

Gluonic Structure of the Constituent Quark

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Constituent and current quarks

- Current quark: Point-like particle with small mass $m_u, m_d \approx 4-7\text{MeV}$
- Constituent quark: Quasi-particle with the size $\rho \approx 0.3\text{ fm}$ and large mass $m_u, m_d \approx 100 - 400\text{MeV}$
- Constituent quark picture describe very well the properties of hadrons at small momentum transfer $|q| \leq \Lambda_{QCD} \approx 1/R_{conf} \approx 200\text{ MeV}$
- Current quark picture is using for the reactions with large momentum transfer



Figure 1: Constituent quark picture of hadron(left panel) and structure of constituent quark in Deeply-Inelastic Scattering (right panel).

Connection between two pictures is coming from the fundamental phenomenon in the strong interaction such as the spontaneous chiral symmetry breaking (SCSB): non-zero value of quark condensate $\langle 0|\bar{q}q|0 \rangle$

Recent discussion by Kopeliovich et al: "Evidences for two scales in hadrons," Phys. Rev. D **76**, 094020 (2007), "Glue drops inside hadrons," Nucl. Phys. A **782**, 24 (2007) and P. Schweitzer, M. Strikman and C. Weiss, "Intrinsic transverse momentum and parton correlations from dynamical chiral symmetry breaking," JHEP **1301**, 163 (2013).

Quark-quark, quark-gluon and quark-gluon-pion interactions induced by interaction with QCD vacuum

Instanton model for QCD vacuum gives the mechanism for SCSB (Shuryak, Diakonov, Petrov etc)

QCD vacuum is not an empty space. There are strong topological fluctuations of gluon fields called **instantons**.

Chromomagnetic and Chromoelectric fields

$$(\vec{E}^a)^2, (\vec{B}^a)^2 \neq 0$$

in the QCD vacuum.

QCD vacuum structure is nontrivial:

it is filled with instantons; quarks jump between them.

Quark-quark interaction induced by instantons

Famous multiquark t'Hooft interaction induced by instantons

For $N_f=3$, $q = u, d, s \Rightarrow$ six-quark effective interaction induced by instantons

In $m_u = m_d = m_s \rightarrow 0$ limit

$$H_{t'Hooft} = \int d\rho n(\rho) (4\pi^2 \rho^3)^3 \frac{1}{6N_C(N_C^2 - 1)} \varepsilon_{f_1 f_2 f_3} \varepsilon_{g_1 g_2 g_3} \times$$

$$\times \left\{ \frac{2N_C + 1}{2N_C + 4} \bar{q}_R^{f_1} q_L^{g_1} \bar{q}_R^{f_2} q_L^{g_2} \bar{q}_R^{f_3} q_L^{g_3} + \right.$$

$$\left. + \frac{3}{8(N_C + 2)} \bar{q}_R^{f_1} q_L^{g_1} \bar{q}_R^{f_2} \sigma_{\mu\nu} q_L^{g_2} \bar{q}_R^{f_3} \sigma_{\mu\nu} q_L^{g_3} + (R \leftrightarrow L) \right\}$$

Very important in some processes: $K \rightarrow \pi\pi$ decays, $\Delta I = 1/2$ rule, CP violation, etc .. (N.K. and V.Vento, "Instantons and the Delta(I) = 1/2 rule," Phys. Rev. Lett. **87** (2001) 111601)

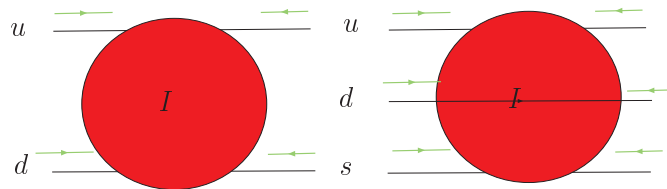


Figure 2: The quark-quark chirality-flip t'Hooft interaction induced instanton .

t'Hooft's quark-quark interaction is important in hadron spectroscopy (solution $U(1)_A$ problem given by a large η' mass, Δ -nucleon mass splitting etc.) but it does not contribute to the high energy reactions with hadrons (its correspond to zero spin exchange $\sigma \rightarrow 1/s^2$, s-is center of mass energy.)

