INFRARED RENORMALON EFFECTS ON LIGHT MESONS' M DISTRIBUTION AMPLITUDES AND $F_M(Q^2)$, $F_{\pi\gamma}(Q^2)$ FORM FACTORS

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The light pseudoscalar (pion, kaon) and longitudinally polarized ρ-meson electromagnetic form factors $F_M(Q^2)$ and $\gamma^*+\gamma\to\pi^0$ transition form factor are calculated using the frozen coupling constant approximation and mesons' distribution amplitudes (DAs) found by taking into account the infrared renormalon effects. In calculations the asymptotic and the model DA are used. Comparisons are made with results obtained by means of the ordinary DAs.

1. INTRODUCTION

One of the fundamental achievements of QCD is the prediction of asymptotic scaling laws for large-angle exclusive processes, hadronic electromagnetic and transition form factors (ffs) and their calculation in the context of the perturbative QCD (pQCD) [1-3]. In the framework of the factorized pQCD the expression for the amplitude of an exclusive process can be written as integral over x, y of hadron DA $\Phi_i(x,\mu_F^2)$ (an initial hadron), $\Phi_f^*(y,\mu_F^2)$ (a final hadron) and a hard-scattering amplitude $T_H(x, y;\mu_R^2,\mu_F^2)$ calculable by means of pQCD. This method allowed one to find a behavior of exclusive cross sections, ffs at large momentum transfer $Q^2>>\Lambda^2$. But recently the new approach, the infrared (ir) renormalon calculus, has been invented, which is using during last years for estimation of power-suppressed $(\Lambda^2/Q^2)^p$ corrections to inclusive as well as exclusive processes' characteristics [4-6]. It is known that ir renormalons are responsible for factorial growth of coefficients in perturbative series for physical quantities [7]. But these series can be resummed by means of the Borel transformation and thus, a «resummed» expression for a physical quantity can be defined [8]. From the mathematical point of view, all order resummation of such $(-\beta_0\alpha_S/4\pi)^n$ corrections corresponds to the calculation of the one-loop Feynman diagrams with the running coupling constant $\alpha_S(-k^2)$ at the vertices, where k is the momentum flowing through the virtual gluon line. From the physical point of view this method extends the domain of applicability of pQCD towards lower values of Q^2 than in traditional approaches, by taking into account the power-suppressed (higher twist) corrections.

In the work [9] authors have computed the ir renormalon corrections to the mesons' DA. In our paper we consider the impact of these corrections on the mesons electromagnetic (elm) ffs $F_M(Q^2)$ and the photon-meson transition $\gamma^*+\gamma\to\pi^0$ form factor $F_{\pi\gamma}(Q^2)$.

2. THE INFRARED RENORMALON CORRECTED DISTRIBUTION AMPLITUDES

The meson M distribution amplitude $\Phi_M(x,\mu^2)$ has two important features, i.e. its dependence on x (or its shape) and evolution depending on the factorization scale μ^2. The DA is a phenomenological model function, and information about its shape should be taken either from non-perturbative calculations (QCD sum rules, for example), or from experiments. But evolution of $\Phi_M(x,\mu^2)$ as a function of μ^2 can be predicted using tools of pQCD.

The evolution equation for $\Phi_M(x,\mu^2)$, that is took into account ir renormalon effects, is given by the formula [9] (see, also [10])

$$\left[\mu^2\frac{\partial}{\partial\mu^2}-b_0\alpha_S^2\frac{\partial}{\partial\alpha_S}\right]\Phi_M(x,\mu^2)=\frac{\alpha_S}{4\pi}\int_0^1 V\left[x,y;\alpha_S(\mu^2)\right]\Phi_M(y,\mu^2)dy \quad , \qquad (1)$$

where $b_0=(11-2n_f/3)/4\pi=\beta_0/4\pi$, α_S is the one-loop QCD coupling constant

