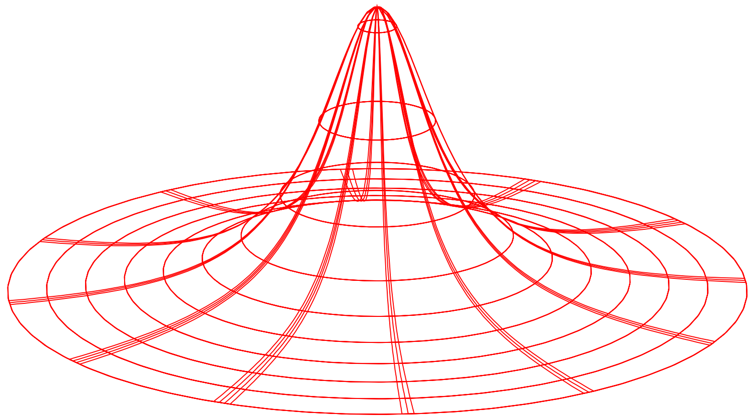
Nonperturbative QCD effects in high energy reactions induced by instantons



Nikolai Kochelev
Joint Institute for Nuclear Research, Dubna, Russia

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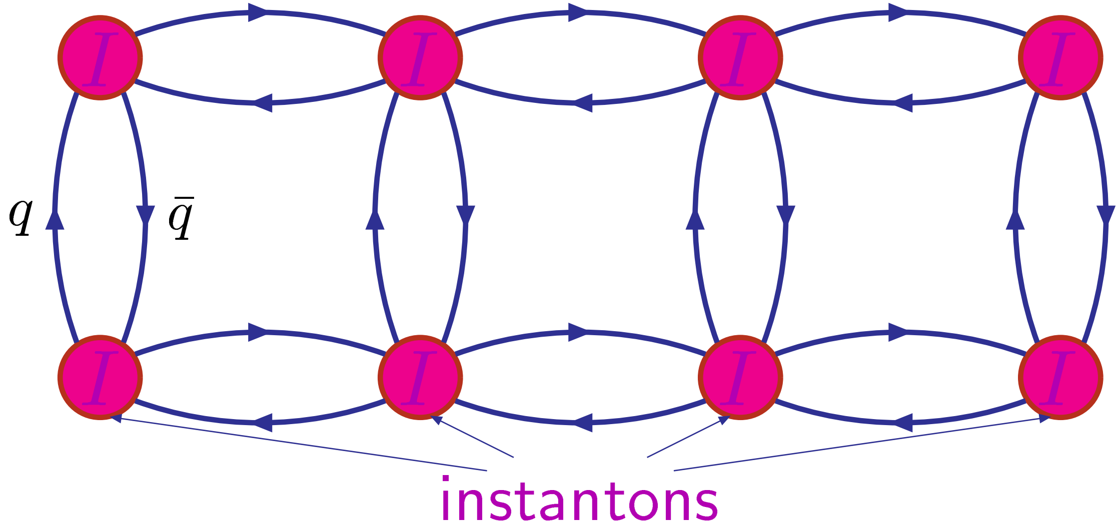
Instanton model for QCD vacuum.

The vacuum is a system of strong fluctuations of gluon fields called instantons (Callan, Dashen, Gross, Shuryak etc)
(review was given in Prof.Musakhanov talk)



QCD vacuum structure is nontrivial: it is filled by instantons; light quarks jump between them.

