Charge form factor of π and K mesons

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The charge form factor of π and K mesons is evaluated adopting a relativistic constituent quark model based on the light-front formalism. The relevance of the high-momentum components of the meson wave function, for values of the momentum transfer accessible to CEBAF energies, is illustrated. The predictions for the elastic form factor of π and K mesons are compared with the results of different relativistic approaches, showing that the measurements of the pion and kaon form factors planned at CEBAF could provide information for discriminating among various models of the meson structure. [S0556-2821(96)05911-5]

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The evaluation of the electromagnetic (em) properties of π and K mesons has recently received a renewed interest, because measurements of the pion and kaon charge form factors are planned at the Continuous Electron Beam Accelerator Facility (CEBAF) [1]. In the past few years, light-front constituent quark models have been extensively applied to relativistic calculations of various electroweak properties of mesons [2–5] and baryons [6,7]. In most of these applications [4–6] it is assumed that (i) the hadron wave function is given by a harmonic oscillator (HO) ansatz, which is expected to describe the effects of the confinement scale only, or has a power-law (PL) behavior, dictated at large momenta by the perturbative QCD theory [8], and (ii) the constituent quarks are pointlike objects as far as their em properties are concerned. In Ref. [2] a different approach is adopted: namely, (i) a light-front mass operator, constructed from the effective $q\bar{q}$ Hamiltonian of Ref. [9] reproducing the meson mass spectra, is considered and the corresponding eigenfunctions are used to describe the dynamics of the constituent quarks inside the meson and (ii) a nonvanishing size of the constituent quarks is assumed and a simple monopole charge form factor for the constituent quarks is introduced. Within this approach existing pion data both at low and high values of the squared four-momentum transfer Q^2 are reproduced. Moreover, it has been shown that the high-momentum components, generated in the wave function by the one-gluon-exchange (OGE) part of the effective $q\bar{q}$ interaction of Ref. [9], sharply affect the pion charge form factor for values of Q^2 up to few $(\mathrm{GeV}/c)^2$, i.e., in a range of values accessible to CEBAF energies. Differently, in Ref. [4] it has been claimed that the charge form factor of pseudoscalar mesons is insensitive to a large class of wave functions, and, moreover, that the high-momentum tail of the wave function does not matter for energies accessible to present experiments. The aim of this Brief Report are (i) to point out that our wave functions do not belong to the limited class of wave functions considered in [4], and (ii) to clarify the relevance of the high-momentum components of the meson wave function, particularly for values of $Q^2\sim$ few $(\mathrm{GeV}/c)^2$, by analyzing in detail the structure of the expression of the pion form factor used in Refs. [2] and [4]. Moreover, our theoretical predictions for the elastic form factor of π^+, K^+, and K^0 mesons are compared with the results obtained within different sophisticated relativistic approaches, showing that the measurements of the pion and kaon form factors planned at CEBAF [1] could provide information for discriminating among various models of the meson structure.

The general expression of the charge form factor of a pseudoscalar meson, $F^P(Q^2)$, obtained within the light-front constituent quark model (see, e.g., Ref. [2]), is

$$F^P(Q^2)=e_q f^q(Q^2)H^P(Q^2;m_q,m_{\bar{q}})+e_{\bar{q}}f^{\bar{q}}(Q^2)H^P(Q^2;m_{\bar{q}},m_q), \tag{1}$$

where e_q (m_q) is the charge (mass) of the constituent quark and $f^q(Q^2)$ its charge form factor. In Eq. (1) the body form factor $H^P(Q^2;m_1,m_2)$ is given explicitly by

$$H^P(Q^2;m_1,m_2)=\int d\vec{k}_\perp d\xi \frac{\sqrt{M_0M_0'}}{4\xi(1-\xi)} \times\sqrt{\left[1-\left(\frac{m_1^2-m_2^2}{M_0^2}\right)^2\right]\left[1-\left(\frac{m_1^2-m_2^2}{M_0'^2}\right)^2\right]}\frac{w^P(k^2)w^P(k'^2)}{4\pi} \times\frac{\xi(1-\xi)[M_0^2-(m_1-m_2)^2]+\vec{k}_\perp\cdot(\vec{k}'_\perp-\vec{k}_\perp)}{\xi(1-\xi)\sqrt{M_0^2-(m_1-m_2)^2}\sqrt{M_0'^2-(m_1-m_2)^2}}, \tag{2}$$

