On multi-particle functions and pion-decay constant in Nambu–Jona-Lasinio model

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Abstract

The system of second-order equations of mean-field expansion is considered for Nambu–Jona-Lasinio model with chiral symmetry of SU(2)-group. The system includes equations for four-particle and three-particle functions and also equations for next-to-leading two-particle function and next-to-next-to-leading quark propagator. Exact solutions for four-particle and three-particle equations are obtained. The solution for four-particle function is a disconnected combination of the leading-order two-particle functions. The connected part of three-particle function includes two-meson and three-meson contributions. The solution of three-particle equation permits to close the equation for next-to-leading two-particle function and to calculate a correction to pion-decay constant $f_\pi$. This correction increases from 14% to 28% when values of quark condensate varies from $-(210\,MeV)^3$ to $-(250\,MeV)^3$.

Introduction and Summary

Nambu-Jona-Lasinio (NJL) model with quark content is one of the most successful effective models of quantum chromodynamics of light hadrons (for review see [1]-[3]). A number of physical applications of NJL model is connected with multi-quark functions, which are the subject of present work. These multi-quark functions arise in higher orders of the mean-field expansion (MFE) for NJL model. To formulate MFE we have used an iteration scheme of solution of Schwinger-Dyson equation with fermion bilocal source, which has been developed in works [4]. We have considered equations for Green functions of NJL model up to the second order of MFE. The leading approximation and the first order of MFE maintain equations for the quark propagator and the two-particle function and also the next-to-leading (NLO) correction to the quark propagator. The second order of MFE includes the equations for four-particle and three-particle functions and also equations for the NLO two-particle function and the next-to-next-to-leading (NNLO) quark propagator.

We have found solutions for the four-particle and three-particle equations. The solution for four-particle function is a disconnected combination of the leading-order two-particle functions, consequently, the physical effects, which connected with four-particle function (i.e., pion-pion scattering), are suppressed in this order of MFE.

The solution of four-particle equation gives us a possibility to close the equation for three-particle function. The solution of three-particle equation contains both disconnected and connected parts. The connected part of three-particle function includes two-meson and three-meson contributions.

The solution of three-particle equation permits to close the equation for NLO two-particle function and to calculate a correction to pion-decay constant $f_\pi$. This correction varies from 14% to 28% when values of quark condensate varying from $-(210\,MeV)^3$ to $-(250\,MeV)^3$.

The correction to pion-decay constant has been calculated early in work [5] in the framework of improved $1/n_c$ expansion by using the partially bosonized version of NJL model (see also [6]). Our
result is in accordance with results of these work, though the method of the calculation is different. This fact demonstrates a self-consistency of NJL model concerning to high-order corrections.

1 Mean-field expansion in bilocal-source formalism

We consider NJL model with chiral symmetry \( SU_V(2) \times SU_A(2) \). The model Lagrangian is

\[
\mathcal{L} = \bar{\psi} i \hat{\partial} \psi + \frac{\mu}{2} \left[ (\bar{\psi} \psi)^2 + (\bar{\psi} i \gamma_5 \tau \psi)^2 \right].
\]

(1)

Here \( \psi \) is the quark field with \( n_c \) colours, \( g \) is the coupling constant of \( m^{-2} \) dimension, \( \tau \) are Pauli matrices.

The mean-field expansion in the bilocal-source formalism for the model can be constructed with the method of work \([4]\) (see also \([7]\))

Generating functional \( G \) of Green functions is the functional integral

\[
G(\eta) = \int D(\psi, \bar{\psi}) \exp i \left\{ \int dx \mathcal{L} - \int dxdy \bar{\psi}(y) \eta(y,x) \psi(x) \right\}.
\]

(2)

Here \( \eta(y,x) \) is the bilocal source of quark field. \( n \)–th derivative of \( G \) over source \( \eta \) is \( n \)-particle (\( 2n \)-point) Green function \( S_n \left( \begin{array}{c} x_1 \\ \cdots \\ x_n \\ y_1 \\ \cdots \\ y_n \end{array} \right) \).

