УДК 539.126.3

ELECTRON-POSITRON ANNIHILATION INTO KAON PAIR IN AN EXTENDED VECTOR-MESON-DOMINANCE FRAMEWORK

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Received June 21, 2006

A model is developed for electromagnetic form factors of the charged and neutral $K-$mesons. The form factors, calculated without fitting parameters, are in a good agreement with experiment for space-like and time-like photon momentum. Contribution of the two-kaon channels to the muon anomalous magnetic moment is calculated.

KEY WORDS: chiral Lagrangians, vector-meson dominance, electromagnetic form factors

Hadronic contribution to the vacuum polarization plays an important role in the test of the Standard Model at the electroweak precision level. It is the main source of the theoretical uncertainties in the prediction of the anomalous magnetic moment of the muon $a_\mu = (g_\mu - 2)/2$. The dominant piece of the hadronic contribution is the $\pi^+\pi^-$ channel, which is expressed in terms of the pion electromagnetic form factor (FF) $F_\pi(s)$. At low energies it accounts for about 70 % of the total hadronic contribution to a_μ, at the same time the other hadronic channels are also important.

In this paper we mailnly concentrate on the electromagnetic (EM) FF's of the kaons, the charged ones K^+, K^-, and the neutral ones K^0, $\overline{K}^0$ in the time-like region (at $\sqrt{s} = 1-2$ GeV). Experimental information on these FF's comes from measurements [1-3] of total cross section of electron-positron annihilation into kaon pair:

$$\sigma(e^+e^- \to K\overline{K}) = \frac{\pi\alpha^2}{3s}(1 - \frac{4m_K^2}{s})^{3/2}\,|F_K(s)|^2, \qquad (1)$$

where $K\overline{K}$ stands for K^+K^- or $K^0\overline{K}^0$ ($K_L K_S$), s is invariant energy squared, m_K is the kaon mass, $\alpha = e^2/4\pi \approx 1/137$. Using aniliticity properties, one can also study FF's in space-like region, where $s \le 0$.

The kaon FF's are conventionally analyzed in terms of the intermediate $J^P = 1^-$ mesons: $\rho(770)$, $\omega(782)$ and $\phi(1020)$. It turns out that at energies above $\sqrt{s} \approx 1$ GeV, vector resonances $\rho' = \rho(1450)$, $\omega' = \omega(1420)$ and $\phi' = \phi(1680)$ also begin to play an important role. The properties of these higher resonances are not well known. Recently a model has been worked out [4] which accounts for main vector-meson contributions. The parameters of that model have been fitted to existing data on pion and kaon FF's.

The aim of the article is calculation of electromagnetic form factors of the charged and neutral $K-$mesons, and evaluation of the $K\overline{K}$-channel contribution to the muon anomalous magnetic moment within the present approach. The present model is based on the chiral perturbation theory (ChPT) with vector mesons. We include some loop corrections beyond the tree level. In particular, there are self-energy polarization operators that modify vector-meson propagators, and loop corrections which lead to «dressing» of the photon-meson vertices. For construction of necessary vertices we apply the anomalous Lagrangian of Wess-Zumino-Witten (WZW) [5,6] for $\gamma\Phi\Phi\Phi$ interactions, and phenomenological Lagrangian from [7] for $V\gamma\Phi$ and $V\Phi\Phi\Phi$ interactions. The total number of parameters in our model is considerably smaller than that in [4].

CHPT LAGRANGIAN

We apply ChPT $O(p^2)$ Lagrangian of Ecker et al. [8]. Expansion of this Lagrangian in powers of momenta[1] describes standard EM interaction of the charged pseudoscalar fields:

$$L^{(1)}_{\gamma\Phi\Phi} = ieB_\mu Tr(Q[\partial_\mu\Phi, \Phi]),$$
$$L^{(2)}_{\gamma\gamma\Phi\Phi} = -e^2/2\, B^\mu B_\mu Tr([\Phi, Q]^2), \qquad (2)$$

where Φ describes the pseudoscalar mesons nonet, B_μ is the EM field and quark charge matrix $Q \equiv diag(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})$.