where the free mass operator M_0 (M_0') and the intrinsic light-front variables $\vec{k}_\perp$ ($\vec{k}'_\perp$), ξ are defined as

$$M_0^2=\frac{m_1^2+k_\perp^2}{\xi}+\frac{m_2^2+k_\perp^2}{(1-\xi)}, \qquad M_0'^2=\frac{m_1^2+k_\perp'^2}{\xi}+\frac{m_2^2+k_\perp'^2}{(1-\xi)},$$
$$\vec{k}_\perp=\vec{p}_{1\perp}-\xi\vec{P}_\perp=-\vec{p}_{2\perp}+(1-\xi)\vec{P}_\perp, \tag{3}$$
$$\vec{k}'_\perp\equiv\vec{k}_\perp+(1-\xi)\vec{Q}_\perp, \qquad \xi=p_1^+/P^+=1-p_2^+/P^+.$$

In Eqs. (2) and (3) the subscript $\perp$ indicates the projection perpendicular to the spin quantization axis, defined by the vector $\hat{n}=(0,0,1)$, and the *plus* component of a four-vector $p\equiv(p^0,\vec{p})$ is given by $p^+=p^0+\hat{n}\cdot\vec{p}$. Moreover,

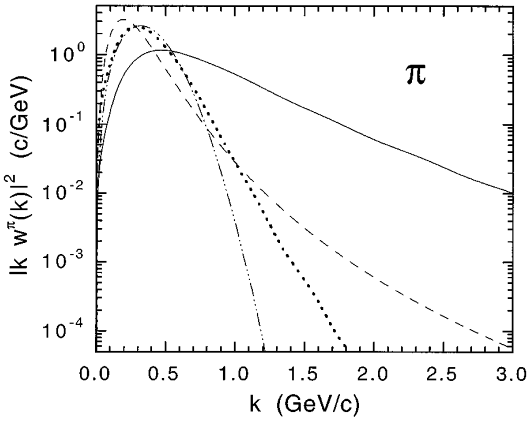

FIG. 1. Pion wave functions $[kw^\pi(k^2)]^2$, calculated using in Eq. (4) different effective $q\overline{q}$ interactions, as a function of the relative momentum k. Dotted line: $w^\pi_{(\mathrm{conf})}$, corresponding to the case in which only the linear confining part of the GI $q\overline{q}$ interaction [9] is considered. Solid line: $w^\pi_{(\mathrm{GI})}$, corresponding to the solution of Eq. (4) obtained using the full GI $q\overline{q}$ interaction. The dot-dashed and dashed lines correspond to the HO and PL wave functions of Ref. [4], respectively.

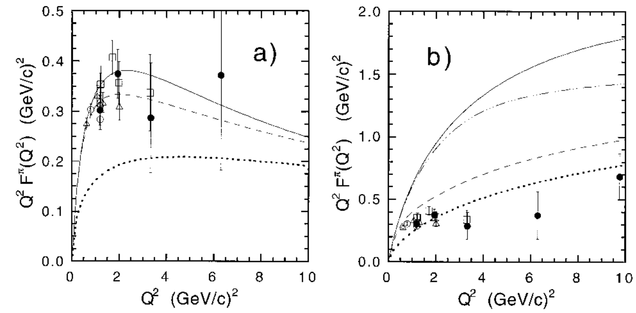

FIG. 2. Charge form factor of the pion, $Q^2F^\pi(Q^2)$, calculated assuming $f^q=1$ in Eq. (1) and using in Eq. (2) the wave functions $w^\pi_{(\mathrm{conf})}$ (a) and $w^\pi_{(\mathrm{GI})}$(b). The various lines correspond to the results obtained by substituting in Eq. (2) $w^\pi(k^2)$ and $w^\pi(k'^2)$ with $\widetilde{w}^\pi(k^2)=\mathcal{N}w^\pi(k^2)\,\theta(k^U_\perp-k_\perp)$ and $\widetilde{w}^\pi(k'^2)=\mathcal{N}w^\pi(k'^2)\,\theta(k^U_\perp-k'_\perp)$, respectively, where $k^U_\perp$ is the cutoff on the transverse momentum (see text). In (a) and (b) the dotted and dashed lines correspond to $k^U_\perp=0.3$ and 0.8 GeV/c, respectively, while in (b) the dot-dashed line corresponds to $k^U_\perp=2$ GeV/c. The solid lines represent the full calculations of the elastic form factor (i.e., when $k^U_\perp\to\infty$). Experimental data from Ref. [13].

