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TWO LOOP CORRECTION TO THE GLUON TRAJECTORY IN QCD

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НОВОСИБИРСК

Two Loop Correction to the Gluon Trajectory in QCD[1]

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Abstract

The gluon trajectory in QCD is obtained in two loop approximation. It is gained from quark-quark scattering amplitude at large energy $\sqrt{s}$ and fixed momentum transfer $\sqrt{-t}$ with gluon quantum numbers in the t-channel calculated in the two loop approximation with one $log\, s$ accuracy.

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1. Introduction

Perturbative QCD has now a lot of remarkable successes in description of hard processes, where its applicability and power are firmly established. For semihard processes situation is more delicate. It's often claimed, that the perturbation theory can be used for calculation of parton distributions and cross sections of these processes since their typical virtuality Q^2 becomes large enough to ensure a smallness of the strong coupling constant $\alpha_s(Q^2)$. But at sufficiently high energy $\sqrt{s}$ of colliding particles logarithm of the ratio $\frac{1}{x} = \frac{s}{Q^2}$ happens to be so large that it becomes necessary to sum up terms of the type $\alpha_s{}^n(ln\frac{1}{x})^m$. In the leading logarithm approximation (LLA), which means here summation of the terms with $n = m$, this problem was solved many years ago [1]. Now results of the LLA are widely used. But these results have at least two serious disadvantages. Firstly, s-channel unitarity constraints are not fulfilled for scattering amplitudes in the LLA that leads to violation of the Froissart bound $\sigma_{tot}\langle c(\ln s)^2$, or, in terms of structure functions, to a strong power increase of the functions in the small x region. Secondly, since the scale dependence of running coupling α_s is beyond of the accuracy of the LLA, numerical results of the LLA can be strongly varied by change of the scale, giving a possibility to make quite different predictions with claims that they are based on the perturbative QCD. Therefore, the problem of calculation of the radiative corrections to the LLA (that means here, the terms with $n = m + 1$) is very important now.

2. Method of calculation

For solution of this problem one can use [2] the property of non-Abelian gauge theories proved [3] in the LLA that gauges bosons are reggeized with the trajectory

$$j(t) = 1 + \omega(t) \,, \tag{1}$$

where in the leading approximation, for the case of the SU(N) gauge group ($N = 3$ for the QCD)

$$\omega(t) = \omega^{(1)}(t) = \frac{g^2 t}{(2\pi)^{3+\varepsilon}} \frac{N}{2} \int \frac{d^{2+\varepsilon} k_\perp}{k_\perp^2 (q-k)_\perp^2} \,, \tag{2}$$

Here g is the coupling constant of the gauge theory, q is the momentum transfer and $t = q_\perp^2$. The integration is performed over the two-dimensional momentum orthogonal to the initial particle momentum plane, and dimensional regularization of Feynman integrals is used:

$$\frac{d^2 k}{(2\pi)^2} \;\longrightarrow\; \frac{d^{2+\varepsilon} k}{(2\pi)^{2+\varepsilon}}, \qquad \varepsilon = D - 4 \,, \tag{3}$$

where D is the space-time dimension ($D = 4$ for the physical case).

The problem of calculation of the radiative corrections to the LLA is reduced [2] to calculation of corrections to the kernel of the Bethe-Salpeter type equation for the t-channel partial amplitude with the vacuum quantum numbers [1]. The equation is constructed in terms of the gluon trajectory and the Reggeon-Reggeon-Gluon (RRG) vertex. Corrections to the vertex are known now [4,5], so the problem of calculation of the contibution $\omega^{(2)}(t)$ to the trajectory in the next (two loop) approximation became most urgent. Since one loop corrections to the Particle-Particle-Reggeon (PPR) vertices became available [4,6,7] this contribution could be obtained from an elastic scattering amplitude caculated in two loop approximation with one *logs* accuracy. Indeed, let us consider Regge asymptotic of the amplitude of the scattering process $A + B \longrightarrow A' + B'$ with the gluon quantum numbers in the t-channel and negative signature. It has the following factorized form:

$$\left(\mathcal{A}_8^{(-)}\right)_{AB}^{A'B'} = \Gamma^c_{A'A} \frac{s}{t} [(\frac{s}{-t})^{\omega(t)} + (\frac{-s}{-t})^{\omega(t)}] \Gamma^c_{B'B} \,, \tag{4}$$