The photon vector-meson coupling is described by effective Lagrangian

$$L_{\gamma V} = e F_V/\sqrt{2}\, F^{\mu\nu} Tr(V_{\mu\nu} Q), \qquad (3)$$

where $F^{\mu\nu} = (\partial^\mu B^\nu - \partial^\nu B^\mu)$, $V_{\mu\nu}$ is antisymmetric vector mesons field, F_V is coupling constant. This interaction is

[1] We keep in the expansion only the lowest-order interaction neglecting the higher-order terms.

explicitly gauge invariant and leads to momentum-dependent vertices for the $<\gamma(\mu)|V(\nu\rho)>$ transition, which are proportional to the factor

$$eF_V(q^\nu g^{\rho\mu} - q^\rho g^{\mu\nu})\,. \tag{4}$$

The interaction of vector mesons with pseudoscalars and photon is given by

$$\begin{aligned} L_{V\Phi\Phi} &= i\sqrt{2}G_V\big/F_\pi^2\, Tr(V_{\mu\nu}\partial^\mu\Phi\partial^\nu\Phi), \\ L_{V\Phi\Phi\gamma} &= e\,F_V\big/(4\sqrt{2}F_\pi^2)\,F^{\mu\nu}Tr([V_{\mu\nu},\Phi][Q,\Phi]). \end{aligned} \tag{5}$$

The pion weak-decay constant $F_\pi = 92.4$ MeV, G_V is coupling constant and one may need $\varepsilon_{\omega\phi} = 0.058$ for ω-ϕ mixing parameter. Often in effective models the vector-field formulation for the vector mesons is used (see, for example, [7]):

$$L'_{\gamma V} = -e\big/(\sqrt{2}f)\,F^{\mu\nu}Tr[Q(\partial_\mu V_\nu - \partial_\nu V_\mu)], \tag{6}$$

$$L'_{V\Phi\Phi} = i\,g\big/\sqrt{2}\,Tr(V_\mu[\partial^\mu\Phi,\Phi]), \tag{7}$$

and we use the latter formalism in the following.

The couplings in eqs. (3),(5-7) satisfy the exact $SU(3)$ symmetry. To have a more flexible model let us introduce independent EM couplings for each vector meson $f_V = (f_\rho, f_\omega, f_\phi)$ (see Tables 1, 2)[2].

Table 1. Values of the EM coupling constants for vector $V = \rho^0, \omega, \phi$

	ρ^0	ω	ϕ
$SU(3): f_V$	f	$3f$	$-3f/\sqrt{2}$
$\Gamma(V \to e^+e^-)$, keV	7.02 ± 0.11	0.60 ± 0.02	1.27 ± 0.04
f_V	4.97 ± 0.04	17.06 ± 0.29	-13.38 ± 0.21

Table 2. $SU(3)$ values of the vector-meson couplings to two pseudoscalar mesons, $g = 5.965$ is fixed from $\rho \to \pi\pi$ decay

	$\pi^+\pi^-$	K^+K^-	$K^0\overline{K}^0$
ρ^0	g	$1/2\,g$	$-1/2\,g$
ω	–	$1/2\,g$	$1/2\,g$
ϕ	–	$-1/\sqrt{2}\,g$	$-1/\sqrt{2}\,g$

ANOMALOUS INTERACTIONS

The WZW Lagrangian [5,6] involves interactions of the photons with pseudoscalar mesons, we keep in it the interaction of one photon with three pseudoscalars, and two photons with one pseudoscalar:

$$L_{\gamma\Phi\Phi\Phi} = -i\sqrt{2}e\big/(4\pi^2F_\pi^3)\,\varepsilon^{\mu\nu\alpha\beta}B_\mu Tr(Q(\partial_\nu\Phi)(\partial_\alpha\Phi)(\partial_\beta\Phi))\,, \tag{8}$$

$$L_{\gamma\gamma\Phi} = 3\sqrt{2}e^2\big/(8\pi^2F_\pi)\,\varepsilon^{\mu\nu\alpha\beta}(\partial_\mu B_\nu)(\partial_\alpha B_\beta)Tr(Q^2\Phi). \tag{9}$$

