Study In-Medium K^+ with a Symmetric Vertex in a Light Front Approach

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Abstract

Using the light-front kaon wave function based on a Bethe-Salpeter amplitude model for the quark-meson interaction, we study the electromagnetic form factors of the kaon in nuclear medium within the framework of light-front field theory. The kaon model we adopt is well constrained by previous studies to explain the kaon properties in vacuum. The above mentioned observables are evaluated for the + component of the electromagnetic current, J^+, in the Breit frame. In order to consistently incorporate the constituent up and strange quarks of the kaon immersed in symmetric nuclear matter, we use the Quark-Meson Coupling model, which has been widely applied to various hadronic and nuclear phenomena in a nuclear medium with success. We predict the in-medium modifications of the kaon electromagnetic form factor in symmetric nuclear matter. It is found that after a fine tuning of the regulator mass, i.e. $m_R = 0.600\,GeV$, the model is suitable to fit the available experimental data within the theoretical uncertainties of kaon.

1. Introduction

The main purpose of this work is to investigate the in-medium modifications of the kaon properties, i.e., the electromagnetic form factor in symmetric nuclear matter, where the kaon model [1] is adjusted so as to provide the best description of the electromagnetic form factor data in vacuum. The study of the lightest pseudoscalar mesons plays an important role in order to understand the low energy QCD, being the lightest strongly bound quark-antiquark states as well as the Goldstone bosons associated with chiral symmetry breaking. Their static and dynamical properties have also been investigated theoretically and experimentally [2, 3, 4, 5]. With respect to the description of bound states on the light cone, a detailed review of hadronic wave functions in QCD models can be found in Ref [7]. Additional important knowledge about the meson's internal structure can be inferred from their valence-quark parton distribution functions. The theoretical framework we adopt is the light-front field theory formalism [6, 7], more specifically, we here ameliorate the light-front approach, where two classes of $(q\bar{q})$ bound-state models for the Bethe-Salpeter amplitude of the K meson must be distinguished: the nonsymmetric and the symmetric vertex model. The light-front component J^+ of the electromagnetic current has been successfully used to calculate elastic form factors. For the symmetric $k-q\bar{q}$ vertex model [10], the components of the current are conveniently obtained in the Drell-Yan frame, where that on the light-cone the bound state wavefunctions are defined on the hypersurface $x^0+x^3=0$ and are covariant under kinematical boosts due to the stability of Fock-state decomposition [7]. In this work, we consider the symmetrical $q,\bar{q}$ bound-state vertex function with the intention to optimize and unify the parameter set which simultaneously reproduces the electromagnetic form factors, for the latter, our numerical results are compared with experimental data up to $10\ GeV^2$ in order to explore the validity of the model at large q^2 transfer.

2. The Model

The electromagnetic current for a two fermions bound state composite system with spin equal 0; i.e., a K meson, considered as $(q\bar{q})$ bound state, is calculated in one-loop approximation (triangle diagram Fig. 1), modelling the Bethe-Salpeter amplitude through a symmetric vertex function in momentum space with a pseudoscalar coupling between K meson and quark degrees of freedom. This coupling is given by the effective Lagrangian below:

$$\mathcal{L}_{eff} = -\imath \frac{\hat{m}}{f_{K^+}} \bar{q} \frac{1}{\sqrt{2}}(\lambda_4 + \imath\lambda_5)\gamma^5 q \frac{1}{\sqrt{2}}(\phi_4 - \imath\phi_5)\Lambda^*, \quad (1)$$

here, $q=(u,d,s)^T$ and $K^+ = \frac{1}{\sqrt{2}}(\phi_4 - \imath\phi_5)$, $\hat{m}$ is given by the $\frac{m_u^*+m_{\bar{s}}}{2}$ with $m_u^* = m_u + V_s$, Λ^* the symmetric vertex function in nuclear medium and f_{K^+} the K^+-meson decay constant. In this study we approximate to use f_{K^+} value in vacuum. In the Hartree mean field approximation the modifications enter as the shift of the quark momentum via $P^\mu \to P^\mu + V^\mu = P^\mu + \delta_0^\mu V^0$ due to the vector potential, and in the Lorentz-scalar part through the the Lorentz-scalar potential V_s as $m_u \to m_u^* + V_s$ [8, 9] and $m_{\bar{s}} \to m_{\bar{s}}^* = m_{\bar{s}}$.