$$\alpha_S(\mu^2)=\frac{4\pi}{\beta_0\ \ln(\mu^2/\Lambda^2)} \qquad (2)$$

In Eq.(1) $V[x,y;\alpha_S(\mu^2)]$ is the evolution kernel obtained after resumming the $(-\beta_0\alpha_S/4\pi)^n$ corrections [9]

$$V[x,y;\alpha_S(\mu^2)]=C_F\frac{1+\alpha}{3}\frac{\Gamma(4+2\alpha)}{\Gamma(1-\alpha)\Gamma^2(2+\alpha)}$$
$$\times\left[\theta(y>x)\left(\frac{x}{y}\right)^{1+\alpha}\left(1+\alpha+\frac{1}{y-x}\right)+(x\leftrightarrow 1-x,\ y\leftrightarrow 1-y)\right]_+ , \qquad (3)$$

where $\Gamma(z)$ is the gamma function, C_F=4/3 is the color factor. Here, the following notations are used:

$$\alpha \equiv \beta_0\alpha_s / 4\pi, [F(x,y)]_+ = F(x,y) - \delta(x-y)\int_0^1 F(t,y)dt$$

The eigenfunctions of the kernel $V[x,y;\alpha_S(\mu^2)]$ are the Gegenbauer polynomials

$$\Phi_n(x,\mu^2) = C_n^{3/2+\alpha}(2x-1), \qquad (4a)$$

and the corresponding eigenvalues are the anomalous dimensions $\gamma_n(\alpha_S)$:

$$\gamma_n(\alpha_s) = C_F \frac{(1+\alpha)^2\Gamma(4+2\alpha)}{3(2+\alpha)\Gamma^3(2+\alpha)\Gamma(1-\alpha)}\left\{1 - \frac{(1+\alpha)(2+\alpha)}{(1+\alpha+n)(2+\alpha+n)} + \frac{2(2+\alpha)}{1+\alpha}\left[\psi(2+\alpha+n) - \psi(2+\alpha)\right]\right\}, \qquad (4b)$$

where $\psi(z) = (d/dz)\ln\Gamma(z)$. Then the meson DA can be expanded over Gegenbauer polynomials $\left\{C_n^{3/2+\alpha}(\zeta)\right\}$

$$\Phi_M(x,\mu^2) = f_M[x(1-x)]^{1+\alpha}\sum_{n=0}^{\infty} b_n(\mu^2)A_n(\alpha_S)C_n^{3/2+\alpha}(2x-1), \qquad (5)$$

In Eq.(5) the sum runs over even n for the pion and ρ_L - meson, and n takes all values in the case of the kaon, because the kaon DA contains also antisymmetric part (under replacement $2x-1 \leftrightarrow 1-2x$). Here, f_M is the meson M decay constant, for the pion normalized to f_π=0.093 GeV. In accordance with this normalization, which differs from that of Ref.[9], $A_n(\alpha_S)$ is given by the expression

$$A_n(\alpha_S) = \frac{\Gamma(3+2\alpha)}{\sqrt{3}\Gamma(1+\alpha)\Gamma(2+\alpha)} \cdot \frac{(n)!}{(2+2\alpha)_n} \cdot \frac{3+2\alpha+2n}{2+2\alpha+n}, \qquad (6)$$

where $(a)_n$ is the Pochhammer symbol, $(a)_n = \Gamma(a+n)/\Gamma(a)$.

In this work we neglect the dependence of $\Phi_M(x,\mu^2)$ on the factorization scale μ^2, therefore we do not write down the expression for $b_n(\mu^2)$. In our calculations we use the Gegenbauer polynomials up to n=4, the explicit expressions of which one can find in Appendix A.

The ir renormalon corrected formulae for $\Phi_M(x,\mu^2)$, $C_n^{3/2+\alpha}(2x-1)$, $\gamma_n(\alpha_S)$ and $A_n(\alpha_S)$ in the limit $\alpha\to 0$ coincide with well known one-loop expressions [1-3].

