + K_\gamma(Q^2, M_{f_1})}, \quad (17)$$

where

$$K_\gamma(Q^2, M_{f_1}) = \frac{4\hat{\alpha}_{\text{IR}}}{3\pi} \int_0^1 d\alpha \alpha(1-\alpha) Q^2 \bar{\mathcal{C}}_1(\omega), \quad (18)$$

with

$$\bar{\mathcal{C}}_1(z) = -\frac{d}{dz} \mathcal{C}(z) = \Gamma(0, z\tau_{\text{UV}}^2) - \Gamma(0, z\tau_{\text{IR}}^2), \quad (19)$$

and

$$\omega = M_{f_1}^2 + \alpha(1-\alpha)Q^2. \quad (20)$$

The behavior of the transverse dressing function $P_T(Q^2)$ is shown in Fig. 6. As expected, one finds $P_T(Q^2) \rightarrow 1$ in the ultraviolet region, recovering the perturbative bare vertex

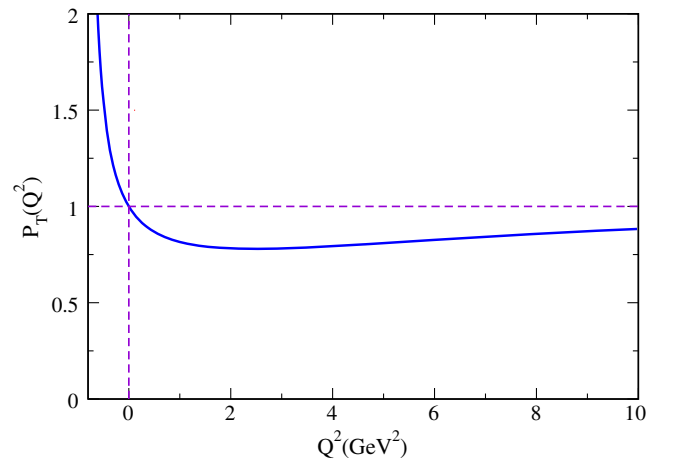


FIG. 6. Transverse dressing function $P_T(Q^2)$ of the quark-photon vertex defined in Eq. (17).

γ_μ . In addition to the longitudinal and transverse components, we incorporate an anomalous magnetic moment contribution into the quark-photon vertex following Ref. [12]. Similar constructions have been employed in previous analyses of spin-1 systems and CI studies of baryons [28,35–37]. The modified vertex is written as

$$\Gamma_\mu^\gamma(Q, M_{f_1}) = \gamma_\mu^\perp P_T(Q^2) + \frac{\xi_{f_1}}{2M_{f_1}} \sigma_{\mu\nu} Q^\nu \exp\left(-\frac{Q^2}{4M_{f_1}^2}\right). \quad (21)$$

Throughout this work, we employ $\xi_{f_1} = 0.5$. Previous studies have considered values ranging from 0.19 to 2/3 [35–37]. In the present framework, the parameter adjustments listed in Table I allow the same value of ξ_{f_1} to be used for both light- and heavy-quark sectors, although a possible flavor dependence cannot be excluded. The anomalous magnetic moment contribution has little impact on scalar and pseudoscalar mesons, but it affects the AV form factors more significantly. In particular, Ref. [28] reported sizable modifications in the magnetic and quadrupole moments of spin-1 systems when such contributions are included. Consequently, the vertex in Eq. (21) provides a more realistic description of the AV meson electromagnetic structure within the CI framework. It is important to emphasize that the CI model represents an effective infrared approximation to QCD. Although the interaction is momentum independent and therefore produces form factors that are typically harder than those obtained in full QCD, the framework successfully reproduces a broad range of hadron masses and static observables with reasonable accuracy. Its algebraic simplicity also makes it particularly useful for exploring the qualitative features of AV meson form factors. In the following subsections, we present the analytical expressions and numerical results for the AV meson electromagnetic form factors.

A. Analytical results

Let us begin with general considerations regarding the electromagnetic interactions of mesons. In the impulse approximation, the $M\gamma M$ vertex, which characterizes the interaction between an AV meson and a photon, is

$$\Lambda_{\mu\nu\lambda}^{AV,f_1} = N_c \int \frac{d^4\ell}{(2\pi)^4} \text{Tr} \mathcal{G}_{\mu\nu\lambda}^{AV,f_1}, \quad (22)$$

where

$$\begin{aligned} \mathcal{G}_{\mu\nu\lambda}^{AV,f_1} = & i\bar{\Gamma}_\mu^{AV}(k_f) S(\ell, M_{\bar{f}_2}) i\Gamma_\nu^{AV}(-k_i) S(\ell + k_i, M_{f_1}) \\ & \times i\Gamma_\lambda^\gamma(Q, M_{f_1}) S(\ell + k_f, M_{f_1}). \end{aligned} \quad (23)$$

The notation assumes that it is the quark f_1 which interacts with the photon while the antiquark $\bar{f}_2$ remains a spectator.

We define $\Lambda^{AV,\bar{f}_2}$ similarly. Furthermore, we denote the incoming photon momentum by Q and the incoming and outgoing momenta of M by $k_i = k - Q/2$ and $k_f = k + Q/2$, respectively. The explicit assignments of momenta flow are shown in the triangle diagram of Fig. 7.