Anomalous quark-gluon and quark-gluon-pion interactions induced by instantons

- In the general case, the interaction vertex of massive quark with gluon can be written in the following form:

$$V_\mu(k_1^2, k_2^2, q^2)t^a = -g_s t^a [\gamma_\mu F_1(k_1^2, k_2^2, q^2) + \frac{\sigma_{\mu\nu} q_\nu}{2M_q} F_2(k_1^2, k_2^2, q^2)],$$

where $k_{1,2}^2$ are virtualities of incoming and outgoing quarks and q is momentum transfer. It is similar to the photon-nucleon vertex

$$\Gamma_\mu^{QED} = \gamma_\mu F_1(q^2) + \frac{\sigma_{\mu\nu} q_\nu}{2M_N} F_2(q^2),$$

where $F_1(q^2), F_2(q^2)$ are Dirac and Pauli nucleon form factors, correspondently. • Anomalous quark chromomagnetic moment (AQCM)

(N.K. (1996))

$$\mu_a = F_2(0, 0, 0).$$

$$\Delta\mathcal{L} = -i\mu_a \frac{g_s}{4M_q} \bar{q} \sigma_{\mu\nu} t^a q G_{\mu\nu}^a$$

The shape of form factor $F_2(k_1^2, k_2^2, q^2)$ within instanton model is fixed:

$$F_2(k_1^2, k_2^2, q^2) = \mu_a \Phi_q(|k_1| \rho/2) \Phi_q(|k_2| \rho/2) F_g(|q| \rho),$$

where

$$\Phi_q(z) = -z \frac{d}{dz} (I_0(z) K_0(z) - I_1(z) K_1(z)),$$

$$F_g(z) = \frac{4}{z^2} - 2K_2(z)$$

are the Fourier-transformed quark zero-mode and instanton fields, respectively, and $I_\nu(z)$, $K_\nu(z)$, are the modified Bessel functions and ρ is the instanton size.

The value of AQCM is determined by the effective density of the

instantons $n(\rho)$ in nonperturbative QCD vacuum

$$\mu_a = -\pi^3 \int \frac{d\rho n(\rho) \rho^4}{\alpha_s(\rho)}.$$

Within Shuryak's instanton liquid model the relation between AQCM and dynamical quark mass is

$$\mu_a = -\frac{3\pi(M_q\rho_c)^2}{4\alpha_s(\rho_c)},$$

where $\rho_c \approx 0.3$ fm and $\alpha_s(\rho_c) \approx 0.5$.

We got the following value for AQCM:

$$\mu_a^{MF} \approx -0.4$$

in mean field approximation. The similar number was recently obtained in the completely different approach based on the Dyson-Schwinger Equations by Craig Roberts et al (see review arXiv:1203.5341)

AQCM is large (perturbative QCD contribution to it is very small $\sim 10^{-2}$) !

Quark-gluon-pion anomalous chromomagnetic interaction

$1/N_c$ correction to AQCM quark-gluon interaction-PCAC (Partially Conserved Axial Current) requirement. Lagrangian of σ model (pion part) from t'Hooft interaction (Diakonov, Petrov etc.):

$$\mathcal{L}_{eff} = \bar{q}[i\hat{\partial} - M_q e^{i\gamma_5 \vec{\tau} \vec{\pi}/F_\pi}]q$$

Including AQCM effect gives the effective quark-gluon-pion interaction (Polyakov, Diakonov 2003):

$$\Delta\mathcal{L}_{eff} = -i\mu_a \frac{g_s}{4M_q} \bar{q} \sigma_{\mu\nu} e^{i\gamma_5 \vec{\tau} \vec{\pi}/F_\pi} t^a q G_{\mu\nu}^a$$

Unpolarized and Polarized Gluon Distributions of the Constituent Quark

The predictions for high energy experiments with unpolarized and polarized beams are very sensitive to the unpolarized and polarized gluon distributions.