$\widetilde{P}\equiv(P^+,\vec{P}_\perp)=\widetilde{p}_1+\widetilde{p}_2$ is the light-front momentum of the meson, $k^2\equiv k^2_\perp+k^2_n$, $k'^2\equiv k'^2_\perp+k'^2_n$, $k_n\equiv(\xi-1/2)M_0+(m^2_2-m^2_1)/2M_0$, and $k'_n\equiv(\xi-1/2)M'_0+(m^2_2-m^2_1)/2M'_0$.

As in [2], the radial wave function $w^P(k^2)$ can be identified with the equal-time radial wave function in the meson rest frame. We will make use of the eigenfunctions of the effective $q\overline{q}$ Hamiltonian, developed by Godfrey and Isgur (GI) [9] to reproduce the meson mass spectra. In case of pseudoscalar mesons one has

$$H_{q\overline{q}}w^P(k^2)|00\rangle\equiv[\sqrt{m^2_q+k^2}+\sqrt{m^2_{\overline{q}}+k^2}+V_{q\overline{q}}]w^P(k^2)|00\rangle = M_{q\overline{q}}w^P(k^2)|00\rangle, \tag{4}$$

where $M_{q\overline{q}}$ is the mass of the meson, $|00\rangle=\Sigma_{\nu\overline{\nu}}\langle\frac{1}{2}\ \nu\ \frac{1}{2}\ \overline{\nu}|00\rangle\chi_\nu\chi_{\overline{\nu}}$ is the usual quark-spin wave function of a pseudoscalar meson, and $V_{q\overline{q}}$ is the effective $q\overline{q}$ potential. The GI interaction $V_{(\mathrm{GI})}$ is composed by an OGE term (dominant at short separations) and a linear-confining term (dominant at large separations). We will consider two types of wave functions: the first one, $w^P_{(\mathrm{conf})}$, is given by the solution of Eq. (4) obtained when the OGE part of $V_{(\mathrm{GI})}$ is switched off, i.e., when only its linear confining term $V_{(\mathrm{conf})}$ is retained, whereas the second choice, $w^P_{(\mathrm{GI})}$, is obtained by solving Eq. (4) with the full GI interaction. Note that the pion mass corresponding to $V_{(\mathrm{conf})}$ in Eq. (4) is 1.024 GeV, whereas the one obtained using $V_{(\mathrm{GI})}$ is 0.149 GeV. The pion wave functions $w^\pi_{(\mathrm{conf})}$ and $w^\pi_{(\mathrm{GI})}$ are shown in Fig. 1 and compared with the HO $[w^\pi_{(\mathrm{HO})}\propto\exp(-k^2/2\alpha^2)]$ and PL $[w^\pi_{(\mathrm{PL})}\propto(1+k^2/\beta^2)^{-2}]$ wave functions used in Ref. [4]. It should be stressed that the latter ones are constrained by imposing the reproduction of the leptonic decay constants of π and ρ mesons and by assuming a pointlike quark electroweak (ew) current. It can clearly be seen that (i) the momentum behaviors of $w^\pi_{(\mathrm{conf})}$ and $w^\pi_{(\mathrm{GI})}$ are sharply different, because of the configuration mixing induced by the OGE part of the effective $q\overline{q}$ interaction, (ii) for $k<1$ GeV/c $w^\pi_{(\mathrm{HO})}$ and $w^\pi_{(\mathrm{PL})}$ are quite similar (possibly because they have to satisfy the above-mentioned constraints) and do not differ significantly from $w^\pi_{(\mathrm{conf})}$, which takes into account the effects of the confinement scale only, and (iii) the high-momentum components of $w^\pi_{(\mathrm{GI})}$, while exhibiting a nominal power-law falloff at large momenta ($|\vec{k}_\perp|>1$ GeV/c), are much higher than the ones pertaining to $w^\pi_{(\mathrm{PL})}$. The average transverse momentum $\overline{k_\perp}\equiv\sqrt{\langle k^2_\perp\rangle}$ turns out to be $\simeq0.8$ GeV/c in case of $w^\pi_{(\mathrm{GI})}$ and $\simeq0.3$ GeV/c for $w^\pi_{(\mathrm{HO})}$, $w^\pi_{(\mathrm{PL})}$, and $w^\pi_{(\mathrm{conf})}$. Thus the HO and PL wave functions adopted in Refs. [4] and [6(c)] can hardly be considered representative of the range of uncertainty of the momentum behavior of the wave function. As a matter of fact, our $w^\pi_{(\mathrm{GI})}$ wave function, which is an eigenfunction of a mass operator reproducing the meson mass spectra, does not belong to the limited class of wave functions considered in Refs. [4] and [6(c)], since it gives rise to an overestimation of the leptonic decay constants when a pointlike quark ew current is adopted (cf. [2]).