The electromagnetic current for K meson with the plus component, is obtained from the covariant expression Eq. (2) corresponding to the triangle diagram in figure 1,

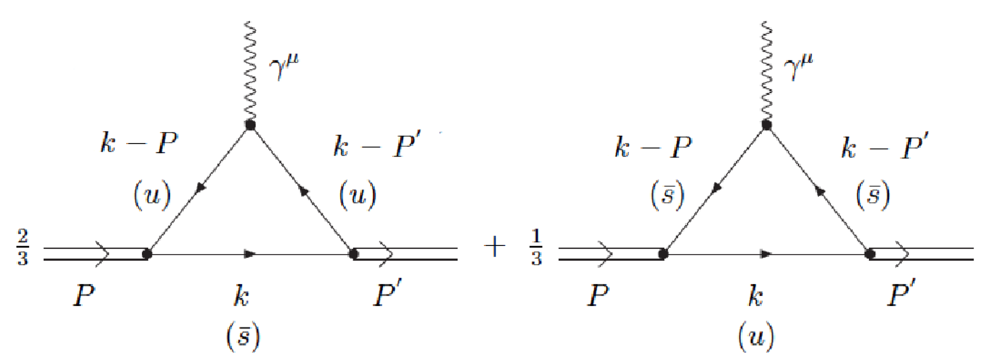

Figure 1: *Diagrams for K^+-meson photon interaction.*

given by

$$J^+(q^2) = -ie\frac{\hat{m}^2}{f_K^2} N_C \times$$
$$\int \frac{d^4k}{(2\pi)^4} \Big\{ \frac{2}{3} Tr[S(k,m_{\bar{s}})\gamma^5 S(k^*-P', m_u^*)\gamma^+ S(k^*-P, m_u^*)\gamma^5] +$$
$$\frac{1}{3} Tr[S(k^*,m_u^*)\gamma^5 S(k-P', m_{\bar{s}})\gamma^+ S(k-P, m_{\bar{s}})\gamma^5] \Big\} \times$$
$$\Lambda^*(k+V,P)\ \Lambda^*(k+V,P'). \quad (2)$$

where $(k^*)^\mu = k^\mu + \delta_0^\mu V^0$, $\Lambda^*(k+V,P')$ and $\Lambda^*(k+V,P)$ are the symmetric vertex function in nuclear medium from inital and final momenta of the system given by [10]

$$\Lambda^*(k+V,P) = \frac{C}{(k+V)^2 - m_R^{*2} + i\epsilon} + \frac{C}{((P-k-V)^2 - m_R^{*2} + i\epsilon)}, \quad (3)$$

and $N_C = 3$ is the number of colors in QCD.

We summarize here the light-front model for the symmetric vertex function (described above) for the pseudoscalar bound states. Also, we work with the Breit frames and using Front-Form variables, i.e., $k^+ = k^0 + k^3$, $k^- = k^0 - k^3$ and $k^\perp = (k^1, k^2)$ one has

$$q^+ = -q^- = \sqrt{-q^2}\sin\alpha,$$
$$q_x = \sqrt{-q^2}\cos\alpha,$$
$$q_y = 0,$$
$$q^2 = q^+q^- - (\vec{q}_\perp)^2, \quad (4)$$

the Drell-Yan condition $q^+=0$ is recovered with $\alpha = 0$.

As well known, the K meson form factor can be extracted from the covariant expression below:

$$F_K^*(q^2) = \frac{1}{e(P+P')^\mu} < P'|J^\mu|P > . \quad (5)$$

If covariance and current conservation are fulfilled in a model calculation, one can obviously use any frame and any nonvanishing component of the current to calculate the electromagnetic form factor.

In the light front approach, however, besides the valence component of the electromagnetic current, we can have the nonvalence contribuition or zero modes; then in the light-front, below this two contributions given the full electromagnetic form factor:

$$F_K(q^2) = F_K^{(I)}(q^2,\alpha) + F_K^{(II)}(q^2,\alpha), \quad (6)$$

where $\alpha = 0^o$, $F_K^{(I)}(q^2,\alpha)$ has the loop integration on k^- constrained by $0 \le k^+ < P^+$, see the light-front time-ordered diagram in Fig. 2 (a), the valence $(u\bar{s})$, and $F_K^{(II)}(q^2,\alpha)$ has the loop integration on k^- in the interval $P^+ \le k^+ \le P'^+$, see Fig. 2 (b), nonvalence, with pair production, contributions with $q^+ > 0$.