where $\Gamma^c_{A'A}$ are the particle-particle-reggeon (PPR) vertices. They can be presented as

$$\Gamma^i_{A'A} = g \langle A'|T^i|A\rangle (\Gamma^{(0)}_{A'A} + \Gamma^{(1)}_{A'A}), \tag{5}$$

where $\langle A'|T^i|A\rangle$ stands for a matrix element of a colour group generator in corresponding representation (i.e. adjoint for gluons and fundamental for quarks), $\Gamma^{(0)}_{A'A}$ and $\Gamma^{(1)}_{A'A}$ are Born and one-loop contributions to the PPR vertices. Using this form one obtains from eq.(4) for the two loop contribution to $\left(\mathcal{A}_8^{(-)}\right)_{AB}^{A'B'}$ calculated with one *log s* accuracy

$$\left(\mathcal{A}_8^{(-)}\right)_{AB}^{A'B'} (\textit{two loop}) = g^2 \langle A'|T^i|A\rangle \langle B'|T^i|B\rangle \frac{s}{t} \times$$
$$\times [\Gamma^{(0)}_{A'A} \frac{1}{2} (\omega^{(1)}(t))^2 ((\ln\frac{s}{-t})^2 + (\ln\frac{-s}{-t})^2) \Gamma^{(0)}_{B'B} + (\Gamma^{(0)}_{A'A}\Gamma^{(1)}_{B'B} + \Gamma^{(1)}_{A'A}\Gamma^{(0)}_{B'B}) \times$$
$$\times\, \omega^{(1)}(t) (\ln\frac{s}{-t} + \ln\frac{-s}{-t}) + \Gamma^{(0)}_{A'A} \omega^{(2)}(t) (\ln\frac{s}{-t} + \ln\frac{-s}{-t}) \Gamma^{(0)}_{B'B}]. \tag{6}$$

Since one loop corrections $\Gamma^{(1)}_{A'A}$ to the PPR vertices became available [4,6,7] the only unknown thing in the r.h.s. of the eq.(6) is the two loop contribution $\omega^{(2)}(t)$ to the gluon trajectory. Therefore one can find it having $\left(\mathcal{A}_8^{(-)}\right)_{AB}^{A'B'}$ (*two loop*) with one *log s* accuracy.

Calculation of $\left(\mathcal{A}_8^{(-)}\right)_{AB}^{A'B'}$ (*two loop*) with one *log s* accuracy could be performed with the help of the t-cnannel unitarity conditions [2]. It can be done with the help of the s-channel unitarity as well. Moreover, it seems, that the s-channel approach is more suitable. Therefore it is used in what follows below.

It is clear from eq.(6) that the two loop correction $\omega^{(2)}(t)$ to the gluon trajectory can be obtained from the s-channel discontinuity $\left[\left(\mathcal{A}_8^{(-)}\right)_{AB}^{A'B'}\right]_s$ of the amplitude $\left(\mathcal{A}_8^{(-)}\right)_{AB}^{A'B'}$ (*two loop*) calculated with the accuracy up to constant terms. By definition the trajectory should not depend on scattered particles, so we may choose any process for its calculation. In this paper the process of quark-quark scattering is used for this purpose. Calculation of the quark-quark scattering amplitude discontinuity is briefly discussed below. Details of the calculation will be given elsewhere [8]. For simplicity the case of massless quarks is considered here. In this case the helicity of each of the colliding particles is strictly conserved, therefore the PPR vertices $\Gamma^c_{A'A}$ have definite spin structure, as well as the colour structure [1,7]:

$$\Gamma^i_{Q'Q} = g \langle Q'|T^i|Q\rangle \delta_{\lambda_{Q'}\lambda_Q} (1 + \Gamma^{(+)}_{QQ}). \tag{7}$$

where $\lambda_{Q'}$, λ_Q are quark helicities and $\Gamma_{QQ}^{(+)}$ is one loop correction to the vertex calculated in Ref. [7].