The relevance of the high-momentum components of the wave function in the calculation of the pion form factor can be investigated by substituting in Eq. (2) $w^P(k^2)$ and $w^P(k'^2)$ with $\widetilde{w}^P(k^2)=\mathcal{N}w^P(k^2)\,\theta(k^U_\perp-|\vec{k}_\perp|)$ and $\widetilde{w}^P(k'^2)=\mathcal{N}w^P(k'^2)\,\theta(k^U_\perp-|\vec{k}'_\perp|)$, respectively, where $k^U_\perp$ is the cutoff on the transverse momentum $k_\perp\equiv|\vec{k}_\perp|$ and $\mathcal{N}$ is a constant ensuring the proper normalization of the wave function. The results of the calculations, obtained assuming $f^q=1$ in Eq. (1) and using in Eq. (2) both $\widetilde{w}^\pi_{(\mathrm{conf})}$ and $\widetilde{w}^\pi_{(\mathrm{GI})}$, are shown in Fig. 2 for values of Q^2 up to 10 (GeV/c)^2. In what follows we will limit ourselves to consider the wave functions $\widetilde{w}^\pi_{(\mathrm{conf})}$ and $\widetilde{w}^\pi_{(\mathrm{GI})}$, because for $Q^2<10$ (GeV/c)^2 the results obtained using the HO and PL wave functions of Ref. [4] do not differ significantly from those calculated with

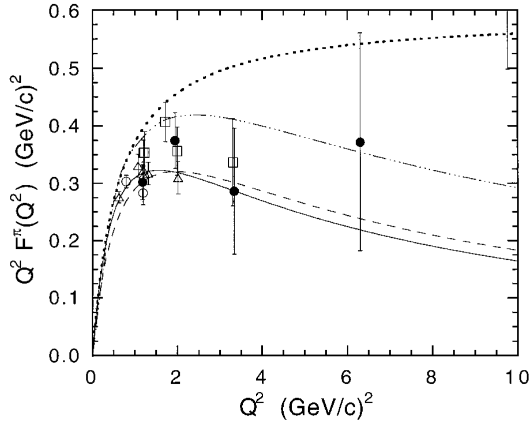

FIG. 3. Elastic form factor of the charged pion, times Q^2, vs Q^2. The solid line represents the results of our RCQM, obtained using in Eq. (2) the eigenfunction of the effective $q\bar{q}$ Hamiltonian of Ref. [9] and adopting in Eq. (1) the monopole charge form factor [Eq. (5)] with $\langle r^2\rangle_u = \langle r^2\rangle_d = (0.48\ \mathrm{fm})^2$. The dashed and dot-dashed lines represent the predictions of the covariant Bethe-Salpeter approach of Ref. [14] and of the QCD sum rule technique of Ref. [15], respectively. The dotted line is the prediction of the VMD model with the ρ-meson pole only [i.e., $F^\pi = (1+Q^2/m_\rho^2)^{-1}$].