$$A^a_\mu = \frac{2}{g_s}\eta_{a\mu\nu}\frac{(x-x_0)_\nu}{(x-x_0)^2+\rho^2}$$

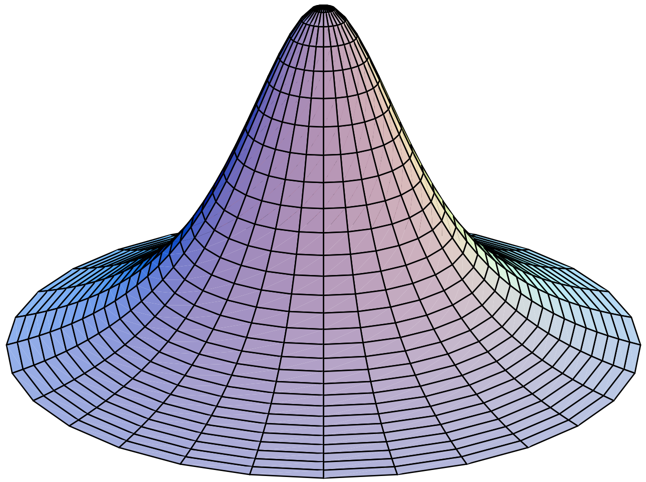
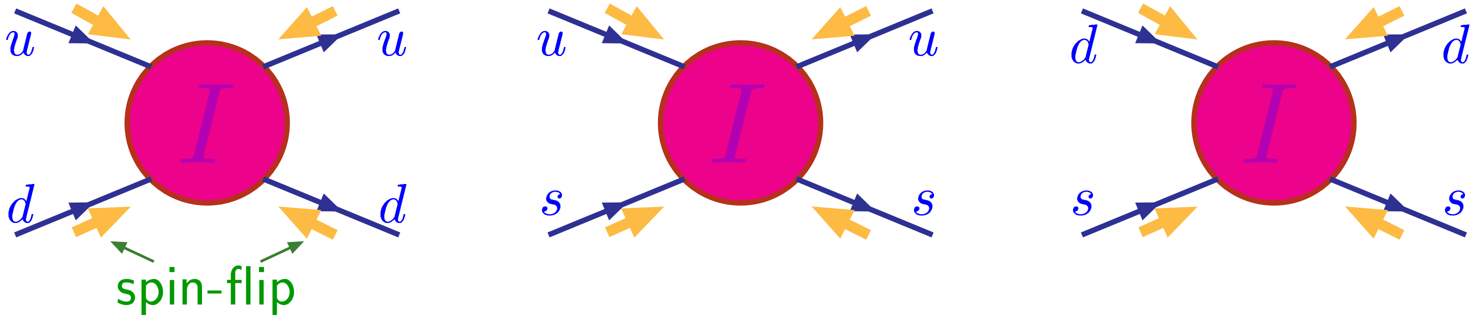


Figure 1: Instanton solution in QCD.

Instanton induced quark-quark and quark-gluon interactios

Quark-quark interaction [t'Hooft, 1976]

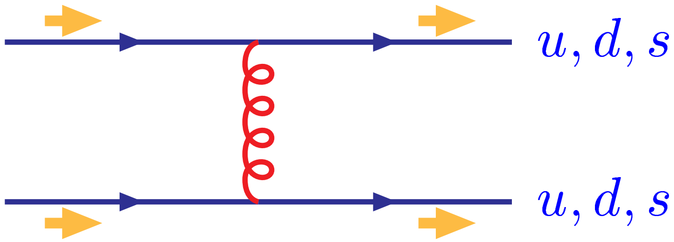


$$V_{q_iq_j}^{inst} = \sum_{i\neq j} \frac{\lambda}{m_i^* m_j^*} \left\{ 1 + \frac{3}{32} \lambda_i^a \lambda_j^a \vec{\sigma}_i \vec{\sigma}_j \right\}$$

Features:

1) Non-zero only for different quark flavors

2) Quark spin-flip differs from the perturbative one gluon exchange



$$V_{q_iq_j}^{OGE} = \sum_{i,j} \frac{\lambda'}{m_i^* m_j^*} \lambda_i^a \lambda_j^a \vec{\sigma}_i \vec{\sigma}_j$$

Multiquark interactions induced by instantons

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

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

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

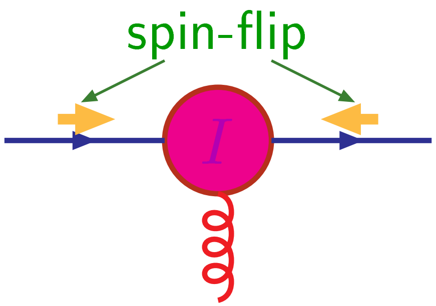
$$\times \left\{ \frac{2N_C+1}{2N_C+4} \bar{q}_R^{f_1} q_L^{g_1} \bar{q}_R^{f_2} q_L^{g_2} \bar{q}_R^{f_3} q_L^{g_3} + \right.$$

$\frac{1}{N_C}$correction

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

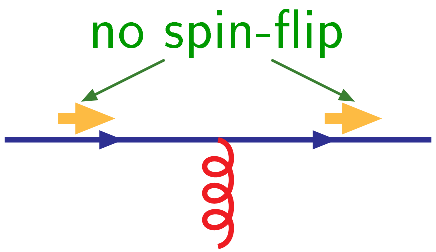
Quark-gluon interaction induced by instantons