As a consequence of translational invariance of the functional-integration measure in (2) we have the functional-derivative Schwinger-Dyson equation:

\[
\delta(x-y)G + i \hat{\partial}_x \frac{\delta G}{\delta \eta(y,x)} + ig \left\{ \delta \frac{\delta G}{\delta \eta(x,x)} \right\} - \gamma_5 \tau \delta \frac{\delta G}{\delta \eta(x,x)} = \int dx_1 \eta(x_1) \frac{\delta G}{\delta \eta(y,x_1)}.
\]

(3)

As a leading approximation for the mean-field expansion we consider equation (3) without right-hand-side. A solution of the leading-order equation is the functional

\[
G^{(0)} = \exp \left\{ \text{Tr} \left[ S * \eta \right] \right\}
\]

(4)

(Here and below Tr denotes the operator trace, and \(*\) denotes the operator multiplication.) Function \( S \) is a solution of the equation

\[
\delta(x) + i \hat{\partial}S(x) + igS(x) \text{ tr } [S(0)] = 0.
\]

(5)

This equation is in essence the coordinate form of the well-known gap equation for the quark propagator. In the leading approximation the unique connected Green function is quark propagator

\[
S_1^{(0)} \equiv S = (m - \not{p})^{-1}.
\]

(Here \( m \) is a quark dynamical mass.

The leading approximation (4) generates the linear iteration scheme:

\[
G = G^{(0)} + G^{(1)} + \cdots + G^{(n)} + \cdots,
\]

where functional \( G^{(n)} \) is a solution of the iteration-scheme equation

\[
G^{(n)} + i \hat{\partial} \frac{\delta G^{(n)}}{\delta \eta} + ig \left\{ \delta \frac{\delta G^{(n)}}{\delta \eta} \right\} - \gamma_5 \tau \delta \frac{\delta G^{(n)}}{\delta \eta} = \eta * \frac{\delta G^{(n-1)}}{\delta \eta}.
\]

(6)
The general solution of equation (6) is the functional
\[ G^{(n)} = P^{(n)} G^{(0)}, \]
where \( P^{(n)} \) is a polynomial of 2\( n \)-th degree on source \( \eta \).

## 2 First-step equations

The functional of the first step of the iteration scheme is
\[
\left\{ \frac{1}{2} \text{Tr} [S_2 \ast \eta^2] + \text{Tr} [S^{(1)} \ast \eta] \right\} G^{(0)}.
\]
Here \( S_2 \) is the two-particle function, \( S^{(1)} \) is the NLO quark propagator. Taking into account the leading-order equations we have the system of equations for \( S_2 \) and \( S^{(1)} \).

The equation for \( S_2 \) has the form
\[
S_2 \left( \begin{array}{cc} x & y \\ x' & y' \end{array} \right) = -S(x-y')S(x'-y) + \]
\[
+ig \int dx_1 \left\{ (S(x-x_1)S(x_1-y)) \text{tr}_u \left[ S_2 \left( \begin{array}{cc} x_1 & x_1 \\ x' & y' \end{array} \right) \right] \right\} -
\]
\[
-(S(x-x_1)\gamma_5 S(x_1-y)) \text{tr}_u \left[ \gamma_5 S_2 \left( \begin{array}{cc} x_1 & x_1 \\ x' & y' \end{array} \right) \right].
\]
Here \( \text{tr}_u \) denotes the trace, which includes the upper line of function \( S_2 \).

A solution of equation (7) is well-known. Usually such equation is solved in momentum space. We give the solution of this equation in coordinate space since a similar method will be used for solving the equation for the three-particle function.