$\Lambda^{AV,f}$ corresponds to the EFFs of different mesons under study. The contribution from the interaction of the photon with quark f_1 can be represented as $F^{AV,f_1}(Q^2)$ (stemming from Λ^{AV,f_1}) while the contribution arising from its interaction with quark $\bar{f}_2$ can be represented as $F^{AV,\bar{f}_2}(Q^2)$ (coming from $\Lambda^{AV,\bar{f}_2}$). The total form factor $F^{AV}(Q^2)$ is defined as follows [57]:

$$F^{AV}(Q^2) = e_{f_1} F^{AV,f_1}(Q^2) + e_{\bar{f}_2} F^{AV,\bar{f}_2}(Q^2), \quad (24)$$

where e_{f_1} and $e_{\bar{f}_2}$ are the quark and the antiquark electric charges, respectively.² For AV mesons, the form factor F^{AV,f_1} is straightforwardly related to the $M\gamma M$ vertex Λ^{AV,f_1} as follows:

$$\Lambda_{\lambda\mu\nu}^{AV,f_1} = \sum_{j=1}^3 T_{\lambda\mu\nu}^{(j)}(k, Q) F_j^{AV,f_1}(Q^2), \quad (25)$$

with the tensors $T_{\lambda\mu\nu}^{(j)}$ expressed as

$$T_{\lambda\mu\nu}^{(1)}(k, Q) = 2k_\lambda \mathcal{P}_{\mu\alpha}^T(k_i) \mathcal{P}_{\alpha\nu}^T(k_f), \quad (26)$$

$$\begin{aligned} T_{\lambda\mu\nu}^{(2)}(k, Q) = & \left[Q_\mu - k_{i\mu} \frac{Q^2}{2M_M^2} \right] \mathcal{P}_{\lambda\nu}^T(k_f) \\ & - \left[Q_\nu + k_{f\nu} \frac{Q^2}{2M_M^2} \right] \mathcal{P}_{\lambda\mu}^T(k_i), \end{aligned} \quad (27)$$

$$\begin{aligned} T_{\lambda\mu\nu}^{(3)}(k, Q) = & \frac{k_\lambda}{M_M^2} \left[Q_\mu - k_{i\mu} \frac{Q^2}{2M_M^2} \right] \\ & \times \left[Q_\nu + k_{f\nu} \frac{Q^2}{2M_M^2} \right]. \end{aligned} \quad (28)$$

The transverse projector in the above relations is given by the following expression:

$$\mathcal{P}_{\alpha\beta}^T(P) = \delta_{\alpha\beta} - \frac{P_\alpha P_\beta}{P^2}. \quad (29)$$

An axial-vector meson has spin-1 and positive parity. A parity transformation, relating vector and axial-vector mesons, flips the direction of a particle's motion relative to the direction of its spin. Despite the fact that axial-vector mesons are the least experimentally and

²For neutral mesons composed of same flavored quarks, the total EFF is simply $F^{AV} = F^{AV,f_1}$.

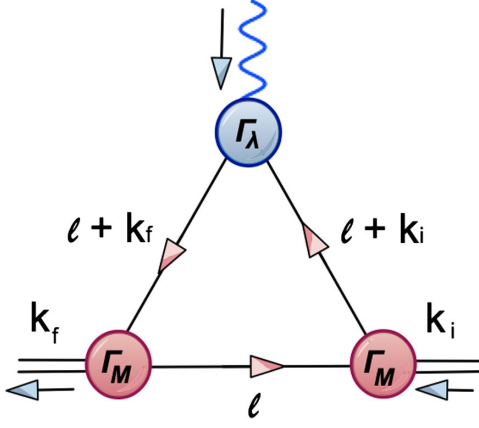


FIG. 7. The triangle diagram for the impulse approximation to the $M\gamma M$ vertex.

phenomenologically studied and constrained, one benefit of the model examined here is its applicability to these puzzling particles. Similarly to vector mesons [25], axial-vector mesons contains three F_i^{AV,f_1} components. By applying projector operators, we find these components,

$$F_i^{AV,f_1}(Q^2) = \frac{3}{4\pi^2} (E^{AV})^2 \int_0^1 d\alpha d\beta \alpha \times [\mathcal{A}_i^{AV} \bar{C}_1(\omega_2) + (\mathcal{B}_i^{AV} - \mathcal{A}_i^{AV} \omega_2) \bar{C}_2(\omega_2)], \quad (30)$$

where the label $i = 1, 2, 3$ corresponds to the three FFs. Moreover, $\mathcal{A}_i^{AV}$ and $\mathcal{B}_i^{AV}$ are tabulated explicitly in the Appendix. Therefore, electric, magnetic, and quadrupole FFs for AV mesons are defined analogously to V mesons in terms of F_1 , F_2 , and F_3 as follows:

$$G_E^{AV}(Q^2) = F_1^{AV}(Q^2) + \frac{2}{3} \eta G_Q^{AV}(Q^2), \quad (31a)$$

$$G_M^{AV}(Q^2) = -F_2^{AV}(Q^2), \quad (31b)$$

$$G_Q^{AV}(Q^2) = F_1^{AV}(Q^2) + F_2^{AV}(Q^2) + [1 + \eta] F_3^{AV}(Q^2), \quad (31c)$$

where $\eta = Q^2/(4M_M^2)$ with M_M being the mass of the AV meson. The values corresponding to the charge, magnetic, and quadrupole moments of the AV meson are defined at $Q^2 = 0$ as

$$G_E^{AV}(Q^2 = 0) = e_{AV}, \quad (32a)$$

$$G_M^{AV}(Q^2 = 0) = \mu_{AV}, \quad (32b)$$

$$G_Q^{AV}(Q^2 = 0) = \mathcal{Q}_{AV}. \quad (32c)$$

Once the preliminaries are established, we can proceed with the explicit and computationally intensive numerical evaluation of the form factors.