Anomalous quark-gluon chromomagnetic moment [N.K. Phys.Lett.B426 (1998) 149]



$$\Delta\mathcal{L} = -\imath\mu_a \frac{g_s}{2m_q^*}\bar{q}\sigma_{\mu\nu}t^a q G^a_{\mu\nu}$$

$\mu_a \approx -0.2\ N_f = 1$ [N.K. 1998]
$\mu_a \approx -0.7\ N_f = 3$ [Diakonov 2002]



pQCD quark-gluon vertex

$$\Delta\mathcal{L} = g_s\bar{q}\gamma_\mu t^a q A^a_\mu$$

Spin structure of nucleon and instantons

A.E.Dorokhov, N.I.K. (1993)

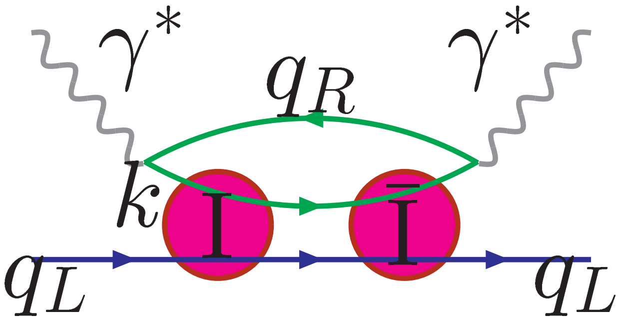
$$I_p(Q^2) = \int_0^1 g_1^p(x, Q^2) dx. \quad (1)$$

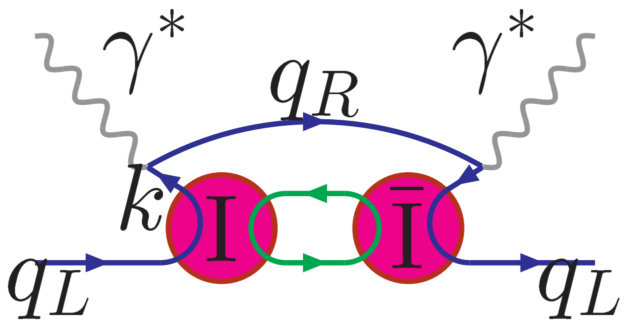
$$I_p = \int_0^1 g_1^p(x) dx = \frac{2}{9}\Delta u + \frac{1}{18}\Delta d + \frac{1}{18}\Delta s$$

$$\Delta\Sigma^{EMC} = \Delta u + \Delta d + \Delta s = 0.01 \pm 0.29.$$

Modern value of quark part of proton spin

$$\Delta\Sigma \approx 0.3 \div 0.4$$





Negative quark polarization induced by instantons

Where is proton spin?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

- RHIC and COMPASS data on value of gluon polarization: $\Delta G \approx 0$

- Large orbital momentum of sea quarks induced by instantons. Rotating $q - \bar{q}$ skin of consituent quark.

Flavor asymmetry of nucleon quark sea induced by instantons

A. E. Dorokhov and N. I. K. Phys. Lett. **B304** (1993) 167.

Gottfried sum rule violation

$$\int_0^1 \frac{[F_2^p(x)-F_2^n(x)]}{x}dx = \frac{1}{3}\int_0^1 \frac{[F_2^p(x)-F_2^n(x)]}{x}dx$$

$$= \frac{1}{3}\int_0^1 (u_V(x) - d_V(x))dx - \frac{2}{3}\int_0^1 (\bar{d}(x) - \bar{u}(x))dx$$