3. ELECTROMAGNETIC FORM FACTOR $F_M(Q^2)$.

In the perturbative QCD the meson M elm form factor $F_M(Q^2)$ has the form [1,3],

$$F_M(Q^2) = \int_0^1\int_0^1 dxdy\Phi_M^*(y,Q^2)T_H(x,y;Q^2,\alpha_S(\mu_R^2))\Phi_M(x,Q^2). \qquad (7)$$

In Eq.(7) Q^2 is the momentum transfer in the process $Q^2=-q^2$, where q^2 is the square of the virtual photon's γ^* four-momentum. The factorization scale μ_F^2 in (7) is chosen equal to Q^2. The function $T_H(x,y;Q^2,\alpha_S(\mu_R^2))$ is the hard-scattering amplitude of the subprocess $q\bar{q}' + \gamma^* \to q\bar{q}'$ and at the leading order of pQCD it is as follows

$$T_H(x,y;Q^2,\alpha_S(\mu_R^2)) = \frac{16\pi C_F\alpha_S(\mu_R^2)}{Q^2}\left[\frac{2}{3}\cdot\frac{1}{(1-x)(1-y)} + \frac{1}{3}\cdot\frac{1}{xy}\right]. \qquad (8)$$

In the frozen coupling constant approximation the appropriate choice for the renormalization scale in Eq.(8) is $\mu_R^2=Q^2/4$ which we further use. The hard-scattering amplitude T_H in (8) is valid for both mesons with symmetric and non-symmetric DA.

The DAs of the pion and longitudinally polarized ρ_L-meson are symmetric and, therefore the sum in Eq.(5) contains only even $C_{2n}^{3/2+\alpha}(2x-1)$. In the literature the various model DAs for these mesons have been proposed [3,11,12]. In our work we consider the general case of DA with n = 0,2,4 in (5).

For our purposes it is convenient to expand the DA in powers of x. After simple calculations, using expressions from Appendix A, we obtain

$$\Phi_M(x,\mu^2) = f_M\left[x(1-x)\right]^{1+\alpha}\sum_{n=0}^{4} B_n(\alpha_S)x^n. \qquad (9)$$

The expressions for new coefficients $B_n(\alpha_S)$ are written down in Appendix B.

Using the distribution amplitude from Eq.(9) and Eqs. (7), (8) for the elm form factor $F_M(Q^2)$ of the pion (ρ_L - meson) we get

$$Q^2F_M(Q^2) = C\frac{16\pi f_M^2}{9}\frac{\alpha_S(Q^2/4)}{(1+\alpha)^2}\left[K(\alpha_S)+L(\alpha_S)\right]^2 , \quad (10)$$

where the functions $K(\alpha_S)$, $L(\alpha_S)$ have the forms

$$K(\alpha_S) = 3+2\alpha+b_2(7+2\alpha)-b_2\frac{(1+\alpha)(5+2\alpha)(7+2\alpha)}{(2+\alpha)(3+2\alpha)} \quad (11)$$

and

$$\begin{aligned} L(\alpha_S) = b_4\Bigg[&\frac{3}{4}\frac{11+2\alpha}{(2+\alpha)(3+\alpha)}+\frac{1}{4}\frac{(3+2\alpha)(7+2\alpha)(11+2\alpha)}{(2+\alpha)(3+\alpha)} \\ &-4\frac{(7+2\alpha)(11+2\alpha)}{3+2\alpha}+6\frac{(4+\alpha)(7+2\alpha)(11+2\alpha)}{(2+\alpha)(3+2\alpha)} \\ &-4\frac{(4+\alpha)(7+2\alpha)(9+2\alpha)(11+2\alpha)}{(2+\alpha)(3+2\alpha)(5+2\alpha)} \\ &+\frac{(4+\alpha)(5+\alpha)(7+2\alpha)(9+2\alpha)(11+2\alpha)}{(2+\alpha)(3+\alpha)(3+2\alpha)(5+2\alpha)}\Bigg] . \end{aligned} \quad (12)$$

For the pion the factor C in Eq.(10) is $C = 1$, for the ρ_L -meson $C = -2$ (the origin of 2 and minus sign has been explained in our work [13]).