We are using DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) approach to calculate the splitting functions coming from anomalous quark-gluon and quark-gluon-pion interactions to obtain the probability to find gluon inside constituent quark with part of its momentum z .

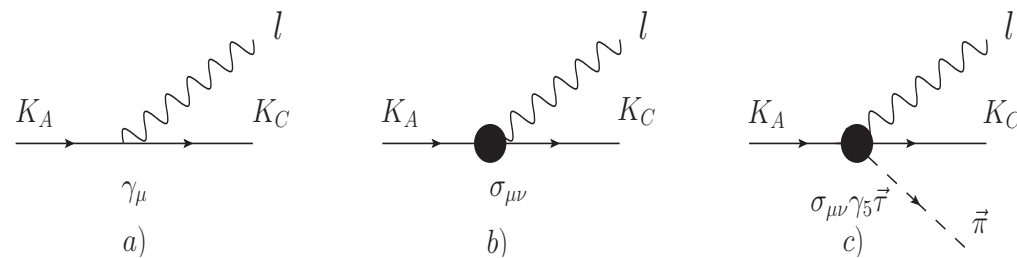


Figure 3: a) corresponds to the contributions from the pQCD to gluon distribution in the quark. b) and c) correspond to the contributions to the gluon distribution in the quark from the non-perturbative quark-gluon interaction and the non-perturbative quark-gluon-pion interaction, respectively.

The Unintegrated Unpolarized and Polarized Gluon Distributions of the constituent quark are

$$\begin{aligned}
 dg^{nonpert,c}(z, p_{\perp}^2) &= C \int_{y_{min}}^{y_{max}} dy F(t, y, z) \\
 &\times \frac{F_g^2(\sqrt{zy+t})}{(zy+t)^2} dp_{\perp}^2, \\
 d\Delta g^{nonpert,c}(z, p_{\perp}^2) &= C \int_{y_{min}}^{y_{max}} dy \Delta F(t, y, z) \\
 &\times \frac{F_g^2(\sqrt{zy+t})}{(zy+t)^2} dp_{\perp}^2,
 \end{aligned} \tag{1}$$

where

$$C = \frac{3C_F}{\alpha_s(\rho_c)} \frac{9}{2^{12}\pi} g_{\pi qq}^2 \rho_c^2, \tag{2}$$

and $g_{\pi qq} = M_q/F_{\pi}$ is the quark-pion coupling constant. The $F(t, y, z)$

and $\Delta F(t, y, z)$ functions in Eq.1 are given by

$$F(t, y, z) = \frac{1-z}{z}(2t^2 + y^2 z^2 + 2zty + z^2 ty)$$

$$\Delta F(t, y, z) = (1-z)y(2t - zt + zy), \quad (3)$$

where $t = p_{\perp}^2 \rho_c^2 / (1-z)$, $y = M_X^2 \rho_c^2 / (1-z)$ and $M_X^2 = (k_C + k_{\pi})^2$ is the invariant mass of the final pion-quark system. As the low limit for the integration over y the value $M_X^{min} = M_q + m_{\pi}$ with $m_{\pi} = 140$ MeV is used and as the upper limit $M_X^{max} = E_{sph}$, where $E_{sph} = 3\pi / (4\alpha_s(\rho_c)\rho_c)$ is so-called sphaleron energy is used. The Integrated Gluon Distributions in the constituent quark are defined by

$$g(\Delta g)(z, Q^2) = \int_{p_{\perp min}^2}^{p_{\perp max}^2} dg(\Delta g)(z, p_{\perp}^2), \quad (4)$$

The integration limits in Eq.4 for the non-perturbative case are $p_{\perp min}^2 = 0$ and $p_{\perp max}^2 = Q^2$. For the perturbative case, it is more natural to use the low limit of integration $p_{\perp min}^2 = 1/\rho_c^2$ because for $p_{\perp}^2 \leq 1/\rho_c^2$ one cannot believe in the validity of pQCD.