B. Numerical results

The predictions of this model for the electric, magnetic, and quadrupole FFs for AV mesons are displayed in Fig. 8. We find that the electric form factors of charged mesons decrease more rapidly for lighter mesons in the vicinity of $Q^2 = 0$, an analogous behavior found for V mesons in Ref. [25]. It occurs similarly for flavor-singlet mesons, and for neutral mesons, the heavier meson increases more rapidly. This observation will be more explicit and physically significant when we compute the charge radii. Moreover, let us recall that for electric form factors the model predicts that the crossing into negative values occurs for the lightest V mesons at around $Q^2 \sim 6 \text{ GeV}^2$.

In Table IV, we present the locations of the zeros in $G_{AV}^E(Q^2)$ in terms of $x = Q^2/M_M^2$. It is noteworthy that the point at which $G^E(Q^2)$ crosses zero shifts by approximately 23%, 32%, 40% to lower values for axial-vector mesons as compared to their vector counterparts. It is due to the fact that we draw the form factors as a function of $x = Q^2/M_M^2$, where M_M is the meson mass. As axial-vector mesons are heavier than their vector counterparts, there is a lower value of x where the corresponding form factors cross zero. Therefore, the zero crossing is governed by the mass generating mechanism which is largely due to dynamical chiral symmetry breaking for light quarks.

Experimental data from JLab suggest that the proton's electric FF might pass through zero at $x \sim 10$ [58–62]. It has been suggested that the likelihood of a zero in the proton elastic electric form factor is 50% for $Q^2 \leq 10.37 \text{ GeV}^2$, and this probability rises to 99.99% for $Q^2 \leq 13.06 \text{ GeV}^2$ [63]. Since the dynamical reasons for the potential appearance of a zero is not expected to be dissimilar in both cases, analyses of $G_V^E(Q^2)$ and $G_{AV}^E(Q^2)$ may provide us with qualitative guidance on the possible appearance and location of a zero in proton's EFF. The magnetic form factors exhibit a distinct variation compared to their respective electric form factors. Near $Q^2 = 0$, the reduction occurs more rapidly for heavier charged and flavor-singlet mesons, whereas for neutral heavier mesons, the increase is more gradual. This behavior is consistent with what has been observed for vector mesons in Ref. [25].

Identifying a clear pattern for the quadrupole form factors for AV mesons is challenging, particularly in their behavior as $Q^2 \rightarrow 0$. This contrasts with the V mesons, which consistently tend in the same direction for small exchanged momentum squared [25]. We examined the sensitivity of the results to slight variations in the choice of parameters, but the overall trend of the form factors remains unchanged. In Fig. 9, we introduce a 5% variation in the