The similar calculations can be done also for the kaon, DA of which contains odd n (see, Eq.(5)). In our computations of $Q^2F_K(Q^2)$ in Eq.(5) we include terms up to n=3. We find

$$Q^2F_K(Q^2) = \frac{16\pi f_K^2}{9}\frac{\alpha_S(Q^2/4)}{(1+\alpha)^2}\left[K^2(\alpha_S)+M^2(\alpha_S)+\frac{2}{3}K(\alpha_S)M(\alpha_S)\right] . \quad (13)$$

Here $M(\alpha_S)$ is

$$\begin{aligned} M(\alpha_S) = &-b_1(5+2\alpha)-b_3(9+2\alpha)+2b_1\frac{(2+\alpha)(5+2\alpha)}{3+2\alpha}+6b_3\frac{(3+\alpha)(9+2\alpha)}{3+2\alpha} \\ &-3b_3\frac{(3+\alpha)(7+2\alpha)(9+2\alpha)}{(2+\alpha)(3+2\alpha)}+2b_3\frac{(3+\alpha)(4+\alpha)(7+2\alpha)(9+2\alpha)}{(2+\alpha)(3+2\alpha)(5+2\alpha)} \end{aligned} \quad (14)$$

The results (10), (13) will be used later for estimation of ir renormalon effects in $F_M(Q^2)$.

4. THE PHOTON-MESON TRANSITION FORM FACTOR $F_{\pi\gamma}(Q^2)$.

The photon-meson transition ff $F_{M\gamma}(Q^2)$ for the pseudoscalar meson M is defined in terms of the amplitude $\Gamma_{\mu\nu}$ for the process $\gamma^*+\gamma\to M$

$$\Gamma_{\mu\nu} = e^2F_{M\gamma}(Q^2)\varepsilon_{\mu\nu\alpha\beta}P^\alpha q^\beta , \quad (15)$$

where P and q are the momenta of the meson and virtual photon, $Q^2=-q^2>0$.

In the framework of pQCD this form factor can be calculated by means of the formula [1]

$$F_{M\gamma}(Q^2) = \int_0^1 dx\Phi_M(x,Q^2)T_H(x,Q^2,\alpha_S(Q^2)) . \quad (16)$$

Here $T_H(x,Q^2,\alpha_S(Q^2))$ is the hard-scattering amplitude of the subprocess $\gamma^*+\gamma\to q\bar{q}$. The amplitude T_H has been computed with the next-to-leading order accuracy [14],

$$T_H(x,Q^2,\alpha_S(Q^2)) = \frac{N}{Q^2}\frac{1}{1-x}\left\{1+C_F\frac{\alpha_S(Q^2)}{4\pi}\left[\ln^2(1-x)-\ln x-9\right]\right\}+\left[x\leftrightarrow(1-x)\right] . \quad (17)$$

In Eq. (17) N is the normalization constant, which for π^0 is

$$N = \sqrt{12}(e_u^2 - e_d^2) \quad . \qquad (18)$$

The factorization and renormalization scales μ_F^2, μ_R^2 in Eq.(17) are taken equal to Q^2.