$\tilde{w}^\pi_{(\mathrm{conf})}$. From Fig. 2 it can clearly be seen that, both for $w^\pi_{(\mathrm{conf})}$ and $w^\pi_{(\mathrm{GI})}$, the calculation of the pion charge form factor is strongly affected by components of the wave function corresponding to $k_\perp > \bar{k}_\perp$. As a matter of fact, in case of $w^\pi_{(\mathrm{conf})}$, about one-half of the form factor at $0.5 < Q^2(\mathrm{GeV}/c)^2 < 5$ is due to components of the wave functions with $k_\perp > 0.3\ \mathrm{GeV}/c$ [$\simeq \langle k_\perp\rangle_{\mathrm{conf}}$], and, moreover, the saturation is not completely reached even when $k_\perp^U \simeq 0.8\ \mathrm{GeV}/c$. In case of $w^\pi_{(\mathrm{GI})}$, the high-momentum components corresponding to $k_\perp > 0.8\ \mathrm{GeV}/c$ [$\simeq \langle k_\perp\rangle_{\mathrm{GI}}$] are responsible for about one-half of the pion form factor at $Q^2 > 1(\mathrm{GeV}/c)^2$ and the saturation at high values of Q^2 is not completely reached even when $k_\perp^U \simeq 2\ \mathrm{GeV}/c$. Such results are simply related to the fact that, for $Q \sim$ few GeV/c, values of $k_\perp \sim 1\ \mathrm{GeV}/c$ can give rise to low values of $k'_\perp$ [$= |\vec{k}_\perp + (1-\xi)\vec{Q}_\perp|$], when $\vec{k}_\perp$ is antiparallel to $\vec{Q}_\perp$ and the struck quark carries an average fraction of the momentum of the meson (i.e., $\xi \sim \bar{\xi} = 0.5$ in the pion). This interplay between $k_\perp$ and $k'_\perp$ implies that, even without the effects of the OGE term of the GI interaction, the pion form factor at $Q \sim$ few GeV/c is affected by the wave function at $k_\perp > \bar{k}_\perp$. In particular, since $\langle k_\perp\rangle_{\mathrm{GI}} \simeq 0.8\ \mathrm{GeV}/c$, configurations both at short and large transverse $q\bar{q}$ separations turn out to be relevant for w^π_{GI}. To sum up, the results reported clearly show that (i) for all the wave functions considered, the high-momentum part at $k_\perp > \bar{k}_\perp$ is relevant for values of Q^2 accessible to CEBAF energies, and (ii) the OGE term of the GI interaction (which, as known, nicely explains the π - ρ mass splitting) generates in the wave function high-momentum components ($k_\perp > 1\mathrm{GeV}/c$), which lead to a strong overestimation of the pion form factor at $Q^2 \sim$ few $(\mathrm{GeV}/c)^2$. In this work we have checked that the same conclusions hold as well for the charge form factor of K meson, whereas they are no longer true in case of heavy pseudoscalar mesons, such as the D and B mesons. As a matter of fact, the explicit calculations of Eqs. (1) and (2) (assuming $f^q = 1$) yield almost the same results in a wide range of values of Q^2 [$Q^2 \gg 1(\mathrm{GeV}/c)^2$] both for $w^{D(B)}_{(\mathrm{conf})}$ and $w^{D(B)}_{(\mathrm{GI})}$ wave functions. We will limit ourselves to comment that such a result can be ascribed to the fact that (i) the body form factor (H^P) corresponding to the virtual photon absorption by the heavy c (b) quark in the D (B) meson is dominant and (ii) the average fraction of the momentum of the meson carried by the heavy quark is very close to 1, leading to $k'_\perp \simeq k_\perp$, which implies a weak dependence of the calculated form factor on the heavy meson wave function in a wide range of values of Q^2.

The results reported in Fig. 2 suggest that, if the constituent quarks are assumed to be pointlike particles (i.e., if $f^q = 1$), the pion form factor calculated with wave functions having $\bar{k}_\perp \sim 0.3\ \mathrm{GeV}/c$ (like, e.g., $w^\pi_{(\mathrm{conf})}$, $w^\pi_{(\mathrm{HO})}$, and $w^\pi_{(\mathrm{PL})}$) is in fairly good agreement with existing data, whereas the one obtained using $w^\pi_{(\mathrm{GI})}$ is not. However, once the assumption $f^q = 1$ is made, the parameters which unavoidably appear in the hadron wave function are usually adjusted in order to fit em (or, more generally, electroweak) hadron properties [see, e.g., Ref. [6(c)]]. In this way the relativistic constituent quark model (RCQM) loses (at least partially) its predictive power, for the wave function is not completely independent of the em observable under investigation. A different approach is to adopt the eigenfunctions of a (light-front) mass operator able to reproduce correctly the hadron mass spectra, so that the wave functions do not depend upon any observable but the hadron energy levels. In this way, the momentum behavior of the hadron wave functions is dictated by the features of the effective $q\bar{q}$ interaction and the investigation of the em properties of hadrons could provide information on those of the constituent quarks. Thus, in order to recover the predictive power of the RCQM, the same em one-body current should be used for all the hadrons. Following this strategy, a monopole ansatz for the charge form factor of the constituent quarks has been considered in Ref. [2], viz.,