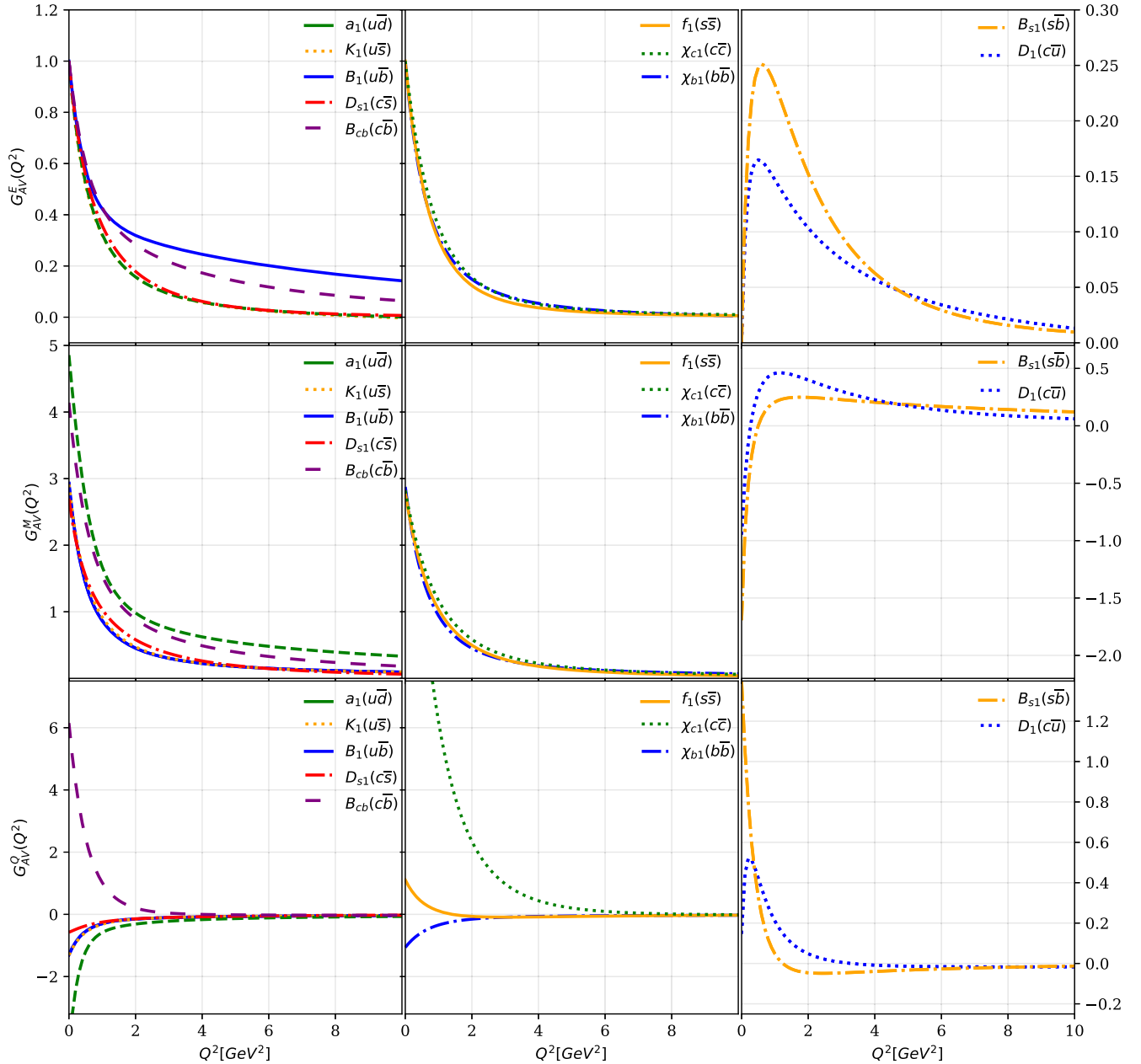


FIG. 8. Electric, magnetic, and quadrupole FFs of AV mesons are displayed in the top, middle, and bottom rows, respectively. A logarithmic scale is displayed in some plots in FFs to distinguish the differences. FFs are depicted on the left, center, and right columns for charged AV mesons composed of different quarks, neutral AV mesons composed of same flavored quarks, and for charged AV mesons, respectively.

charge radius derived from the electric form factors through modifying a single parameter, τ_{uv} . We focus on the electric form factor, as it is the most likely of the three to be determined experimentally, if at all. We then analyze how this variation propagates into the other two form factors across the entire range of Q^2 where calculations have been performed. See all the plots in Fig. 9 for a comprehensive comparison. In the future, it will be valuable to move beyond the CI approach by incorporating algebraic models or a full Schwinger–Dyson equations analysis. This would

allow for more definitive statements on the detailed behavior of these form factors.

TABLE IV. Comparison of the points where the elastic form factors cross zero for light V and AV mesons.

AV	$G^E(Q^2) = 0$	V	$G^E(Q^2) = 0$
$a_1(u\bar{d})$	$x = 4.97$	$\rho(u\bar{d})$	$x = 6.35$
$K_1(u\bar{s})$	$x = 4.65$	$K^*(u\bar{s})$	$x = 6.65$
$f_1(s\bar{s})$	$x = 4.71$	$\phi(s\bar{s})$	$x = 7.59$

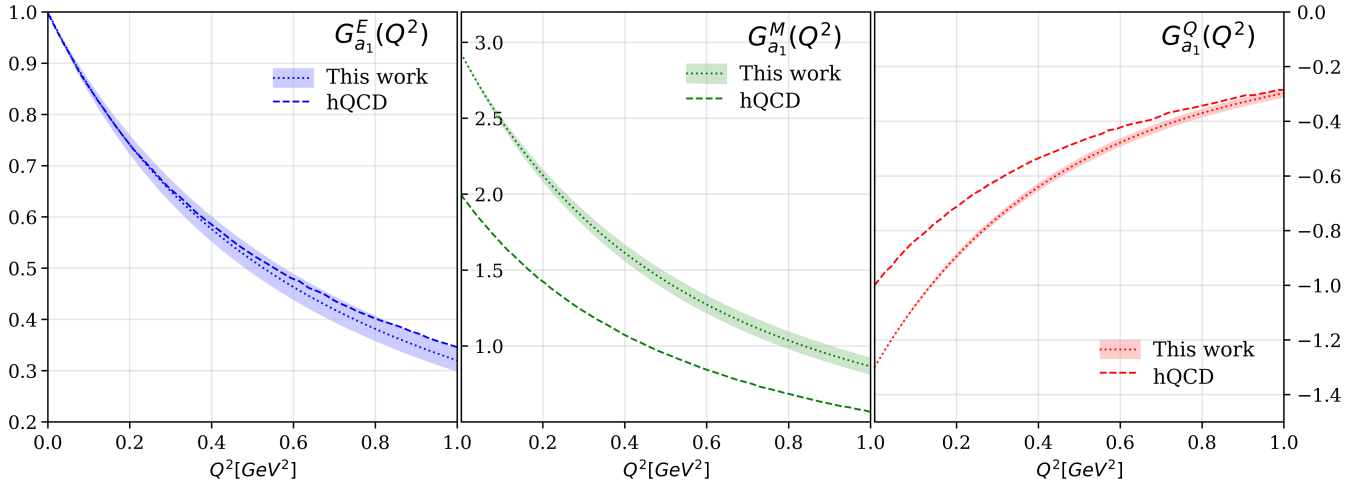


FIG. 9. Electromagnetic (blue), magnetic (green), and quadrupole (red) FFs for a_1 meson. The central curve in each case is obtained using the τ_{UV} value from Table I. The width of the band represents a 5% variation in the charge radius. The meson life is so short that it is challenging to carry out experimental measurements of its EFFs. The graph illustrates a comparison between our results and those obtained using holographic QCD (hQCD) [33].