Let us go to the amputated function
\[
F_2 = S^{-1} \ast S^{-1} \ast S_2 \ast S^{-1} \ast S^{-1}
\]
and define the connected part
\[
F_2^c \left( \begin{array}{cc} x & y \\ x' & y' \end{array} \right) = F_2 \left( \begin{array}{cc} x & y \\ x' & y' \end{array} \right) + S^{-1}(x-y')S^{-1}(x'-y).
\]

Then for the function \( F_2^c \) we obtain the equation
\[
F_2^c \left( \begin{array}{cc} x & y \\ x' & y' \end{array} \right) = -ig\delta(x-y)\delta(x-y')\delta(x'-y) \{ 1 \cdot 1 - \gamma_5 \tau \cdot \gamma_5 \tau \} +
\]
\[
+ig\delta(x-y) \int dx_1 dy_1 \left\{ \text{tr}_u[S(x-x_1)F_2^c \left( \begin{array}{cc} x_1 & y_1 \\ x' & y' \end{array} \right) S(y_1-y)] \right\} -
\]
\[
-\gamma_5 \tau \text{tr}_u[\gamma_5 \tau S(x-x_1)F_2^c \left( \begin{array}{cc} x_1 & y_1 \\ x' & y' \end{array} \right) S(y_1-y)].
\]

Iterations of this equation reproduce the discrete algebraic structure (colour, isotopic and Lorentz) of the inhomogeneous term. This circumstance permits to write the general form of the solution
\[
F_2^c \left( \begin{array}{cc} x & y \\ x' & y' \end{array} \right) = \delta(x-y)\delta(x'-y') \{ 1 \cdot 1 A_\sigma(x-x') + \gamma_5 \tau \cdot \gamma_5 \tau A_\pi(x-x') \}
\]
\[ (8) \]
Here $A_\sigma$ is the scalar (sigma-meson) amplitude, $A_\pi$ is the pseudoscalar (pion) amplitude. These amplitudes are solutions of equations

$$A_\sigma(x) = -ig\delta(x) + ig \int dx_1 \text{tr} [S(x - x_1)S(x_1 - x)] A_\sigma(x_1),$$

$$A_\pi(x) = ig\delta(x) - ig \int dx_1 \text{tr} [\gamma_5 S(x - x_1)\gamma_5 S(x_1 - x)] A_\pi(x_1).$$

In momentum space

$$A_\sigma(p) = \frac{1}{4n_c(4m^2 - p^2)I_0(p)}; \quad A_\pi(p) = \frac{1}{4n_c p^2 I_0(p)},$$

where

$$I_0(p) = \int \frac{d^4q}{(2\pi)^4} \frac{1}{(m^2 - (p + q)^2)(m^2 - q^2)}.$$ (10)

The integral in equation (10) is divergent and should be dealt with by some regularization.

The equation for the NLO propagator $S^{(1)}$ is a system of simple algebraic equations. Introducing the first-order mass operator with formula $\Sigma^{(1)} = S^{-1} * S^{(1)} * S^{-1}$, we obtain for $\Sigma^{(1)}$ the following expression

$$\Sigma^{(1)}(x) = ig\delta(x) \text{tr} [S^{(1)}(0)] + S(x)A_\sigma(x) + 3\gamma_5 S(x)\gamma_5 A_\pi(x).$$ (11)

### 3 Second-step equations. Solutions for four-particle and three-particle functions

The second-step generating functional is

$$G^{(2)} = \left\{ \frac{1}{4!} \text{Tr} \left( S_4 * \eta^4 \right) + \frac{1}{3!} \text{Tr} \left( S_3 * \eta^3 \right) + \frac{1}{2!} \text{Tr} \left( S_2^{(1)} * \eta^2 \right) + \text{Tr} \left( S^{(2)} * \eta \right) \right\} G^{(0)},$$

i.e., second-step equations define four-particle function $S_4$, three-particle function $S_3$, and also NLO two-particle function $S_2^{(1)}$ and NNLO propagator $S^{(2)}$. For these four functions we have a system of four integral equations. All these equations (and all equations of following steps of the iteration scheme) possess the common structure, which is similar to the structure of equation (7):

$$S_n \left( \begin{array}{cccc} x_1 & y_1 \\ \vdots & \vdots \\ x_n & y_n \end{array} \right) = S_n^0 \left( \begin{array}{cccc} x_1 & y_1 \\ \vdots & \vdots \\ x_n & y_n \end{array} \right) +$$

$$+ ig \int dx'_1 \left\{ (S(x_1 - x'_1)S(x'_1 - y_1)) \text{tr} u \left[ S_n \left( \begin{array}{cccc} x'_1 & x'_1 \\ \vdots & \vdots \\ x_n & y_n \end{array} \right) \right] -$$

$$-(S(x_1 - x'_1)\gamma_5 \tau S(x'_1 - y_1)) \text{tr} u \left[ \gamma_5 \tau S_n \left( \begin{array}{cccc} x'_1 & x'_1 \\ \vdots & \vdots \\ x_n & y_n \end{array} \right) \right] \right\}$$