3. s-channel discontinuity of the quark-quark scattering amplitude

The discontinuity under consideration can be divided in two parts: contribution coming from two particle intermediate state in the s-channel and from three particle one:

$$\left[\mathcal{A}_{AB}^{A'B'}\right]_s = \left[\mathcal{A}_{AB}^{A'B'}\right]_s^{(2)} + \left[\mathcal{A}_{AB}^{A'B'}\right]_s^{(3)} \qquad (8)$$

Let us start with the first contribution. We are interested in the discontinuity of the amplitude with the gluon quantum numbers and negative signature in the t-channel. In the s -channel unitarity relation

$$\left[\mathcal{A}_{AB}^{A'B'}\right]_s^{(2)} = i\int d\Phi_2(p_A+p_B;p_{A_1},p_{B_1})\sum_{A_1B_1}\mathcal{A}_{AB}^{A_1B_1}\mathcal{A}^{*}{}_{A'B'}^{A_1B_1}, \qquad (9)$$

where summation is performed over discrete quantum states of the intermediate particles and

$$d\Phi_2(P;p_1,....,p_n) = (2\pi)^D\delta^D(P-\sum_{i=1}^{n}p_i)\prod_{i=1}^{n}\frac{d^{(D-1)}p_i}{(2\pi)^{(D-1)}2E_i}, \qquad (10)$$

we need to take in the r.h.s the full amplitudes $\mathcal{A}_{AB}^{A_1B_1}$ and $\mathcal{A}^{*}{}_{A'B'}^{A_1B_1}$ which are given by a sum of amplitudes with colour singlet and colour octet states in corresponding t-channels, and to project their product to the octet colour state in the t-channel. But due to the fact that with the accuracy required the colour singlet parts of the amplitudes under consideration as well as the colour octet parts with positive signature are zero in Born approximation and are pure imaginary in one loop approximation, whereas colour octet parts with negative signature are pure real in Born approximation, only the colour octet parts with negative signature can contribute to the two loop discontinuity. These parts are known [7]. With the accuracy up to constant terms we have

$$\left(\mathcal{A}_8^{(-)}\right)_{AB}^{A'B'} = \langle A'|T^i|A\rangle\langle B'|T^i|B\rangle\delta_{\lambda_{A'}\lambda_A}\delta_{\lambda_{B'}\lambda_B}g^2\frac{s}{t}\times$$

$$\times\left(2+\frac{g^2}{(4\pi)^{\frac{D}{2}}}(-t)^{\frac{D}{2}-2}\left[a_T\left(\ln\frac{s}{-t}+\ln\frac{-s}{-t}\right)+4a_\Gamma\right]\right), \qquad (11)$$

where a_T and a_Γ are the coefficients connected with one loop contributions to the gluon trajectory $\omega^{(1)}(t)$ and the helicity conserving part of the quark-quark-reggeon vertex $\Gamma_{QQ}^{(+)}$ [7] correspondingly:

$$\omega^{(1)}(t) = \frac{g^2}{(4\pi)^{\frac{D}{2}}}(-t)^{\frac{D}{2}-2}a_T, \qquad a_T = 2N\frac{\Gamma(2-\frac{D}{2})\Gamma^2(\frac{D}{2}-1)}{\Gamma(D-3)}; \qquad (12)$$

$$\Gamma_{QQ}^{(+)} = \frac{g^2}{(4\pi)^{\frac{D}{2}}}(-t)^{\frac{D}{2}-2}a_\Gamma, \qquad a_\Gamma = \frac{\Gamma(2-\frac{D}{2})\Gamma^2(\frac{D}{2}-1)}{\Gamma(D-2)}\times$$
$$\times\left[-\frac{n_f(D-2)}{2(D-1)}-\frac{1}{2N}\left(D-4+\frac{D}{D-4}\right)+N(D-3)\left(\psi\left(3-\frac{D}{2}\right)\right.\right.$$
$$\left.\left.-2\psi\left(\frac{D}{2}-2\right)+\psi(1)\right)+N\left(\frac{1}{4(D-1)}-\frac{2}{D-4}-\frac{7}{4}\right)\right]. \qquad (13)$$