In particular, the results for the elastic form factors of the a_1 meson are readily comparable to those obtained using holographic QCD (hQCD) [33]. The agreement is particularly striking for the electric form factor. Following the ideas presented for V mesons, we fit electric, magnetic, and quadrupole FFs to the following relations:

$$G_E^{AV} = \frac{e_{AV} + a_{AV}^E Q^2 + b_{AV}^E Q^4}{1 + c_{AV}^E Q^2 + d_{AV}^E Q^4},$$

$$G_M^{AV} = \frac{\mu_{AV} + a_{AV}^M Q^2 + b_{AV}^M Q^4}{1 + c_{AV}^M Q^2 + d_{AV}^M Q^4},$$

$$G_Q^{AV} = \frac{Q_{AV} + a_{AV}^Q Q^2 + b_{AV}^Q Q^4}{1 + c_{AV}^Q Q^2 + d_{AV}^Q Q^4}.$$

We show the values of the coefficients in Table V. We notice that most b_{AV}^i coefficients, where $i \in \{E, M, Q\}$, are negligibly smaller than d_{AV}^i , preserving the observed $1/Q^2$

behavior for the corresponding AV mesons except for those for which $a_{AV}^i \rightarrow 0$ too, leading to an observed $1/Q^4$ fall. The corresponding radii can be calculated as

$$r_i^2 = -6 \frac{dG_i(Q^2)}{dQ^2} \Big|_{Q^2=0}, \quad (33)$$

where $i \in \{E, M, Q\}$. We caution that positive slopes appear in some EFFs; in those cases, the definition for charge radii squared is opted to remove the minus sign in the equation to avoid imaginary numbers. We display our detailed results for the charge, magnetic, and quadrupole radii in Table VI, where we also include the corresponding moments, compared with other approaches [32,33,64–67]. To further assess the robustness of the present framework, we performed sensitivity analyses under $\pm 5\%$ variations of both Z_H and the ultraviolet regulator Λ_{UV} . Overall, the observables exhibit a relatively mild dependence on these parameters. In particular, the axial-vector meson masses

TABLE V. Parameters for the fits in Eq. (33), for the electric magnetic and quadrupole AV FFs. The form factors for which $b_{AV}^i \rightarrow 0$ exhibit a $1/Q^2$ behavior for large values of Q^2 , with the exception of those for which $a_{AV}^i \rightarrow 0$ also, depicting a $1/Q^4$ behavior.

	a_{AV}^E	b_{AV}^E	c_{AV}^E	d_{AV}^E	a_{AV}^M	b_{AV}^M	c_{AV}^M	d_{AV}^M	a_{AV}^Q	b_{AV}^Q	c_{AV}^Q	d_{AV}^Q
$u\bar{d}$	0.196	-0.033	1.817	0.833	-0.128	0.102	1.200	0.999	-0.170	-0.064	1.999	1.992
$u\bar{s}$	0.246	-0.035	1.762	0.998	0.056	0.072	1.200	0.999	-0.256	-0.050	1.999	1.999
$s\bar{s}$	0.155	-0.021	1.634	0.995	0.118	0.037	1.200	0.998	-0.054	-0.019	1.232	1.132
$c\bar{u}$	0.192	-0.004	-1.294	0.999	1.000	-0.027	0.330	0.629	-1.058	0.042	1.999	1.999
$c\bar{s}$	-0.081	0.001	1.254	0.320	-0.023	0.001	1.200	0.298	-0.061	0.001	1.242	0.309
$u\bar{b}$	-0.010	0.000	0.637	-0.001	0.999	-0.001	1.199	0.394	-0.816	-0.002	1.999	1.999
$s\bar{b}$	0.001	0.000	-0.350	0.031	0.787	-0.003	-0.655	0.534	-0.051	0.000	0.885	0.106
$c\bar{b}$	0.000	0.000	0.919	0.055	0.249	0.000	1.199	0.245	-1.325	0.004	1.945	1.999
$c\bar{c}$	-0.048	0.000	1.151	0.992	0.025	0.000	1.020	0.678	-0.801	0.014	-1.099	1.797
$b\bar{b}$	-0.020	0.000	1.012	0.636	0.225	0.000	0.887	0.698	-1.894	0.005	1.720	1.999

TABLE VI. Charge radii, magnetic, and quadrupole radii (all in fermi) and moments of AV mesons. In the columns corresponding to the magnetic and quadrupole moments, two sets of values are presented: one that incorporates the quark's anomalous magnetic moment (columns five and seven) and another that omits it (columns six and eight, respectively). The last three columns with the subscript “o” indicate the values obtained from other models, that is, holographic QCD [33], light cone sum rules method [32,64,65], a bag model [66], and the basis light front quantization (BLFQ) approach [67].

	r^E	r^M	r^Q	μ		$\mathcal{Q}$		r_o^E	μ_o	$\mathcal{Q}_o$
$u\bar{d}$	0.618	1.088	0.772	2.92	2.15	-1.29	-0.52	0.62 [33]	3.8 [64]	-0.90 [64]
$u\bar{s}$	0.600	1.038	0.753	2.91	2.19	-1.31	-0.45	0.62 [33]	0.28 [64]	-0.008 [64]
$s\bar{s}$	0.594	0.972	0.571	2.87	2.11	-1.06	-0.30	...	...	...
$c\bar{u}$	0.593	1.196	0.946	-0.94	-1.35	1.39	-0.01	0.28 [33]	0.90 [32]	-0.60 [32]
$c\bar{s}$	0.581	0.946	0.330	2.70	2.09	-0.57	0.22	0.32 [33]	0.87 [32]	-0.59 [32]
$c\bar{c}$	0.572	0.877	0.714	2.79	2.05	1.10	1.84	0.27 [67]	...	...
$u\bar{b}$	0.555	1.135	1.769	4.85	6.02	-4.34	0.35	...	0.60 [32]	-0.78 [32]
$s\bar{b}$	0.543	1.531	1.023	-1.69	-2.09	0.14	-1.54	...	0.13 [32]	-0.10 [32]
$c\bar{b}$	0.534	1.113	1.644	4.14	3.50	6.14	7.87	...	-0.47 [65]	...
$b\bar{b}$	0.519	0.807	2.260	2.81	2.07	18.53	19.28	0.16 [67]	...	...

remain remarkably stable, displaying variations below approximately 0.4% under changes in Z_H , and even smaller variations under changes in Λ_{UV} . The magnetic moments and electromagnetic radii also show only minor variations, typically at the level of one percent or less. Larger relative variations observed in some quadrupole observables are mainly associated with the smallness of their corresponding central values, which naturally enhances the percentage variation. These results indicate that the main physical conclusions of the present work are robust against moderate variations of both Z_H and Λ_{UV} within the nonperturbative regime considered here.