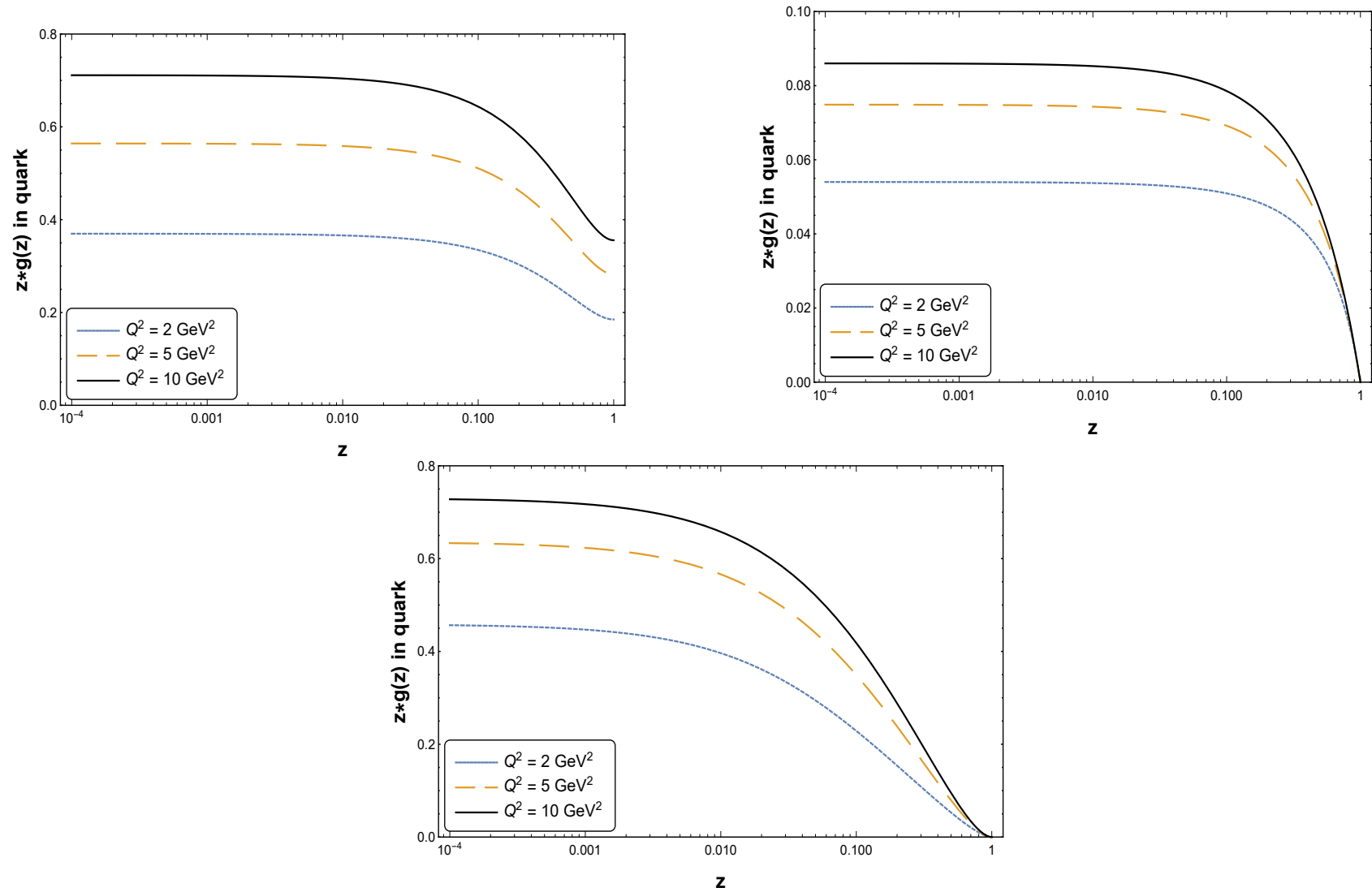


Figure 4: The z dependency of the contributions to the the unpolarized gluon distribution in the constituent quark from the pQCD (left panel), from the non-perturbative interaction without pion (central panel), and from the non-perturbative interaction with pion (right panel). The dotted line corresponds to $Q^2 = 2 \text{ GeV}^2$, the dashed line to $Q^2 = 5 \text{ GeV}^2$ and the solid line to $Q^2 = 10 \text{ GeV}^2$.