$$f^q(Q^2) = (1 + Q^2\langle r^2\rangle_q/6)^{-1}. \tag{5}$$

When the wave function $w^\pi_{(\mathrm{GI})}$ is adopted in Eq. (2), the value $\langle r^2\rangle_u = \langle r^2\rangle_d = (0.48\ \mathrm{fm})^2$ has to be chosen in order to reproduce the experimental value of the pion charge radius $\langle r^2\rangle^{(\pi)}_{\mathrm{expt}} = (0.660 \pm 0.024\ \mathrm{fm})^2$ [10]. It should be pointed out that such a value of the constituent quark radius is in nice agreement with the ansatz $\langle r^2\rangle_q = \kappa/m_q^2$, suggested in Ref. [11], from the analysis of the so-called strong interaction radius of hadrons, when the values $\kappa \simeq 0.3$, extracted from the chiral quark model of Ref. [12], and $m_u = m_d = 0.220\mathrm{GeV}$ [9] are adopted.[1] Moreover, it should be stressed that, though the $u(d)$-quark charge radius is fixed only by the pion data at very low values of Q^2, the predictions of our RCQM compare very favorably with the data also at high values of Q^2 (see Ref. [2]). This is illustrated in Fig. 3, where our results for the pion charge form factor are compared with the experimental data [13] and also with the predictions of different relativistic approaches, like the covariant Bethe-Salpeter approach of Ref. [14] and the QCD sum rule technique of Ref. [15]. The predictions of the simple vector meson dominance (VMD) model, including the ρ-meson pole only, are also shown in the same figure. It can be seen that existing pion data do not discriminate among calculations based on different models of the pion structure.

By using in Eq. (2) the appropriate eigenfunctions of the GI Hamiltonian (4), the elastic form factors of charged K^+ and neutral K^0 mesons have been calculated. In Fig. 4 the results of our calculations, performed adopting different choices of the charge radius of the constituent s quark ($\langle r^2 \rangle_s$), are reported and compared with the predictions of Ref. [14], based on a covariant Bethe-Salpeter approach. It can be seen that for $Q^2 > 1(\mathrm{GeV}/c)^2$ the calculated charge form factors of K^+ and K^0 mesons are remarkably sensitive to the value used for $\langle r^2 \rangle_s$, so that their experimental investigation could provide information on the em structure of light constituent quarks. From Fig. 4 it can also be seen that, unlike the case of the pion, the measurement of the kaon form factor at $Q^2 > 1(\mathrm{GeV}/c)^2$ could discriminate among different models of the meson structure.

In conclusion, the charge form factor of π and K mesons has been evaluated within a light-front constituent quark model. The use of the eigenfunctions of a mass operator, constructed from the effective $q\bar{q}$ Hamiltonian of Ref. [9] reproducing the meson mass spectra, and the introduction of a phenomenological charge form factor for the constituent quarks have been briefly discussed. It has been shown that the high-momentum components generated in the meson wave function by the effective one-gluon exchange interaction (namely, $k_\perp > 1$ GeV/c) are essential in determining the behavior of the form factor for values of Q^2 accessible to CEBAF. Therefore, the investigation of π and K form factors at CEBAF represents a powerful tool to study the short-range structure of mesons. The predictions of our relativistic constituent quark model for the charge form factor of π and K mesons have been compared with those of different relativistic approaches, showing that the planned experiments at CEBAF [1], aimed at measuring independently the pion and kaon form factor for $Q^2 < 3(\mathrm{GeV}/c)^2$, could provide relevant information on the em structure of light constituent quarks and could represent an interesting tool to discriminate among different models of the meson structure.