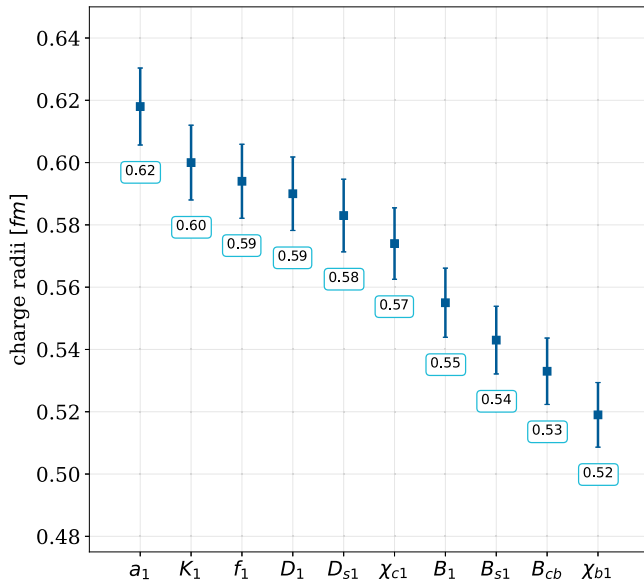


FIG. 10. Charge radii of ground state AV mesons in the CI computed using Eq. (33). It is clear from this plot that the radii tend to decrease as the dressed quark masses increase. This significant behavior is addressed in Sec. V.

In columns five and seven, we have incorporated the term associated with the anomalous magnetic moment in our calculations with the modified quark-photon vertex from Eq. (21), whereas in columns six and eight, this term has been omitted. The absolute values of the magnetic and quadrupole moments are generally larger for most AV mesons when the anomalous magnetic term is included. Our results show that the inclusion of this factor in the photon-quark vertex increases the meson magnetic moment by a minimum of 18% for the f_1 meson and by a maximum of 36% for the B_{cb} meson. The enhancement in the quadrupole moment is even more pronounced when this vertex is incorporated. The results from the model presented here reveal a clear inverse correlation between the meson mass and its charge radius: the heavier the meson, the smaller its charge radius, see Fig. 10. In addition to the hierarchy within mesons of the same type in Table VII, we also present the charge radii for PS, S, V, and AV mesons. It is readily noticeable that the AV exhibit the largest radii. The greatest difference between the charge radii of V and

TABLE VII. Charge radii (in fermi) of PS, S, and V mesons, obtained in Refs. [25,26], compared with the ones of AV mesons obtained herein. The last column shows the percentage difference between the radii of the V and AV mesons.

	PS	S	V	AV	Diff. (%)
$u\bar{d}$	0.45	0.55	0.56	0.62	10
$u\bar{s}$	0.42	0.54	0.54	0.60	12
$s\bar{s}$	0.36	0.50	0.47	0.59	26
$c\bar{u}$	0.36	0.47	0.42	0.59	40
$c\bar{s}$	0.26	0.44	0.37	0.58	58
$c\bar{c}$	0.20	0.43	0.35	0.57	63
$u\bar{b}$	0.34	0.42	0.34	0.56	66
$s\bar{b}$	0.24	0.41	0.30	0.54	81
$c\bar{b}$	0.17	0.40	0.29	0.53	84
$b\bar{b}$	0.07	0.39	0.28	0.52	86

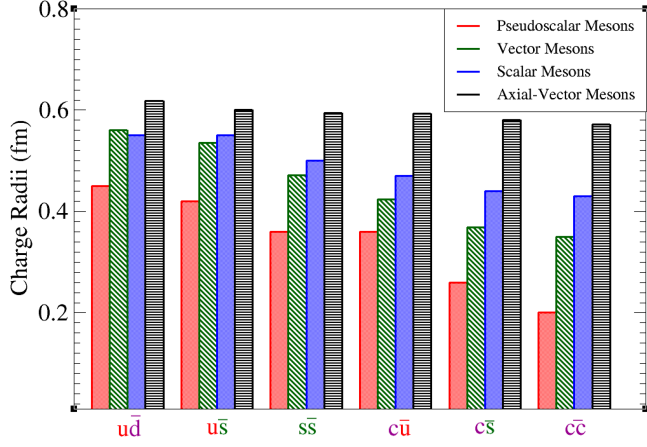


FIG. 11. Charge radii for PS, V, S, and AV mesons composed of u , d , s , and c quarks. The results for the charge radii of V mesons are taken from [25], and those for S and PS mesons are from [26], using the same formalism employed here for the AV mesons.

AV mesons is found for the Υ and χ_{b1} mesons, with an 86% disparity, while the smallest difference occurs for the ρ and a_1 mesons, with a mere 10% deviation. This behavior is easily observed in Figs. 11 and 12 for the various mesons composed of u , d , s , c , and b quarks.

Finally, in Table VIII, we also present a comparison of the magnetic and quadrupole moments for V and AV mesons, including the ratio between these two moments. It is noticeable that the lighter V mesons are closer to the value of $\mu/Q = -2$ expected of *structureless* V mesons [25,68]. For AV mesons, the a_1 meson has a value $\mu/Q = -2.26$ which differs by 13% from the value of -2 . It is straightforward to observe that the value found for the a_1 meson is closer to -2 than that for the ρ meson.