Here $\psi(x)$ is the logarithmic derivative of the gamma function:

$$\psi(x) = \frac{\Gamma'(x)}{\Gamma(x)}.$$

Let us present the s-channel discontinuity of the part $\mathcal{A}_8^{(-)}$ of the amplitude with gluon quantum numbers in the t-channel and negative signature in the following form

$$\left[\left(\mathcal{A}_8^{(-)}\right)_{AB}^{A'B'}\right]_s = g^2\langle A'|T^i|A\rangle\langle B'|T^i|B\rangle\delta_{\lambda_A\lambda_{A'}}\delta_{\lambda_B\lambda_{B'}}\left(\frac{-2\pi is}{t}\right)\Delta_s. \qquad (14)$$

Then, since the element $d\Phi_2$ of two-body phase space can be presented as

$$d\Phi_2(p_A+p_B;p_{A_1},p_{B_1}) = \frac{1}{2s}\frac{d^{(D-2)}q_{1\perp}}{(2\pi)^{(D-2)}}, \qquad (15)$$

where $q_1 = p_A - p_{A_1}$, the unitarity relation (9) with the help of eqs. (11)-(13) gives us

$$\Delta_s^{(2)} = \frac{-g^4Nt}{2(4\pi)^{\frac{D}{2}}}\int\frac{d^{(D-2)}q_{1\perp}}{(2\pi)^{(D-1)}}\frac{1}{(q_1-q)_\perp^2(-q_{1\perp}^2)^{3-\frac{D}{2}}}\times$$

$$\times\left[2a_T \ln(\frac{s}{-q_{1\perp}^2}) + 4a_\Gamma\right] \tag{16}$$

Let us consider now the three particle intermediate state contribution. It can be presented as

$$\left[\mathcal{A}_{AB}^{A'B'}\right]_s^{(3)} = i\int d\Phi_3(p_A + p_B; p_{A_1}, p_G, p_{B_1}) \sum_{A_1,G,B_1} \mathcal{A}_{AB}^{A_1GB_1}\mathcal{A}^{*A_1GB_1}_{A'B'}, \tag{17}$$

where G is a produced gluon. Contrary to the LLA case, where the discontinuity should be calculated with logarithmic accuracy, so only a multi-Regge kinematics could contribute, here we need to take into account regions of fragmentation of particles A, A' and B, B' as well. In terms of Sudakov variables defined by decomposition

$$p_i = \beta_i p_A + \alpha_i p_B + p_{i\perp}, \qquad i = A_1, G, B_1,$$

the fragmentation region of the particle A, A' is determined by relations:

$$|(p_{i\perp})^2| \sim |t|, \qquad \beta_{A_1} \sim \beta_G \sim \alpha_{B_1} \sim 1, \qquad \alpha_{A_1} \sim \alpha_G \sim \beta_{B_1} \sim \frac{|t|}{s}. \tag{18}$$

Let us consider the contribution of this region. With accuracy here required we have

$$\mathcal{A}_{AB}^{A_1GB_1} = \frac{2g^3}{s}\bar{u}(p_{A_1})\left\{\langle A_1|T^jT^c|A\rangle \not{p}_B \frac{\not{p}_A - \not{p}_G}{-2(p_Ap_G)}\not{e}_G^*\right.$$
$$+\langle A_1|T^cT^j|A\rangle \not{e}_G^* \frac{\not{p}_{A_1} + \not{p}_G}{2(p_{A_1}p_G)}\not{p}_B - if_{ijc}\langle A_1|T^i|A\rangle \frac{2}{(p_{A_1} - p_A)^2}\left[\not{e}_G^*(p_Bp_G)\right.$$
$$\left.\left.-\not{p}_G(p_Be_G^*) - \not{p}_B\left(\left(p_A - p_{A_1} + \frac{(p_B - p_{B_1})^2}{2(p_Bp_G)}p_B\right)e_G^*\right)\right]\right\} u(p_A)\epsilon_G^{*c}\times$$
$$\times\langle B_1|T^j|B\rangle \frac{1}{(p_{B_1} - p_B)^2}\bar{u}(p_{B_1})\not{p}_A u(p_B). \tag{19}$$

The element $d\Phi_3$ of three-body phase space in this region can be wrritten as

$$d\Phi_3(p_A + p_B; p_{A_1}, p_G, p_{B_1}) = \frac{1}{4s}\frac{d\beta}{\beta(1-\beta)}\frac{d^{(D-2)}q_{1\perp}d^{(D-2)}q_{2\perp}}{(2\pi)^{(2D-3)}}. \tag{20}$$

where

$$\beta \equiv \beta_G, \qquad q_1 = p_A - p_{A_1}, \qquad q_2 = p_{B_1} - p_B. \tag{21}$$