In the phenomenological model of [7] the $\gamma\Phi\Phi\Phi$ interaction is written in form, similar to (8), but with $c = -e/(4\pi^2)$ as a free parameter. For the anomalous interactions involving vector mesons we use the phenomenological Lagrangians from [7]:

$$L^{(ph)}_{VV\Phi} = g_{VVP}\big/(\sqrt{2}F_\pi)\,\varepsilon^{\mu\nu\alpha\beta}Tr((\partial_\mu V_\nu)(\partial_\alpha V_\beta)\Phi), \tag{10}$$

$$L^{(ph)}_{V\gamma\Phi} = 4d\big/F_\pi\,\varepsilon^{\mu\nu\alpha\beta}\partial_\mu B_\nu Tr(QV_\alpha\partial_\beta\Phi), \tag{11}$$

with free parameters g_{VVP} and d. Further, the $V\Phi\Phi\Phi$ interaction is

$$L^{(ph)}_{V\Phi\Phi\Phi} = ih\big/F_\pi^3\,\varepsilon^{\mu\nu\alpha\beta}Tr(V_\mu\,(\partial_\nu\Phi)(\partial_\alpha\Phi)\,(\partial_\beta\Phi)). \tag{12}$$

The parameter $d = -0.033$ is fixed from the width of the $\omega \to \gamma\pi^0$ decay. To obtain h and g_{VVP} we use experimental values [9] for the three-pion decay widths of ω and ϕ mesons[3]. According to [10-12] the direct decays are suppressed with respect to the process $\omega \to \rho\pi \to \pi\pi\pi$ (and $\phi \to \rho\pi \to \pi\pi\pi$). In view of these constraints we obtain $g_{VVP} = 1.321$ and very small $h = 0.003$.

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[2] If the couplings can be determined from experiment (in particular, f_V can be fixed from the decay widths Γ ($V \to l^+ l^-$)), those values will be used (see Table 1).

[3] It is usually supposed that the ϕ-meson decays into the three pions via the $\omega-\phi$ mixing (for other options see [13-15]), and that the amplitudes for the direct decay, $\phi \to \pi\pi\pi$, and decay through the intermediate state, $\phi \to \rho\pi \to \pi\pi\pi$, sum up incoherently [16].

KAON ELECTROMAGNETIC FORM FACTORS

The kaon electromagnetic FF's are defined in terms of the quark EM current (see, e.g., [7])

$$j^{\mu}_{em}(x) = 2/3\bar{u}(x)\gamma^{\mu}u(x) - 1/3\bar{d}(x)\gamma^{\mu}d(x) - 1/3\bar{s}(x)\gamma^{\mu}s(x),$$

$$< K^{+}(p_1)K^{-}(p_2)\,|\, j^{\mu}_{em}(0)\,|\,0 > \equiv (p_1 - p_2)^{\mu} F_{K^+}(q^2), \tag{13}$$

$$< K^{0}(p_1)\bar{K}^{0}(p_2)\,|\, j^{\mu}_{em}(0)\,|\,0 > \equiv (p_1 - p_2)^{\mu} F_{K^0}(q^2), \tag{14}$$

where p_1, p_2 are the kaon momenta, $q = p_1 + p_2$ and $q^2 \equiv s$. These FF's, being defined in the time-like region $s \ge 4m_K^2$, due to the analyticity describe also the space-like region $s < 0$ corresponding to elastic electron scattering on the kaon. Using the mentioned effective Lagrangians one gets the following form for FF's:

$$F_{K^+}(s) = 1 - \sum_{V=\rho^0,\omega,\phi} A_V(s)\, g_{VK^+K^-} \big/ f_V(s),$$
$$F_{K^0}(s) = - \sum_{V=\rho^0,\omega,\phi} A_V(s)\, g_{VK^0\bar{K}^0} \big/ f_V(s), \tag{15}$$

$$A_V(s) \equiv \frac{s}{s - m_V^2 - \Pi_V(s)}, \tag{16}$$

where $\Pi_V(s)$ is the self-energy operator for the vector meson $V = \rho, \omega, \phi$ and couplings $g_{VK^+K^-}$, $g_{VK^0\bar{K}^0}$ are given in Table 2. It is seen that due to gauge invariance of the photon vector-meson interaction (4) the correct normalization conditions for the FF's are fulfilled:

$$F_{K^+}(0) = 1, \qquad F_{K^0}(0) = 0. \tag{17}$$

An additional energy dependence of the coupling constants $f_V(s)$ arises due to higher-order corrections.