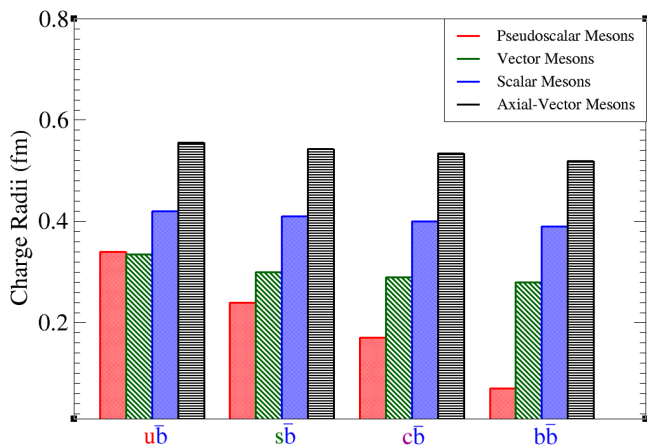


FIG. 12. Charge radii for PS, V, S, and AV mesons composed of u , s , c , and b quarks. The results for the charge radii of V mesons are taken from [25], and those for S and PS mesons are from [26], using the same formalism employed here for the AV mesons.

TABLE VIII. Magnetic and quadrupole moments of V and AV mesons. Columns six and seven display the ratio between the magnetic and quadrupole moments. The only AV mesons that exhibit a sign change in their quadrupole moment compared to their V counterparts are the χ_{c1} , B_{cb} , and χ_{b1} mesons.

	μ		Q		μ/Q	
	V	AV	V	AV	V	AV
$u\bar{d}$	2.11	2.92	-0.85	-1.29	-2.48	-2.26
$u\bar{s}$	2.18	2.91	-0.90	-1.31	-2.42	-2.22
$s\bar{s}$	2.09	2.87	-0.83	-1.06	-2.51	-2.70
$c\bar{u}$	-1.51	-0.94	1.05	1.39	-1.43	-0.67
$c\bar{s}$	2.10	2.70	-0.71	-0.57	-2.95	-4.73
$c\bar{c}$	2.03	2.79	-0.70	1.10	-2.90	2.53
$u\bar{b}$	3.80	4.85	-2.06	-4.34	-1.84	-1.11
$s\bar{b}$	-1.82	-1.69	1.20	0.14	-1.51	-12.07
$c\bar{b}$	2.95	4.14	-1.37	6.14	-2.15	0.67
$b\bar{b}$	2.01	2.81	-0.69	18.53	-2.91	0.15

V. SUMMARY AND PERSPECTIVE

In this work, we have presented, to the best of our knowledge, the first comprehensive study of the elastic EFFs of AV mesons within a symmetry-preserving CI framework. By computing their electric, magnetic, and quadrupole FFs, together with the associated charge radii and electromagnetic moments, we have provided a unified description of ten axial-vector mesons spanning the light-, heavy-light-, and heavy-quark sectors. The present analysis should be understood in the context of an effective symmetry-preserving infrared model formulated in the Landau gauge, rather than as a fully gauge-covariant realization of QCD. Within this framework, the physically relevant quantity is the effective interaction strength $\hat{\alpha}_{\text{IR}}$, together with the infrared and ultraviolet regulators, rather than the individual model parameters separately. Although the CI does not fully mimic exact QCD-akin momentum dependence of the Green functions, it provides a simple and phenomenologically successful description of a broad class of hadronic observables. Moreover, the detailed sensitivity analyses performed in the present work indicate that the main predictions remain robust under moderate variations of the model parameters within the nonperturbative regime considered here. Within this context, our analysis leads to the following main findings:

- (i) We calculate the electric, magnetic, and quadrupolar form factors for the AV mesons. The results are presented in Fig. 8. In the CI, the three form factors exhibit a $1/Q^2$ behavior at large values of Q^2 , except for a few with $1/Q^4$ fall-off.
- (ii) In the case of the lightest AV meson, allowing for a 5% variation in the charge radius, we compare it with the results obtained using hQCD [33], finding good agreement between the two.

- (iii) We present the fits for all the elastic form factors of the AV mesons in Eq. (33), using the parameters provided in Table V.
- (iv) We compute the charge, magnetic, and quadrupole radii, along with the corresponding moments, which are presented in Table VI. These results are compared with those obtained using holographic QCD [33], light-cone sum rules [32,64,65], a bag model [66], and the basis light front quantization (BLFQ) approach [67].
- (v) We have introduced a term that incorporates the anomalous magnetic moment in the quark-photon vertex of Eq. (21), leading to an increase of 18% to 30% in the magnetic moments, which is in good agreement with the results obtained in [28] for AV diquarks. This is presented in Table VI, where we compare the results with and without the inclusion of this term.
- (vi) Our results for the charge radii show good agreement with the hierarchy observed for PS, V, and S mesons, where

$$\begin{aligned}
 r_{u\bar{d}} &> r_{u\bar{s}} > r_{c\bar{u}} > r_{u\bar{b}}, \\
 r_{u\bar{s}} &> r_{s\bar{s}} > r_{c\bar{s}} > r_{s\bar{b}}, \\
 r_{c\bar{u}} &> r_{c\bar{s}} > r_{c\bar{c}} > r_{c\bar{b}}, \\
 r_{u\bar{u}} &> r_{s\bar{s}} > r_{c\bar{c}} > r_{b\bar{b}}.
 \end{aligned}$$

This behavior is also graphically shown in Fig. 10.