After some calculations we obtain

$$F_{\pi\gamma}(Q^2) = \frac{N}{Q^2} f_\pi \left\{ \frac{K(\alpha_S) + L(\alpha_S)}{\sqrt{3}(1+\alpha)} + C_F \frac{\alpha_S(Q^2)}{4\pi} \sum_{n=0}^{4} B_n(\alpha_S)\left[f_n(\alpha_S) + g_n(\alpha_S)\right] \right. \quad . \qquad (19)$$

In Eq.(19) the functions $f_n(\alpha_S)$ and $g_n(\alpha_S)$ are

$$\begin{aligned} f_n(\alpha_S) = B(1+\alpha, n+2+\alpha)\{&[\psi(1+\alpha) - \psi(n+3+2\alpha)]^2 + \psi'(1+\alpha) \\ &- \psi'(n+3+2\alpha) - [\psi(n+2+\alpha) - \psi(n+3+2\alpha)] - 9\} \end{aligned} \qquad (20)$$

and

$$\begin{aligned} g_n(\alpha_S) = B(2+\alpha, n+1+\alpha)\{&[\psi(n+1+\alpha) - \psi(n+3+2\alpha)]^2 + \psi'(n+1+\alpha) \\ &- \psi'(n+3+2\alpha) - [\psi(2+\alpha) - \psi(n+3+2\alpha)] - 9\} \end{aligned} \qquad (21)$$

with $B(x,y)$ being the Beta function $B(x,y)=\Gamma(x)\Gamma(y)/\Gamma(x+y)$.

5. NUMERICAL RESULTS AND CONCLUDING REMARKS

For estimation of the ir renormalon effects and their phenomenological consequences it is instructive to introduce the ratio

$$R\left(F_{M(\pi\gamma)}\right) = \frac{\left[Q^2 F_{M(\pi\gamma)}\left(Q^2\right)\right]^{ren.}}{\left[Q^2 F_{M(\pi\gamma)}\left(Q^2\right)\right]^0} \quad , \qquad (22)$$

where $[Q^2 F_{M(\pi\gamma)}(Q^2)]^{ren}$ is the meson M elm form factor or photon-pion transition form factor found using DAs from Eq.(5), $[Q^2 F_{M(\pi\gamma)}(Q^2)]^o$ are the same quantities, but obtained by means of the ordinary DAs .

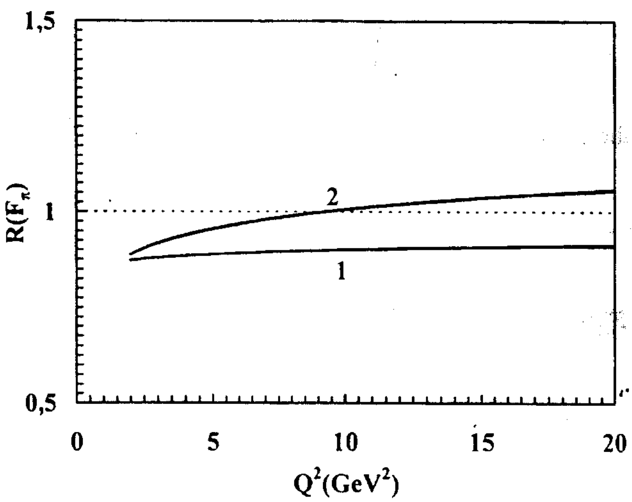

Fig.1. The ratio $R(F_\pi)$ as a function of Q^2. The curve 1 is calculated using the asymptotic DA, the curve 2 - model DA.

Results for the ratio $R(F_M)$ calculated using the asymptotic DA (n=0 in Eq.(5)) coincide with each other, because in this case form factors $F_{\pi(K,\rho_L)}(Q^2)$ differ only by factors C and f_M, canceling in the ratio (22). The ratio $R(F_M)$ for $\phi_M^{asy}(x)$ is shown in Fig.1 (curve 1). As is seen, ir renormalon effects are approximately stable in the considered region $2GeV^2 \le Q^2 \le 20GeV^2$. Indeed, if $R(F_M) \cong 0.87$ at $Q^2=2GeV^2$ then at $Q^2=20GeV^2$ it takes the value $R(F_M) \cong 0.91$, the difference being only 0.04. The same ratio calculated for the pion using model DA is depicted in Fig.1 (curve 2). It is