Self-energy operators

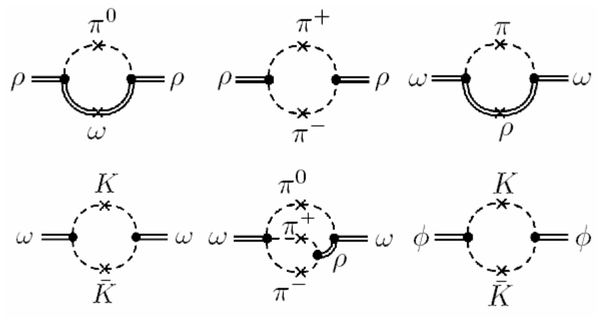

Fig. 1. Loops included in self-energy of vector mesons

Let us recall that the dressed propagator of vector particles includes the self-energy operators $\Pi_V(s)$, which are already included in eq. (16). In the energy region $\sqrt{s}$ about few GeV's the dominant contributions to $\Pi_V(s)$ consist of the loops in Fig. 1. We collect these diagrams in the self-energy operators, as follows

$$\Pi_{\rho} = \Pi_{\rho(\pi^0\omega)\rho} + \Pi_{\rho(\pi\pi)\rho}, \tag{18}$$

$$\Pi_{\omega} = \Pi_{\omega(\pi^0\rho)\omega} + \Pi_{\omega(KK)\omega} + 2\Pi_{\omega(3\pi,\pi\rho)\omega}, \tag{19}$$

$$\Pi_{\phi} = \Pi_{\phi(KK)\phi}, \tag{20}$$

where the subscript notation is explained in Fig. 1.

In the following we include only the imaginary parts of the loop contributions. These will be the dominant[4] contributions giving rise to the energy-dependent widths

$$\Gamma_V(s) = -1/m_V\, \mathrm{Im}\,\Pi_V(s). \tag{21}$$

Applying the Cutkosky rules [17, Ch.6.3] to the diagrams shown in Fig. 1 one can find the imaginary parts of self-energy (SE) operators. In order to restrict the fast growth of the partial widths with s we introduce cut-off in the particular form [13]. All the expressions for the self-energy operators should be multiplied by the corresponding FF squared.

Electromagnetic vertex modification

To be consistent with the approximation for the self-energy contributions in the previous subsection, we include only the imaginary part of the loop contributions to the photon vector-meson vertex functions.

In numerical calculation the following formulae are used:

$$\begin{aligned}
&\mathrm{Im}\,\Pi_{\gamma(\pi^0\omega)\rho}(s) = 2d/g_{vvp}\, \mathrm{Im}\,\Pi_{\rho(\pi^0\omega)\rho}(s),\\
&\mathrm{Im}\,\Pi_{\gamma(\pi\pi)\rho}(s) = e/g\, \mathrm{Im}\,\Pi_{\rho(\pi\pi)\rho}(s),\\
&\mathrm{Im}\,\Pi_{\gamma(\pi^0\rho)\omega}(s) = 2d/3g_{vvp}\, \mathrm{Im}\,\Pi_{\omega(\pi^0\rho)\omega}(s),\\
&\mathrm{Im}\,\Pi_{\gamma(KK)\omega}(s) = e/g\, \mathrm{Im}\,\Pi_{\omega(KK)\omega}(s),\\
&\mathrm{Im}\,\Pi_{\gamma(KK)\phi}(s) = -e/(\sqrt{2}g)\, \mathrm{Im}\,\Pi_{\phi(KK)\phi}(s),\\
&\mathrm{Im}\,\Pi_{\gamma(3\pi,\pi\rho)\omega}(s) = -e/(12\pi^2 h)\, \mathrm{Im}\,\Pi_{\omega(3\pi,\pi\rho)\omega}(s).
\end{aligned} \tag{22}$$

[4] An approximation, consisting in neglecting the real part of the loop contributions compared to the imaginary part, is often used in scattering theory and is known as K-matrix approach. For an example of successful application of the coupled-channel K-matrix approach to reactions on the nucleon see [18].