Difference becomes apparent in the structure of inhomogeneous terms. The inhomogeneous term in the equation for $S_4$ is

$$S_4^0 \left( \begin{array}{cccc} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_4 \end{array} \right) = - \left\{ S(x_1 - y_2)S(x_2 - y_1)S_2 \left( \begin{array}{cccc} x_3 & y_3 \\ x_4 & y_4 \end{array} \right) \right\} - \left\{ 2 \leftrightarrow 3 \right\} - \left\{ 2 \leftrightarrow 4 \right\}.$$

(13)
where $S_2$ is defined in preceding section, i.e. the equation for $S_4$ does not include another three second-step functions. The inhomogeneous term in the equation for three-particle function $S_3$ includes function $S_4$. This inhomogeneous term has the form

$$S_3^0\left(\begin{array}{ccc} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \end{array}\right) = -S(x_1 - y_2)S(x_2 - y_3)S(x_3 - y_1)S(x_4 - y_1) - S(x_1 - y_3)S(x_3 - y_1)S(x_4 - y_2) - \quad (14)$$

$$-S(x_1 - y_2)S_2(x_2 - y_3) - S(x_1 - y_3)S_2(x_3 - y_2) +$$

$$+ig \int dx_1 S(x_1 - x_1')\left\{ \text{tr}_u[S_4\left(\begin{array}{ccc} x_1' & x_1 \\ x_2' & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \end{array}\right)] - \gamma_5 \tau \text{tr}_u[\gamma_5 \tau S_4\left(\begin{array}{ccc} x_1' & x_1 \\ x_2' & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \end{array}\right)]\right\}$$

Similarly, the inhomogeneous term in equation for $S_2^{(1)}$ includes function $S_3$, and the inhomogeneous term of the equation for $S_2^{(2)}$ includes function $S_4^{(1)}$.

Due to such structure of the system its solution should be started by equation for four-particle function $S_4$, then should be solved the equation for three-particle function $S_3$, etc.

The equation for four-particle function $S_4$ with the inhomogeneous term (13) has the simple solution (see also [8])

$$S_4\left(\begin{array}{ccc} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_4 \end{array}\right) = S_2\left(\begin{array}{ccc} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_4 \end{array}\right) S_2\left(\begin{array}{ccc} x_3 & y_3 \\ x_4 & y_4 \end{array}\right) + \left\{ 2 \leftrightarrow 3 \right\} + \left\{ 2 \leftrightarrow 4 \right\} \quad (15)$$

This solution is disconnected, and it means the absence of physical effects due to four-particle functions in the given order of mean-field expansion. Particularly, the pion-pion scattering is absent in the given order and will appear in the next order.

Solution (15) of the equation for four-particle function gives us the closed equation of type (12) for three-particle function $S_3$. The solution of this equation with inhomogeneous term (14) can be obtained likewise to solving of equation (7) for the two-particle function. We go to the amputated function

$$F_3 = S^{-1} * S^{-1} * S^{-1} * S_3 * S^{-1} * S^{-1} * S^{-1}$$

and then separate the functions with the algebraic structures, which are reproduced after iterations. Connected part of the amputated three-particle function possesses two-meson and three-meson contributions. The explicit form of this function in momentum space see in Appendix.