- (vii) Our analysis also demonstrates that within the CI the charge radii of AV mesons are the largest compared to those of other types of mesons, as shown in Figs. 11, 12, and Table VII,

$$r_{AV}^E > r_S^E > r_V^E > r_{PS}^E.$$

Masses of the AV mesons are also the largest [22].

- (viii) We compare the magnetic and quadrupole moments of V and AV mesons in Table VIII, where we also present the ratio between these two values. It is well known that for structureless spin-1 mesons this ratio should be equal to -2 [68]. For the lightest AV meson, this value is -2.26 , differing from -2 by 13%, which is closer than the result obtained for the ρ -meson.
- (ix) The work presented here also highlights the location at which the electric form factor crosses zero, comparing them with those of the V mesons in Table IV. We emphasize that the zero-crossing point of the G^E decreases for AV mesons compared to their V counterparts.

This study on the elastic form factors of axial-vector mesons marks the culmination of an extensive investigation into the elastic form factors of pseudoscalar and scalar mesons [26,27], as well as vector (V) mesons [25], all

composed of both heavy and light quarks. Additionally, it paves the way for future research into these form factors, either through more sophisticated algebraic models or a QCD-inspired analysis based on the Schwinger-Dyson and Bethe-Salpeter equations.

We acknowledge the need for experimental insights to explore the key characteristics of axial-vector meson form factors. Currently, valuable data from electron-positron colliders provide crucial information on processes such as $e^+e^- \rightarrow e^+e^-f_1$, $e^+e^- \rightarrow \pi^+\pi^-f_1$. These results impose stringent constraints on the high-energy behavior of these reactions, enabling the determination of the couplings associated with the corresponding transition form factors. However, the direct measurement of electromagnetic form factors is likely to remain an elusive challenge for the foreseeable future.

Our calculation represents an initial step toward computing the electromagnetic and transition form factors of baryons within the contact interaction model. The results presented here for axial-vector mesons are directly connected to those of vector diquarks. These diquarks play a crucial role in the calculation of baryon form factors within the quark-diquark framework, a key area of investigation for major laboratories. Therefore, baryon studies in experiments can provide us with indirect probe to investigate the electromagnetic form factors of axial-vector mesons.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX: FORM FACTOR FORMULAS

In this appendix, we provide the analytic expressions for all coefficients required to determine the axial-vector

electromagnetic form factors (EFFs) within the contact interaction (CI) model. In order to add the anomalous magnetic moment piece to the quark-photon vertex in an adequate manner, which probes the electromagnetic form factors of the axial-vector mesons through the interaction $M_{AV}\gamma M_{AV}$, we define

$$\zeta_{f_1} = \frac{\xi_{f_1}}{2M_{f_1}} \exp\left(-\frac{Q^2}{4M_{f_1}^2}\right), \quad (\text{A1})$$

and find the expressions,

$$\mathcal{A}_i^{AV} = \mathcal{A}_i^P P_T(Q^2) + \mathcal{A}_i \zeta_{f_1}, \quad (\text{A2})$$

$$\mathcal{B}_i^{AV} = \mathcal{B}_i^P P_T(Q^2) + \mathcal{B}_i \zeta_{f_1}, \quad (\text{A3})$$

where $\mathcal{A}_1 = \mathcal{A}_3 = 0$, $\mathcal{A}_2 = -4M_{f_1}$,

$$\begin{aligned} \mathcal{A}_1^P &= 2 - \alpha, & \mathcal{A}_2^P &= -2 - 2\alpha(1 - \beta), \\ \mathcal{A}_3^P &= \frac{4\alpha(1 - 2\beta)M_M^2}{Q^2 + 4M_M^2}, \end{aligned}$$

with

$$\begin{aligned} \mathcal{B}_1^P &= 2(\alpha M_{f_1}^2 - 2(1 - \alpha)M_{f_1}M_{\bar{f}_2} + (1 - \alpha)^2\alpha M_M^2 - (2 - \alpha)(1 - \beta)\alpha^2\beta Q^2), \\ \mathcal{B}_2^P &= 4(M_{f_1}M_{\bar{f}_2} - \alpha(1 - \beta)M_{f_1}^2 + (1 - \beta)^2\alpha^3\beta Q^2 - (1 - \alpha)(\alpha + (1 - \alpha)\beta)\alpha M_M^2), \\ \mathcal{B}_3^P &= \frac{8\alpha M_M^2}{4M_M^2 + Q^2}[(1 - 2\beta)M_{f_1}^2 + (1 - \beta)(2 - \alpha(3 - 2\beta))\alpha\beta Q^2 - (1 - \alpha)(1 - 2\beta - \alpha(1 + 6\beta - 8\beta^2))M_M^2], \end{aligned}$$

and

$$\begin{aligned} \mathcal{B}_1 &= 2(\alpha M_{f_1} - (1 - \alpha)M_{\bar{f}_2})Q^2, \\ \mathcal{B}_2 &= 4(M_{f_1}^2 M_{\bar{f}_2} + (1 - \alpha)^2 M_{\bar{f}_2} M_M^2 - 2(1 - \alpha)\alpha M_{f_1} M_M^2 - \alpha(M_{\bar{f}_2} - \alpha M_{f_1} + \alpha(-1 + \beta)M_{\bar{f}_2})(1 - \beta)Q^2), \\ \mathcal{B}_3 &= \frac{8M_M^2(\alpha M_{f_1} - (1 - \alpha)M_{\bar{f}_2})}{4M_M^2 + Q^2}(4(1 - \alpha)M_M^2 + (1 - 2\alpha(1 - \beta))Q^2). \end{aligned} \quad (\text{A4})$$

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