All expressions above have to be multiplied by the cut-off FF [13].

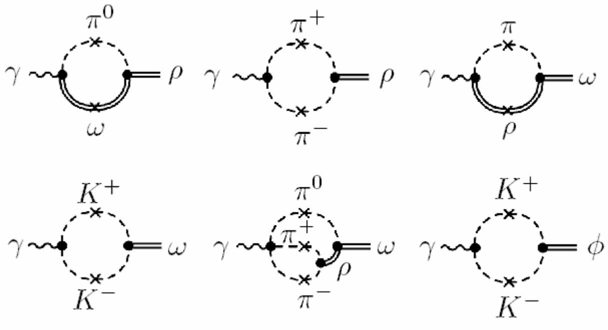

Fig. 2. Loops for EM vertex modification

The equations for the modified EM couplings read in terms of the loop corrections

$$1/f_V(s) = 1/f_V^{(0)} - i/(es)\sum_c \mathrm{Im}\Pi_{\gamma(c)V}(s), \tag{23}$$

for $V=\rho^0,\omega,\phi$, and where index $c=(\pi^0\omega,\pi\pi,\ \pi^0\rho,KK,$ $3\pi,3\pi-\rho\pi)$ stands for the diagrams shown in Fig. 2. Note that $\mathrm{Im}f_V^{(0)}=0$. The modified couplings $f_V(s)$ at $s=m_V^2$ have to describe the leptonic decay widths of the vector mesons:

$$|f_V(s=m_V^2)|^2 = \frac{4}{3}\pi\alpha^2\frac{m_V}{\Gamma(V\to e^+e^-)}. \tag{24}$$

This allows us to find the bare couplings:

$$\frac{1}{(f_V^{(0)})^2} = \frac{1}{|f_V(s=m_V^2)|^2} - \frac{1}{e^2 m_V^4}\Big(\sum_c \mathrm{Im}\Pi_{\gamma(c)V}(s=m_V^2)\Big)^2. \tag{25}$$

Using the particle properties [9] we obtain

$$f_\rho^{(0)} = 5.026,\quad f_\omega^{(0)} = 17.060,\quad f_\phi^{(0)} = 13.382, \tag{26}$$

and for arbitrary s the real and imaginary parts of $f_V(s)$ are calculated from (23).

Contribution from higher resonances

The contribution from the higher resonances ρ',ω',ϕ' is included by adding

$$\Delta F_{K^+}(s) = -\sum_{V'=\rho',\omega',\phi'} A_{V'}(s)\, g_{V'K^+K^-}/f_{V'}(s),$$
$$\Delta F_{K^0}(s) = -\sum_{V'=\rho',\omega',\phi'} A_{V'}(s)\, g_{V'K^0\bar{K}^0}/f_{V'}(s), \tag{27}$$

to FF's. The masses and widths can be taken from [9].

If we assume the $SU(3)$ relation for the *ratios* of the strong and EM couplings for the «primed» resonances (see Tables 1 and 2) and use known branching ratios [9], we obtain $g_{\rho'K^+K^-}/f_{\rho'} = -0.063$, $g_{\omega'K^+K^-}/f_{\omega'} = -0.021$ and $g_{\phi'K^+K^-}/f_{\phi'} = -0.036$.

RESULTS OF CALCULATION

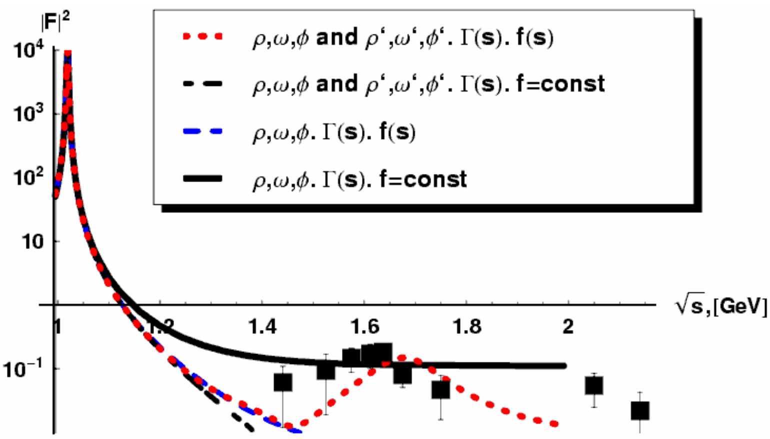

Fig. 3. Neutral kaon EM form factor in the time-like region. Data (boxes) [3].