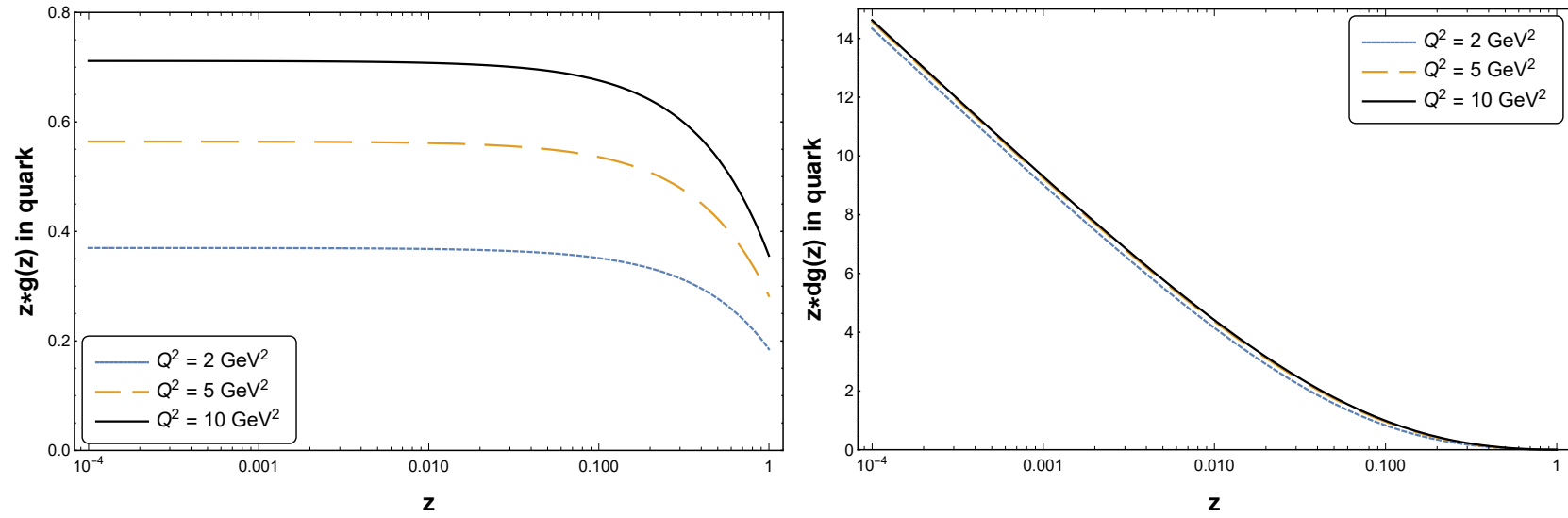


Figure 5: The z dependency of the contributions to the polarized gluon distribution in the constituent quark from the pQCD (left panel), and from the non-perturbative interaction with pion (right panel). The notations are the same as in the Fig.2. In the right panel the result for $Q^2 = 5 \text{ GeV}^2$ does not shown because it is practically identical to the $Q^2 = 10 \text{ GeV}^2$ case.