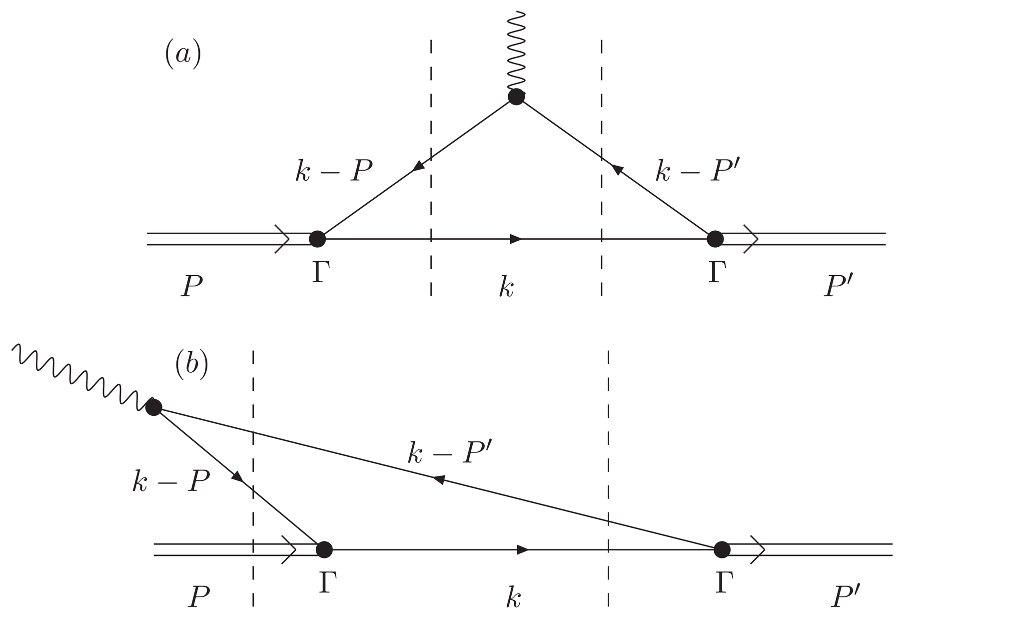

Figure 2: *Light-Front diagrams: (a) valence contribution and (b) non-valence contributions.*

Moreover, after k^- integration from J^+ current Eq. (2) through the Cauchy's Teorem, a light-front wave function emerges which for a symmetric $(u\bar{s})$ vertex function with the change of variable $x^*P^{*+} = xP^+ + V^+$ where $x = \frac{k^+}{P^+}$, is defined as:

$$\Phi(x,\vec{k}_\perp) = \frac{P^+}{m_K^{*2} - M_0^2}\left[\frac{\mathcal{N}}{(1-x)(m_K^{*2} - \mathcal{M}_0^2)} + \frac{\mathcal{N}}{x(m_K^{*2} - \mathcal{M}_R^2))}\right], \quad (7)$$

with $[u \leftrightarrow \bar{s}]$ where $\mathcal{N}$ is a normalization factor, $\mathcal{M}_0^2$ is a mass free oparator and $\mathcal{M}_R^2$ is a regulator mass function.

3. Numerical Results

We have two model parameters: the regulator mass, m_R, the quark masses, m_u^* and the anti-quark, $m_{\bar{s}}$. The main aim of this work is to jointly analyze the K meson's elastic form factors to determine more accurately the model's quark masses in view of future applications and to test whether a single mass scale, m_R, can satisfactorily describe experimental data for K meson. We consider the parameters described in Table 1. Following the graphs obtained from the calculations of the model:

Table 1: *Parameters*

ρ/ρ_0	0.00	0.10	0.20	0.30	0.40	0.50
$m_K\ [GeV]$	0.494	0.485	0.476	0.468	0.460	0.453
$m_u\ [GeV]$	0.220	0.203	0.188	0.172	0.157	0.143
$m_{\bar{s}}\ [GeV]$	0.440	0.440	0.440	0.440	0.440	0.440
$m_R\ [GeV]$	0.600	0.600	0.600	0.600	0.600	0.600
$V\ [GeV]$	0.000	0.012	0.023	0.035	0.047	0.058

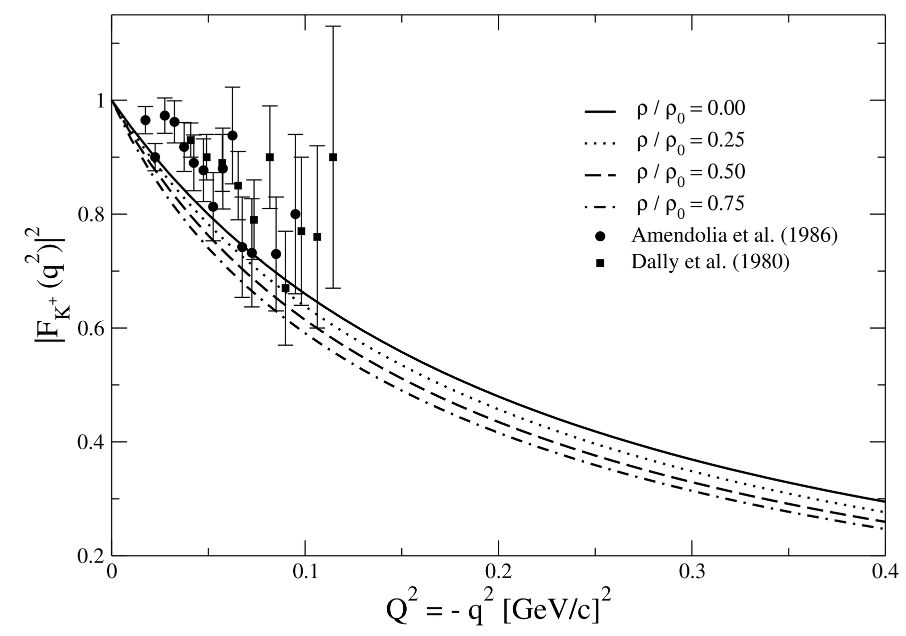

Figure 3: *K meson form factor squared with different density. There also the experimental data given by references [11, 12].*

4. Summary

We have began studies the modifications of the kaon properties in symmetric nuclear matter based on the constituent quark model of the kaon on the light front, where the kaon model reproduces well experimental data in vacuum. The next step is finished the calculations to charge radius and decay constant in this approch so that in the future may be extended to the other mesons like ρ and D.

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