The FF's, calculated from (15) and (27) in the time-like region of photon momentum, are shown in Figs. 3 and 4. The solid curves (see legends in the plots) represent a simple VMD-like model in which only ρ, ω and ϕ resonances are included. The meson widths are taken s-dependent while the couplings of vector mesons to photon are independent of momentum. As known, such a model can describe experiment only in vicinity of the $\phi(1020)$ resonance.

The long-dashed curves include in addition the momentum-dependent EM couplings. Taking into consideration ρ', ω' and φ' resonances with momentum-dependent widths, and constant couplings f_V, we obtain the dot-dashed curves in figures for FF's. The short-dashed curves represent the main results of the paper. These curves include the momentum-dependent widths for all intermediate states, «dressed» EM vertices (for the lower vector-meson resonances) and cut-off FF's in the self-energies and EM vertices. We have not attempted to develop the vertex «dressing» for the higher resonances due to the present experimental uncertainties in their decay rates.

We note that the authors of [4] also obtained a good description of the data by fixing the values of the parameters f_V from the fit. In our procedure of «dressing» the couplings, a reasonable agreement is achieved without need for fitting the parameters.

Finally the plot in Fig. 5 shows the charged kaon FF in the space-like region of photon momentum. This figure demonstrates agreement with available data [19], and a weak sensitivity of the FF to the model ingredients.

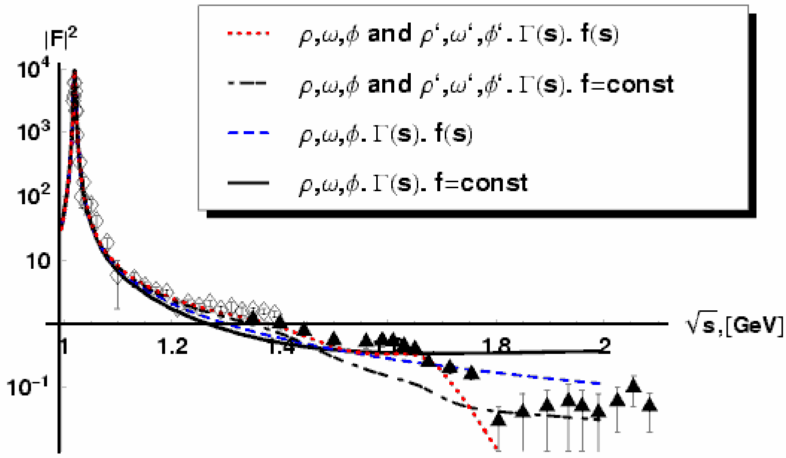

Fig. 4. Charged kaon EM form factor in the time-like region.
Data: diamonds [1], triangles[2].

The corresponding contribution of the $K\bar{K}$ – channel to a_μ is directly related to $F_{K^+}(s)$ (or $F_{K^0}(s)$) via the dispersion integral [20] (see also [21]). The calculated values are presented in Table 3.We can compare our result with that of [21] ($a_\mu^{had,\ K\bar{K}}{}_{(\exp)} = (35.24 \pm 1.44\times10^{-10})$) for the $K\bar{K}$ channels obtained directly from e^+e^- annihilation cross sections. It is seen that our model gives $a_\mu^{had,\ K\bar{K}}$ very close to the value $a_\mu^{had,\ K\bar{K}}{}_{(\exp)}$.