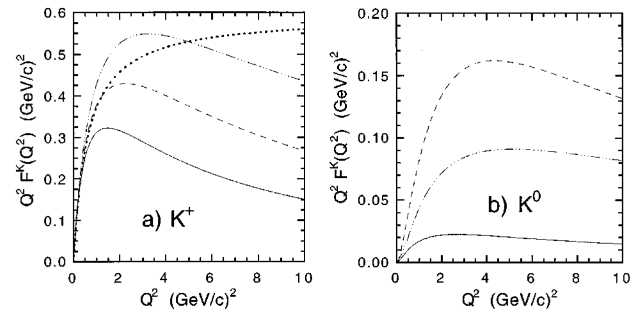

FIG. 4. Elastic form factor of charged K^+ (a) and neutral K^0 (b) mesons, times Q^2, as a function of Q^2. The solid line represents the results of our RCQM, obtained using in Eq. (2) the appropriate eigenfunctions of the effective $q\bar{q}$ Hamiltonian of Ref. [9] [see Eq. (4)] and adopting in Eq. (1) a SU(3) symmetric (monopole) charge form factor for the constituent quarks with $\langle r^2 \rangle_u = \langle r^2 \rangle_d = \langle r^2 \rangle_s = (0.48\mathrm{fm})^2$. The dot-dashed lines are the results of the calculations of Ref. [14], based on a covariant Bethe-Salpeter approach. The dashed lines represent the predictions of our RCQM, calculated using $\langle r^2 \rangle_s = (0.25\ \mathrm{fm})^2$ and $\langle r^2 \rangle_u = \langle r^2 \rangle_d = (0.48\ \mathrm{fm})^2$. Note that these values correspond to the ansatz $\langle r^2 \rangle_q = \kappa / m_q^2$ [11], adopting $\kappa \simeq 0.3$ [12], $m_u = m_d = 0.220$ GeV and $m_s = 0.419$ GeV [9]. Eventually, the dotted line in (a) is the prediction of the VMD model including the ρ-meson pole only.

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[1] CEBAF Proposals E-93-012, E-93-018, E-93-021 (unpublished).
[2] F. Cardarelli *et al.*, Phys. Lett. B **332** 1 (1994).
[3] F. Cardarelli *et al.*, Phys. Lett. B **349**, 393 (1995); **359**, 1 (1995).
[4] F. Schlumpf, Phys. Rev. D **50**, 6895 (1994).
[5] P.L. Chung, F. Coester, and W.N. Polyzou, Phys. Lett. B **205**, 545 (1988); W. Jaus, Phys. Rev. D **44**, 2851 (1991), and references therein quoted; B.D. Keister, *ibid.* **49**, 1500 (1994).
[6] (a) P.L. Chung and F. Coester, Phys. Rev. D **44**, 229 (1991); (b) M. Yabu, M. Takizawa, and W. Weise, Z. Phys. A **345**, 193 (1993); (c) F. Schlumpf, Phys. Rev. D **47**, 4114 (1993); **49**, 6246E (1994); S. Brodsky and F. Schlumpf, Phys. Lett. B **329**, 111 (1994).
[7] F. Cardarelli *et al.*, Phys. Lett. B **357**, 267 (1995).
[8] G.P. Lepage and S.J. Brodsky, Phys. Rev. D **22**, 2157 (1980); S.J. Brodsky and G.P. Lepage, in *Perturbative Quantum Chromodynamics*, edited by A.H. Mueller (World Scientific, Singapore, 1989), p. 93.
[9] S. Godfrey and N. Isgur, Phys. Rev. D **32**, 185 (1985).
[10] S.R. Amendolia *et al.*, Phys. Lett. **146B**, 116 (1984).
[11] B. Povh and J. Hüfner, Phys. Lett. B **245**, 653 (1990); see also S.M. Troshin and N.E. Tyurin, Phys. Rev. D **49** 4427 (1994).
[12] U. Vogl *et al.*, Nucl. Phys. **A516**, 469 (1990).
[13] C.N. Brown *et al.*, Phys. Rev. D **8**, 92 (1973); C.J. Bebek *et al.*, *ibid.* **9**, 1229 (1974); **13**, 25 (1976); **17**, 1693 (1978).
[14] W.W. Buck, Phys. Lett. B **351**, 24 (1995); H. Ito, W.W. Buck, and F. Gross, Phys. Rev. C **45**, 1918 (1992); Phys. Lett. B **287**, 23 (1992).
[15] V.A. Nesterenko and A.V. Radyushkin, Phys. Lett. **115B**, 410 (1982).