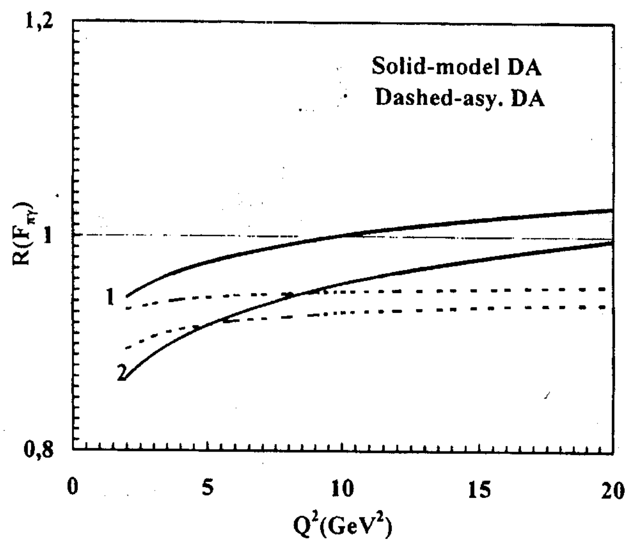

Fig.2. The same, but for $R(F_{\pi\gamma})$. The curves 1 (solid and dashed) are calculated using only the leading order expression for $F_{\pi\gamma}$, curves 2 - by means of the LO+NLO result.

worth noting that the coefficients $b_n(\mu^2)$ in Eq.(5) are taken at the normalization point $\mu_0^2=1GeV^2$ and are equal to [9]

$$b_0=1 \quad , \quad b_2=1.1 \quad , \quad b_4=1,$$

for the ordinary DA and to

$$b_0=1 \quad , \quad b_2=1.7 \quad , \quad b_4=1.6,$$

for the ir renormalon corrected DA. Now impact of the ir renormalons on the form factor $F_\pi(Q^2)$ in various domains of the region is different. Thus, for $Q^2<10GeV^2$ we have $R(F_\pi)<1$, whereas for $Q^2\geq 10GeV^2$ - $R(F_\pi)\geq 1$, and the difference is

$$R(20GeV^2)-R(2GeV^2)\cong 0.17 .$$

The situation with the photon-pion transition form factor $F_{\pi\gamma}(Q^2)$ is approximately the same. In Fig.2 one can observe the results of our numerical computations for $R(F_{\pi\gamma})$. For asymptotic DA (with and without the next-to-leading order correction) $R<1$ in the whole region $2GeV^2\leq Q^2\leq 20GeV^2$. For model DA the ratio $R>1$ for $Q^2\geq 10GeV^2$, when we use only the leading order expression and $R<1$, if we take into account also NLO correction. In the both cases (model and asymptotic DA) the ratio $R(F_{\pi\gamma})$ calculated using the LO result and NLO correction is lower than one found by considering only LO expression. In other words, NLO correction to $F_{\pi\gamma}(Q^2)$ is more sensitive to ir renormalon contributions than the LO.

In this work we have computed $F_M(Q^2)$ and $F_{\pi\gamma}(Q^2)$ using the frozen coupling constant approximation and DAs, where the ir renormalon effects have been taken into account. Almost in the all cases the ir renormalon effects reduce the hard contributions to $F_M(Q^2)$, $F_{\pi\gamma}(Q^2)$ and numerical values of these effects depend on a process and a distribution amplitude under consideration. Our next step is calculation of these form factors in the context of the running coupling constant method and DAs from Eq.(5), and comparing the results with our previous works [6,13] and with experimental data.

APPENDIX A.