Gluonic distributions in the nucleon

We will apply the convolution model to obtain the gluon distributions in the nucleon from the gluon distributions in the constituent quark. It means that the probability to find gluon which carry the part of nucleon momentum xP is the product of the probability to find constituent quark with yP momentum inside nucleon and probability to find gluon inside constituent quark with definite momentum x/yP . Within this model the unpolarized and polarized gluon distributions in the nucleon are given by

$$g_N(x, Q^2) = \int_x^1 \frac{dy}{y} q_V(y) g_q\left(\frac{x}{y}, Q^2\right),$$
$$\Delta g_N(x, Q^2) = \int_x^1 \frac{dy}{y} \Delta q_V(y) \Delta g_q\left(\frac{x}{y}, Q^2\right),$$

where $q_V(y)$ ($\Delta q_V(y)$) is unpolarized (polarized) distribution of constituent quark in the nucleon and $g_q(z, Q^2)$ ($\Delta g_q(z, Q^2)$) is the gluon distribution in the constituent quark obtained above. For the

unpolarized constituent quark distribution, we take

$$q_V(y) = 60y(1 - y)^3.$$

At the large y this distribution is in accord with the quark counting rule. Its behavior in small y region and its normalization are fixed by the requirements $\int_0^1 dy q_V(y) = 3$ and $\int_0^1 dy y q_V(y) = 1$. It means that total momentum of nucleon at $Q^2 \rightarrow 0$ is carried by the three constituent quarks. For the polarized constituent quark distribution the simple form is assumed

$$\Delta q_V(y) = 2.4(1 - y)^3.$$

This form is also in agreement with the quark counting rule at $y \rightarrow 1$. The normalization has been fixed from the hyperon weak decay data as