Table 3 Contribution of $K\bar{K}$ – channels to anomalous magnetic moment of the muon in units 10^{-10}

	K^+K^-	$K^0\bar{K}^0$	total $K\bar{K}$
$a_\mu^{had,K\bar{K}}$	19.06±0.57	15.64±0.44	34.01±1.01

CONCLUSIONS

We developed a model for electromagnetic FF's of the charged and neutral kaon in the time-like ($\sqrt{s} = 1-2$ GeV), and space-like ($s \le 0$) regions of the photon momentum. The model is based on the chiral perturbation theory (ChPT) with vector mesons [8]. Beyond the tree level the model includes certain loop corrections, such as self-energy polarization operators in vector-meson propagators, and “dressed” photon-meson vertices. For construction of $\gamma\Phi\Phi\Phi$ vertices we apply the anomalous WZW Lagrangian, and effective Lagrangians for $V\gamma\Phi$ and $V\Phi\Phi\Phi$ interactions. The parameters are fixed from experimental decay widths of the resonances.

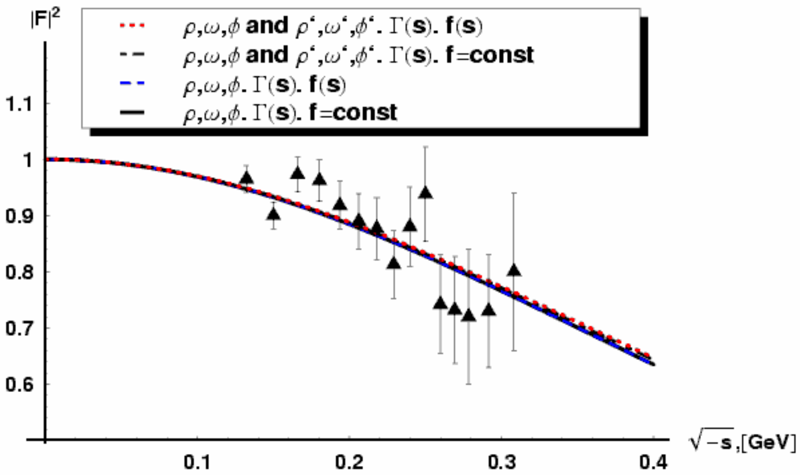

Fig 5. Charged kaon EM form factor in the space-like region. Data are from [19]

Comparison of the calculations with available data for the FF's and e^+e^- annihilation cross sections indicates that the model is consistent with experimental information in the $\sqrt{s} = 1-1.75$ GeV energy region. Using the dressed photon-meson vertices and adding the resonances $\rho' = \rho(1450)$, $\omega' = \omega(1420)$ and $\phi' = \phi(1680)$ considerably improve description of the data. A reasonable agreement is achieved without fitting the parameters of the model. Although the most important contributions are included, deviations from the data appear at high energies, $\sqrt{s} \approx 2$ GeV. Those may be attributed to missing contribution from the higher (“double-primed”) resonances $\rho(1700)$ and $\omega(1650)$ [9], or possibly experimental uncertainty in parameters of the ρ', ω' and ϕ'.

The calculated FF's allowed us also to evaluate leading-order contribution of the $K\bar{K}$ – channel to the anomalous magnetic moment of the muon. The calculated value $a_\mu^{had,K^+K^-} + a_\mu^{had,K^0\bar{K}^0} = (34.01 \pm 1.01)\times10^{-10}$ is in agreement with results [21] obtained from the experimental e^+e^- annihilation cross sections.

ACKNOWLEDGEMENT

We would like to thank S. Eidelman and N. Merenkov for useful suggestions and remarks.

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ЭЛЕКТРОН-ПОЗИТРОННАЯ АННИГИЛЯЦИЯ В КАОННУЮ ПАРУ В РАСШИРЕННОЙ МОДЕЛИ ДОМИНАНТНОСТИ ВЕКТОРНЫХ МЕЗОНОВ

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Предложена модель для электромагнитных форм-факторов заряженного и нейтрального K-мезонов. Форм-факторы, рассчитанные без подгоночных параметров, находятся в хорошем соответствии с экспериментальными данными для пространственно-подобных и времени-подобных импульсов фотона. Рассчитан вклад K^+K^- и $K^0\bar{K}^0$ каналов в аномальный магнитный момент мюона.

КЛЮЧЕВЫЕ СЛОВА: киральный лагранжиан, доминантность векторных мезонов, электромагнитные форм-факторы