The Gegenbauer polynomials $C_n^{3/2+\alpha}(\xi)$ which we use in our calculations, have the following form

$$C_0^{3/2+\alpha}(\xi) = 1 , \quad C_1^{3/2+\alpha}(\xi) = (3+2\alpha)\xi ,$$

$$C_2^{3/2+\alpha}(\xi) = \frac{3+2\alpha}{2}\left[(5+2\alpha)\xi^2-1\right],$$

$$C_3^{3/2+\alpha}(\xi) = \frac{(3+2\alpha)(5+2\alpha)}{6}\xi\left[(7+2\alpha)\xi^2-3\right],$$

$$C_4^{3/2+\alpha}(\xi) = \frac{(3+2\alpha)(5+2\alpha)}{24}\left[(7+2\alpha)(9+2\alpha)\xi^4-6(7+2\alpha)\xi^2+3\right].$$

APPENDIX B.

The coefficients $B_n(\alpha_S)$ of the DA are given as

$$B_0(\alpha_S) = A_0(\alpha_S)+b_2A_2(\alpha_S)(3+2\alpha)(2+\alpha)+\frac{A_4(\alpha_S)b_4}{8}(3+2\alpha)(5+2\alpha) \times\left[1+\frac{1}{3}(7+2\alpha)(3+2\alpha)\right],$$

$$B_1(\alpha_S) = -2A_2(\alpha_S)b_2(3+2\alpha)(5+2\alpha)-\frac{2}{3}A_4(\alpha_S)b_4(3+\alpha)(3+2\alpha)(5+2\alpha)(7+2\alpha),$$

$$B_2(\alpha_S) = 2A_2(\alpha_S)b_2(3+2\alpha)(5+2\alpha)+2A_4(\alpha_S)b_4(4+\alpha)(3+2\alpha)(5+2\alpha)(7+2\alpha),$$

$$B_3(\alpha_S) = -\frac{4}{3}A_4(\alpha_S)b_4(3+2\alpha)(5+2\alpha)(7+2\alpha)(9+2\alpha),$$

$$B_4(\alpha_S) = \frac{2}{3}A_4(\alpha_S)b_4(3+2\alpha)(5+2\alpha)(7+2\alpha)(9+2\alpha).$$

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YÜNGÜL *M* MEZONLARIN PAYLANMA FUNKSİYALARINDA İNFRAQIRMIZI RANORMALON EFFEKTLƏRİ VƏ $F_M(Q^2)$, $F_{\pi\gamma}(Q^2)$ FORMFAKTORLARI

Yüngül psevdoskalyar (pion, kaon) və uzununa polyarizə olunmuş ρ-mezonun elektromaqnit formfaktorları $F_M(Q^2)$ və $\gamma^*+\gamma\to\pi^0$ keçid formfaktoru "donmuş" qarşılıqlı tə`sir sabiti yaxınlaşmasında, mezonların infraqırmızı renormalon effektlərini nəzərə alan paylanma funksiyalarının (PF) köməyilə hesablanmışdır. Hesablamalarda asimptotik və model PF-dan istifadə olunmuşdur. Adi PF vasitəsilə alınmış nəticələrlə müqayisə aparılmışdır.

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ЭФФЕКТЫ ИНФРАКРАСНЫХ РЕНОРМАЛОНОВ НА ФУНКЦИЯХ РАСПРЕДЕЛЕНИЯ ЛЕГКИХ МЕЗОНОВ *M* И ФОРМФАКТОРЫ $F_M(Q^2)$, $F_{\pi\gamma}(Q^2)$

Электромагнитные формфакторы $F_M(Q^2)$ легких псевдополярных (пион, каон) и продольно поляризованного ρ-мезона и формфактор перехода $\gamma^*+\gamma\to\pi^0$ вычислены с помощью приближения «замороженной» константы связи и функций распределения (ФР) мезонов, в которых учтены эффекты инфракрасных ренормалонов. При вычислениях использованы асимптотическая и модельная ФР. Проведено сравнение с результатами, полученными с использованием обычных ФР.

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