$$\int_0^1 dy \Delta q_V(y) = \Delta u_V + \Delta d_V \approx 0.6.$$

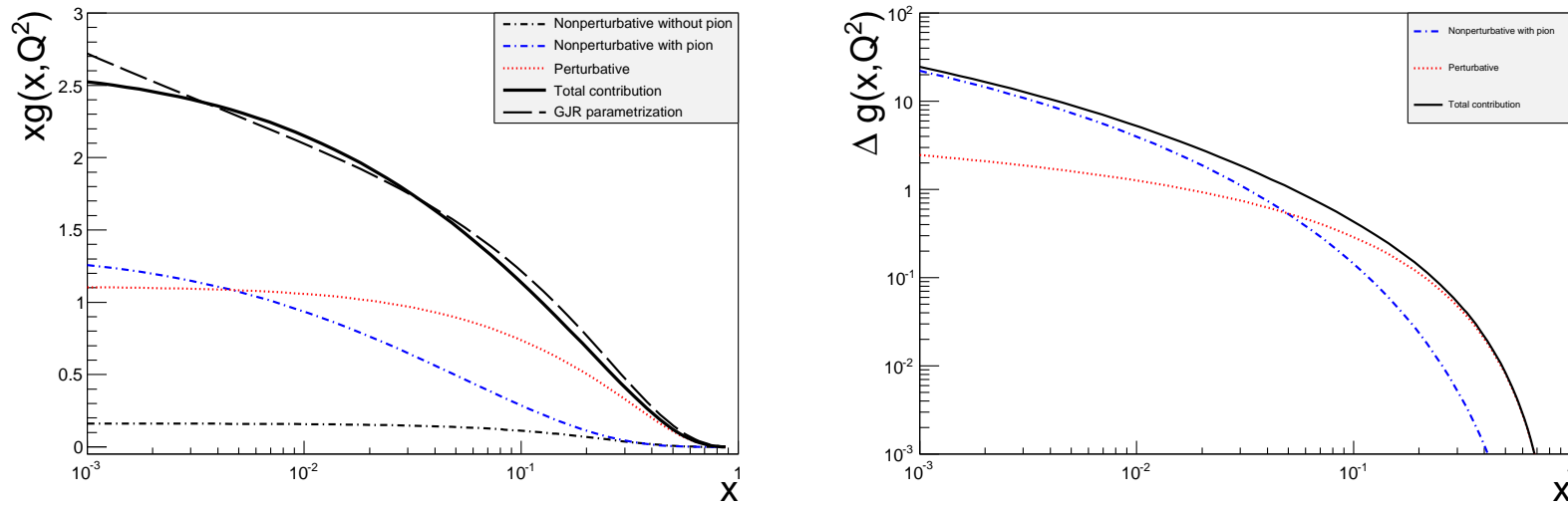


Figure 6: Unpolarized (left panel), and the polarized (right panel) gluon distributions in the nucleon at the scale $Q^2 = 2 \text{ GeV}^2$. The dotted line in red corresponds to the contribution from pQCD, the dotted-dashed in blue to the contribution from the non-perturbative interaction with pion, dotted-dashed in black to the contribution from the non-perturbative interaction without pion, and the solid line to the total contribution.

"Spin Crisis": Where the Proton Spin is?

The famous proton spin problem is one of the longstanding puzzle in the QCD . The decomposition of the proton spin by Jaffe and Manohar is

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g,$$

where the first term is quark contribution, $\Delta G = \int_0^1 dx \Delta g(x)$ is the gluon polarization in nucleon and the last two terms are the contributions from the orbital motions of the quarks and the gluons. The main problem is how to explain very small value of the proton spin carried by quark. At the present, the typical value is $\Delta\Sigma(Q^2 = 2\text{GeV}^2) \approx 0.25$, which is far away from $\Delta\Sigma = 1$ given by the non-relativistic quark model. The relativistic motion of the quarks in the confinement region results in sizable decreasing of total helicity of quarks. For example, within the bag model one obtains $\Delta\Sigma = 0.65$. We should point out that this value is in agreement with the weak hyperon decay data, but it is not enough to explain the small value coming from deep inelastic scattering (DIS) at large $Q^2 \geq 1 \text{ GeV}^2$. Just after appearance of the EMC data on the small part of the spin of the proton carried by the quarks, the axial anomaly

effect in DIS was considered as the primary effect to solve this problem . For the three light quark flavors, it gives the following reduction of the quark helicity in the DIS

$$\Delta\Sigma_{DIS} = \Delta\Sigma - \frac{3\alpha_s}{2\pi}\Delta G \quad (5)$$

It is evident that one needs to have a huge positive gluon polarization, $\Delta G \approx 3 \div 4$, in the proton to explain the small value of the $\Delta\Sigma_{DIS}$. The modern experimental data from the inclusive hadron productions and the jet productions exclude such a large gluon polarization in the accessible intervals of x and Q^2 . Our model also exclude the large polarization of gluons (see Fig.5, right panel) in these intervals.