We consider now the contribution $\Delta^{(3A)}$ of the region of fragmentation of the particles A, A' to the $\Delta_s^{(3)}$. It is convenient to devide it into two pieces:

$$\Delta^{(3A)} = \Delta_a^{(3A)} + \Delta_{na}^{(3A)}, \tag{22}$$

The first one has an abelian nature, and only this part survives in the abelian case; the second is essentially nonabelian. Calculating the r.h.s. of eq.(17) with the help of eqs.(19,20) and extracting the colour octet part in the t-channel with negative signature we obtain

$$\Delta_a^{(3A)} = \frac{g^4}{8}t\int \frac{d^{(D-2)}q_1}{(2\pi)^{(D-1)}}\frac{d^{(D-2)}q_2}{(2\pi)^{(D-1)}}\int_{\beta_0}^1 \frac{d\beta}{\beta}\frac{\beta^2}{q_2^2(q_2-q)^2}\left[1 + (1-\beta)^2\right. \tag{23}$$
$$\left.+\beta^2\frac{(D-4)}{2}\right]\left[\frac{-q^2}{k^2(k+\beta q)^2} + \frac{q_2^2}{k^2(k+\beta q_2)^2} + \frac{(q_2-q)^2}{(k+\beta q)^2(k+\beta q_2)^2}\right].$$

Here and below all vectors are $(D-2)$-dimensional transversal to the p_A, p_B-plane; $k = q_1 - q_2$; β_0 is an artificially introduced boundary of the region of fragmentation of particles A, A' . Let us note that for the abelian-like contribution $\Delta_a^{(3A)}$ the value of β_0 can be putted equal to 0, in accordance with well known fact in QED, that cones of photon emission by two scattered particles don't overlapp at high energies.

For the nonabelian part we have

$$\Delta_{na}^{(3A)} = \frac{g^4N^2t}{8}\int \frac{d^{(D-2)}q_1}{(2\pi)^{(D-1)}}\frac{d^{(D-2)}q_2}{(2\pi)^{(D-1)}}\int_{\beta_0}^1 \frac{d\beta}{\beta}\frac{(1-\beta)^2}{q_2^2(q_2-q)^2}\times$$
$$\times\left[1 + (1-\beta)^2 + \beta^2\frac{(D-4)}{2}\right]\left[\frac{q^2}{q_1^2(q_1 - q(1-\beta))^2}\right.$$
$$\left.-\frac{q_2^2}{q_1^2(q_1 - q_2(1-\beta))^2} - \frac{(q_2-q)^2}{(q_1 - q(1-\beta))^2(q_1 - q_2(1-\beta))^2}\right]. \tag{24}$$

Three particle s-channel discontinuity can be presented as a sum of contributions of the region of fragmentation of particles A, A', the region of fragmentation of particles B, B' and the multi-Regge region. The last region is an intermediate between two fragmentation regions. Its contribution to the discontinuity is well known [1]. It is seen from eq.(24), that it is given by this equation with integration over β inside the region $1 > \beta \gg \frac{|t|}{s}$. It means, that the integrand of the eq.(24) calculated formally for the fragmentation region, i.e. for $\beta \sim 1$, is applicable for more wide region, namely for $1 > \beta \gg \frac{|t|}{s}$. Therefore, it is not necessary to consider separately the multi-Regge region; moreover, this region may be included in any you like of two fragmentation regions, which become overlapping. It is clear, that the contribution of the region of fragmentation of particles B, B' is obtained from $\Delta^{(3B)}$ by substitution $q_{1,2} \leftrightarrow -q_{2,1}$, $\quad q \leftrightarrow -q$, $\quad \beta \to \alpha \equiv \alpha_G = \frac{-k^2}{s\beta}$; therefore, the regions of applcability of integrands in $\Delta^{(3A)}$ and $\Delta^{(3B)}$ are overlapping. The total three particle discontinuity can be obtained as sum of contributions of fragmentation regions with parameters β_0 andα_0 satisfying condition $s\beta_0\alpha_0 = -k^2$. From symmetry it is obvious that it can be obtained as doubled $\Delta^{(3A)}$ calculated with $\beta_0 = \alpha_0 = \sqrt{\frac{-k^2}{s}}$.