### 4 Two-particle function and pion-decay constant

The solution of the equation for three-particle function permits to close the equation for NLO two-particle function $S_2^{(1)}$. This equation differs from equation (7) only by inhomogeneous term. The inhomogeneous term in equation for $S_2^{(1)}$ is

$$S_2^{0(1)}\left(\begin{array}{ccc} x & y \\ x' & y' \end{array}\right) = -S(x - y')S^{(1)}(x' - y) +$$

$$+ig \int dx_1 S(x - x_1)\left\{ \text{tr}_u[S_3\left(\begin{array}{ccc} x_1 & x_1 \\ x_1 & y \\ x & y' \end{array}\right)] - \gamma_5 \tau \text{tr}_u[\gamma_5 \tau S_3\left(\begin{array}{ccc} x_1 & x_1 \\ x' & y \\ x' & y' \end{array}\right)]\right\}$$
The two-particle function of the second step enables to calculate a correction to pion-decay constant \( f_\pi \), which is one of the basic strong-interaction parameters. The pion-decay constant is defined by the relation

\[
i f_\pi \delta^{bb'} P_\mu = < 0 | J^b_\mu | P, b' >,
\]

where \( | P, b' > \) is the pion state with momentum \( P \) and isospin \( b \), and \( J^b_\mu = \bar{\psi} \gamma_\mu \gamma_5 \frac{T^b}{2} \psi \) is the axial current. If the two-particle function has a pole term \( S_2^{pole} \), which corresponds to the pion, then, taking into account these definitions, this pole term is connected with the pion-decay constant by relation

\[
\tilde{\delta}(P - P') f_\pi^2 = i \int dx dx' e^{i(P x - P' x')} \text{tr}_{u,d}[\gamma_\mu \gamma_5 \frac{T}{2} \cdot \gamma_\mu \gamma_5 \frac{T}{2} S_2^{pole} (x \ x \ x \ x')].
\]

Here \( \text{tr}_{u,d} \) denotes the traces over up and down lines of function \( S_2^{pole} \).

In the leading order we obtain from (16) the well-known expression for the pion-decay constant (see, for example, [1]):

\[
(f_\pi^{(0)})^2 = -4in_c m^2 I_0(0),
\]

where \( I_0 \) is defined by formula (10). For a regularization with four-dimensional cutoff \( I_0(0) = \frac{i}{(4\pi)^2} \left[ \log \frac{\Lambda^2 + m^2}{m^2} - \frac{\Lambda^2}{\Lambda^2 + m^2} \right] \), where \( \Lambda \) is the cutoff parameter.

In the next-to-leading order formula (16) defines correction \((f_\pi^{(1)})^2\) to expression (17). Surely, to calculate this correction it is no need in a complete solution of the NLO two-particle equation. In correspondence with (16) it is quite enough to calculate the pion-pole part only.

The results of calculation of ratio \( r_f = \frac{(f_\pi^{(1)})^2}{(f_\pi^{(0)})^2} \) in the scheme with four-dimensional cutoff are shown in Table for three sets of model parameters. These sets are correspond to different values of chiral quark condensate \( c = \langle \frac{1}{2} \bar{\psi} \psi \rangle \) at physical value of pion-decay constant \( f_\pi = 93 \text{ MeV} \).

| \( c \) (GeV) | \( m \) (GeV) | \( \Lambda \) (GeV) | \( \kappa = 3g\Lambda^2/2\pi^2 \) | \( r_f = \frac{(f_\pi^{(1)})^2}{(f_\pi^{(0)})^2} \) |
|---|---|---|---|---|
| -0.21 | 0.42 | 0.73 | 1.87 | 0.14 |
| -0.23 | 0.28 | 0.87 | 1.33 | 0.20 |
| -0.25 | 0.24 | 1.03 | 1.19 | 0.28 |

Table: Values of ratio \( r_f = \frac{(f_\pi^{(1)})^2}{(f_\pi^{(0)})^2} \) in scheme with four-dimensional cutoff for different sets of values of chiral quark condensate \( c \), quark mass \( m \), regularization parameter \( \Lambda \) and dimensionless coupling \( \kappa \).

Apparently the correction to value of the pion-decay constant increases from 14% to 28% when the absolute value of the quark condensate increases from \((0.21 \text{ GeV})^3\) to \((0.25 \text{ GeV})^3\). These values of the correction to pion-decay constant are not far from results of calculations in works [5]-[6], though the method of calculations is different. This principal correspondence seems to be a reflection of some stability of NJL model with regard to quantum corrections.