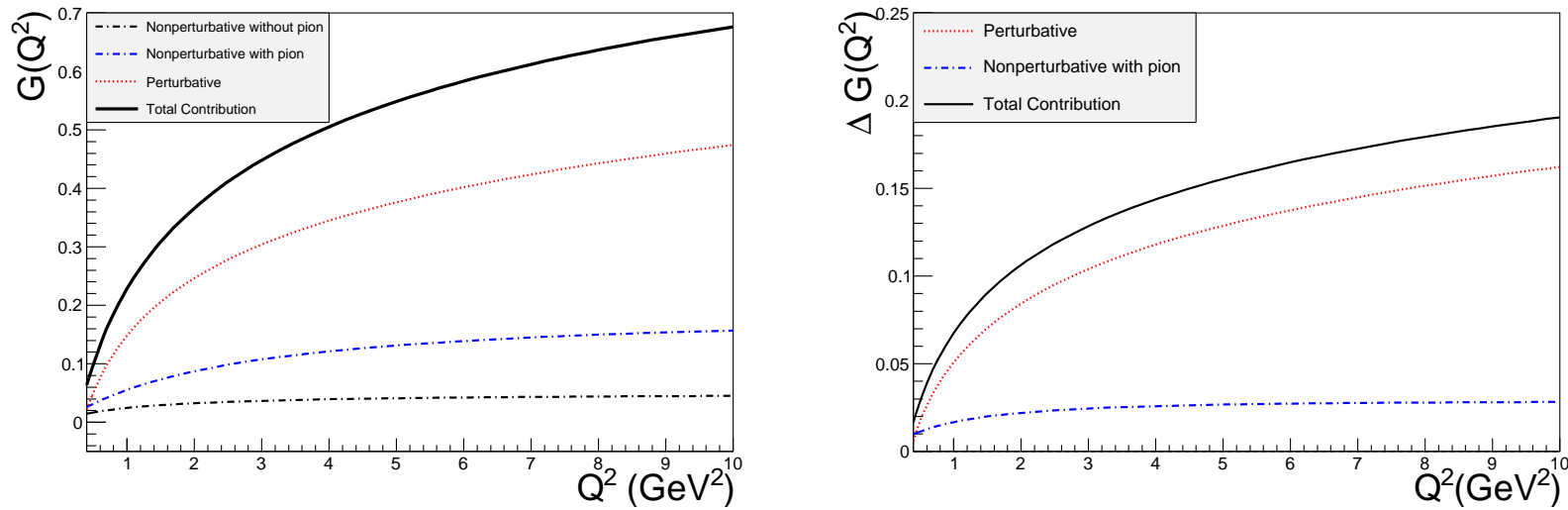


Figure 7: The part of the nucleon momentum carried by gluons (left panel), and the contribution of the gluons to nucleon spin (right panel) as the function of Q^2 .

For example, at $Q^2 = 10 \text{ GeV}^2$ the $\int_0^1 dx \Delta g(x) = 0.19$ in our model. This value is in agreement with recent fit of available data on spin asymmetry from the jet productions and the inclusive hadron productions.

Therefore, the axial anomaly effect, suggested by Efremov-Teryaev-Altarelli-Ross, cannot explain the proton spin problem!

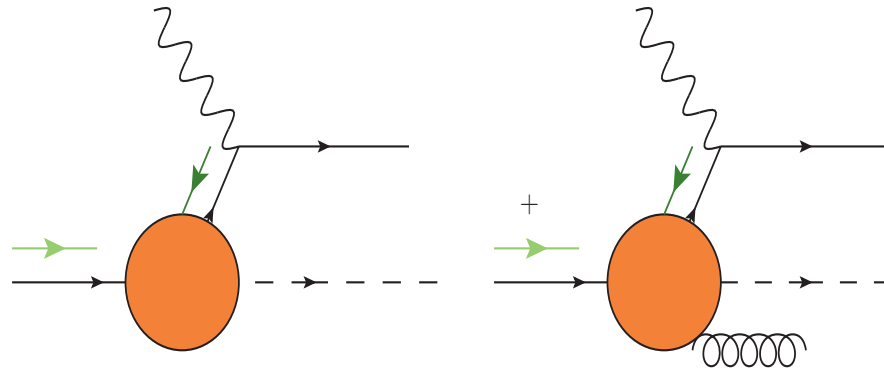


Figure 8: Quark depolarization induced by anomalous quark-gluon interaction. The green arrows are the direction of quark spin.

We should stress that the helicity of the initial quark is flipped in the non-perturbative vertices in Fig.7. As the result, such vertices should lead to the *screening* of the quark helicity. It is evident that at the $Q^2 \rightarrow 0$ such screening is vanished and the total spin of the proton is carried by its constituent quarks. Due to the total angular momentum conservation, for $Q^2 \neq 0$, the flip of the quark helicity by the non-perturbative interactions should be compensated partially by the orbital momenta of the partons and pion *inside* the constituent quark.

CONCLUSION

- Strong fluctuations of gluon fields in QCD vacuum induce a large anomalous quark-gluon and quark-gluon-pion chromomagnetic interactions
- The interaction with pion gives the dominating contribution to the unpolarized and polarized gluon distributions in the constituent quark and in the nucleon
- It gives the fundamental QCD mechanism to solve the "Spin Crisis" (calculation in the progress)

Thank you very much for your attention!