Performing integration over β in the region $1 > \beta > \sqrt{\frac{-k^2}{s}}$, we obtain

$$\Delta_a^{(3A)}(\beta_0 = \sqrt{\frac{-k^2}{s}}) = \frac{g^4 t}{8}(\frac{2}{D-4} - \frac{2}{D-3} + \frac{1}{2}) \int \frac{d^{(D-2)}q_1 d^{(D-2)}q_2}{(2\pi)^{(2D-2)} q_1^2 q_2^2} \times$$
$$\times \left[\frac{-q^2}{(q_1-q)^2(q_2-q)^2} + \frac{2}{(q_1+q_2-q)^2}\right], \tag{25}$$

and

$$\Delta_{na}^{(3A)}(\beta_0 = \sqrt{\frac{-k^2}{s}}) = \frac{g^4 N^2 t}{8} \int \frac{d^{(D-2)}q_1 d^{(D-2)}q_2}{(2\pi)^{(2D-2)} q_2^2 (q_2-q)^2} [2(\psi(D-3) - \psi(1)$$
$$+ \frac{3}{4(D-3)}) \left(\frac{-q^2}{q_1^2(q_1-q)^2} + \frac{2q_2^2}{q_1^2(q_1-q_2)^2}\right) + \frac{q^2 \ln(\frac{s}{-k^2})}{q_1^2(q_1-q)^2} - \frac{2q_2^2 \ln(\frac{s}{-q_1^2})}{q_1^2(q_1-q_2)^2}\Bigg] \tag{26}$$

The total three particle intermediate state contribution to Δ_s is equal

$$\Delta_s^{(3)} = 2\Delta_a^{(3A)}(\beta_0 = \sqrt{\frac{-k^2}{s}}) + 2\Delta_{na}^{(3A)}(\beta_0 = \sqrt{\frac{-k^2}{s}}), \tag{27}$$

where $\Delta_a^{(3A)}$ and $\Delta_{na}^{(3A)}$ are given by eqs.(25) and (26) correspondingly.

4. Two loop correction to the gluon trajectory

Calculating s-channel discontinuity of both parts of the eq.(6) we obtain

$$\omega^{(2)}(t) = \Delta_s^{(2)} + \Delta_s^{(3)} - \frac{g^4(-t)^{D-4}}{(4\pi)^D}(a_T^2 \ln(\frac{s}{-t}) + 2a_T a_\Gamma). \tag{28}$$

Here the coefficients a_T and a_Γ connected with one loop contributions to the gluon trajectory and the quark-quark-reggeon vertex are defined in eqs. (12), (13), and two and three particle contributions to the s-channel discontinuity $\Delta_s^{(2)}$ and $\Delta_s^{(3)}$ are given by eqs. (16) and (25)-(27) correspondingly. Using these equations one can check that the terms in eq.(28) containing *log s* cancel each other. After the cancellation the correction to the trajectory can be present as:

$$\omega^{(2)}(t) = \frac{g^4 t}{4} \int \frac{d^{(D-2)}q_1 d^{(D-2)}q_2}{(2\pi)^{(2D-2)} q_1^2 q_2^2} \Bigg[\frac{q^2 N^2}{(q_1-q)^2(q_2-q)^2}(\ln(\frac{q^2}{(q_1-q_2)^2}) - 2\frac{a_\Gamma}{a_T}) +$$
$$\frac{2N^2}{(q_1+q_2-q)^2}(\ln(\frac{q_1^2}{(q_1-q)^2}) + 2\frac{a_\Gamma}{a_T}) + \left(\frac{-q^2}{(q_1-q)^2(q_2-q)^2} + \frac{2}{(q_1+q_2-q)^2}\right)$$
$$\times \left(\frac{2}{D-4} - \frac{2}{D-3} + \frac{1}{2} + 2N^2(\psi(D-3) - \psi(1) + \frac{3}{4(D-3)})\right)\Bigg] \tag{29}$$

It is the basic result of the paper, which will be used in calculation of radiative corrections to the Bethe-Salpeter type equation describing the Pomeron in QCD.

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