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Appendix

The connected part of the three-particle function in the momentum space is

\[ F^c_3 = F^{two-meson}_3 + F^{three-meson}_3 \]

\[ F^{two-meson}_3 = -(S(p + P') + S(p + P'')) \cdot A_\sigma(P') \cdot A_\sigma(P'') - \]

\[ -A_\sigma(P) \cdot (S(p' + P'') + S(p' + P)) \cdot A_\sigma(P') - \]

\[ -A_\sigma(P) \cdot A_\sigma(P') \cdot (S(p'' + P) + S(p'' + P')) + \]

\[ + (\gamma_5 S(p + P') \gamma_5 + \gamma_5 S(p + P'') \gamma_5) \cdot A_\pi(P') \cdot A_\pi(P'') + \]

\[ + A_\sigma(P) \cdot (\gamma_5 S(p' + P'') + S(p' + P) \gamma_5) \cdot \tau \cdot A_\pi(P'') + \]

\[ + A_\sigma(P) \cdot A_\pi(P') \cdot \tau (S(p'' + P) \gamma_5 + \gamma_5 S(p'' + P')) + \]

\[ + (S(p + P') \gamma_5 + \gamma_5 S(p + P'')) \cdot \tau \cdot A_\sigma(P') \cdot A_\pi(P'') + \]

\[ + A_\pi(P) \cdot \tau (S(p' + P'') \gamma_5 + \gamma_5 S(p' + P)) \cdot A_\sigma(P'') + \]

\[ + A_\pi(P) \cdot A_\pi(P') \cdot (\gamma_5 S(p'' + P) \gamma_5 + \gamma_5 S(p'' + P') \gamma_5) + \]

\[ + i(\gamma_5 S(p + P') \gamma_5 - \gamma_5 S(p + P'') \gamma_5) \cdot [A_\pi(P') \times A_\pi(P'')] + \]

\[ + i A_\pi(P) \cdot [(\gamma_5 S(p' + P'') \gamma_5 - \gamma_5 S(p' + P) \gamma_5) \times A_\pi(P'')] + \]

\[ + i A_\pi(P) \cdot [A_\pi(P') \times \tau (\gamma_5 S(p'' + P) \gamma_5 + \gamma_5 S(p'' + P') \gamma_5)] \].

\[ F^{three-meson}_3 = 2 n_c A_\sigma(P) \cdot A_\sigma(P') \cdot A_\sigma(P'') [\Delta_{sss}(P; P + P') + \Delta_{sss}(P; P + P'')] - \]

\[ -2 n_c A_\sigma(P) \cdot A_\pi(P') \cdot A_\pi(P'') [\Delta_{spp}(P; P + P') + \Delta_{spp}(P; P + P'')] - \]

\[ -2 n_c A_\pi(P) \cdot A_\pi(P') \cdot A_\sigma(P'') [\Delta_{spp}(P''; P' + P'') + \Delta_{spp}(P''; P + P'')] - \]

\[ -2 n_c A_\pi(P) \cdot A_\sigma(P') \cdot A_\pi(P'') [\Delta_{spp}(P''; P' + P'') + \Delta_{spp}(P''; P + P')]. \]

Here \( p = p_{x_1,} P = p_{x_1} + p_{y_1}, p' = p_{x_2}, P' = p_{x_2} + p_{y_2}, p'' = p_{x_3}, P'' = p_{x_3} + p_{y_3}, \) are quark momenta and \( P + P' + P'' = 0. \) We also use the notations \( A_\sigma = 1 \circ A_\sigma \) for the scalar-singlet function, \( A_\pi = \gamma_5 \tau \circ A_\pi \) for the pseudoscalar-isovector function (see (9)) and

\[ \Delta_{sss}(P; Q) = \int d\eta \text{tr} [S(P + q)S(Q + q)S(q)], \quad \Delta_{spp}(P; Q) = \int d\eta \text{tr} [S(P + q)\gamma_5 S(Q + q)\gamma_5 S(q)] \]

for quark triangles. (In last formulae the traces are taken over Lorentz spinor indices only.)
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