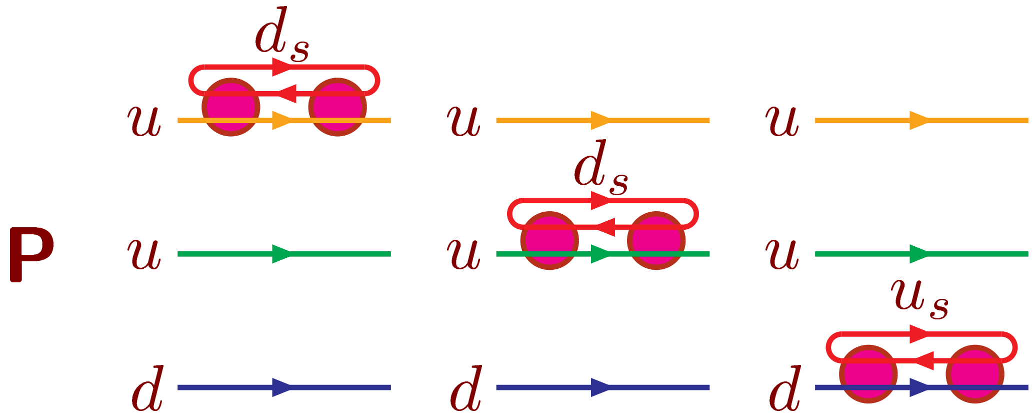
NMC Collaboration

$$\int_0^1 (\bar{d}(x) - \bar{u}(x))dx = 0.11 \pm 0.02$$

NA51 Collaboration

$$\bar{d} \approx 2\bar{u}, \quad < x > \approx 0.18$$

Instanton induced flavor asymmetry of sea $d_s \approx 2u_s$



Soft Contribution to Quark-Quark Scattering Induced by an Anomalous Chromomagnetic Interaction

N.K. JETP Lett. 83(2006)623

Chromomagnetic interaction contribution to quark-quark scattering

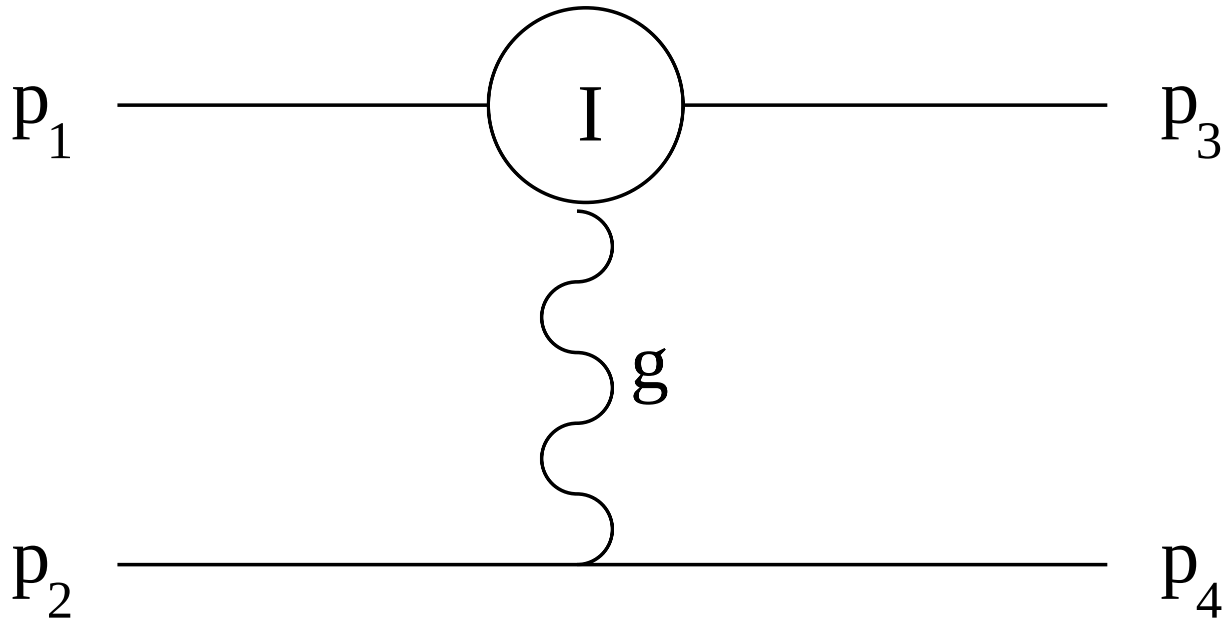


Figure 2: The Feynman diagram representing the contribution of the quark chromomagnetic moment to high energy quark-quark scattering.

$$\frac{d\sigma^{chrom}}{dt} = \frac{2\mu_a^2|t|(F(\sqrt{|t|}\rho_c))^2}{M_q^2}\frac{d\sigma^{pert}}{dt}$$

Instanton form factor:

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

where $z = q\rho_c$.

The asymptotic behaviour of the nonperturbative contribution for large $p_\perp$ is determined by the instanton form factor

$$\frac{d\sigma^{chrom}}{dp_\perp} \approx \frac{const}{p_\perp^6},$$

This $p_\perp$ dependence is steeper than is predicted by leading-twist pQCD, which anticipates $1/p_\perp^4$. The value $n^{chrom} = 6$ is in agreement with the result $n_{eff} = 6.33 \pm 0.54$ found in the recent analysis of RHIC data on inclusive neutral pion production.

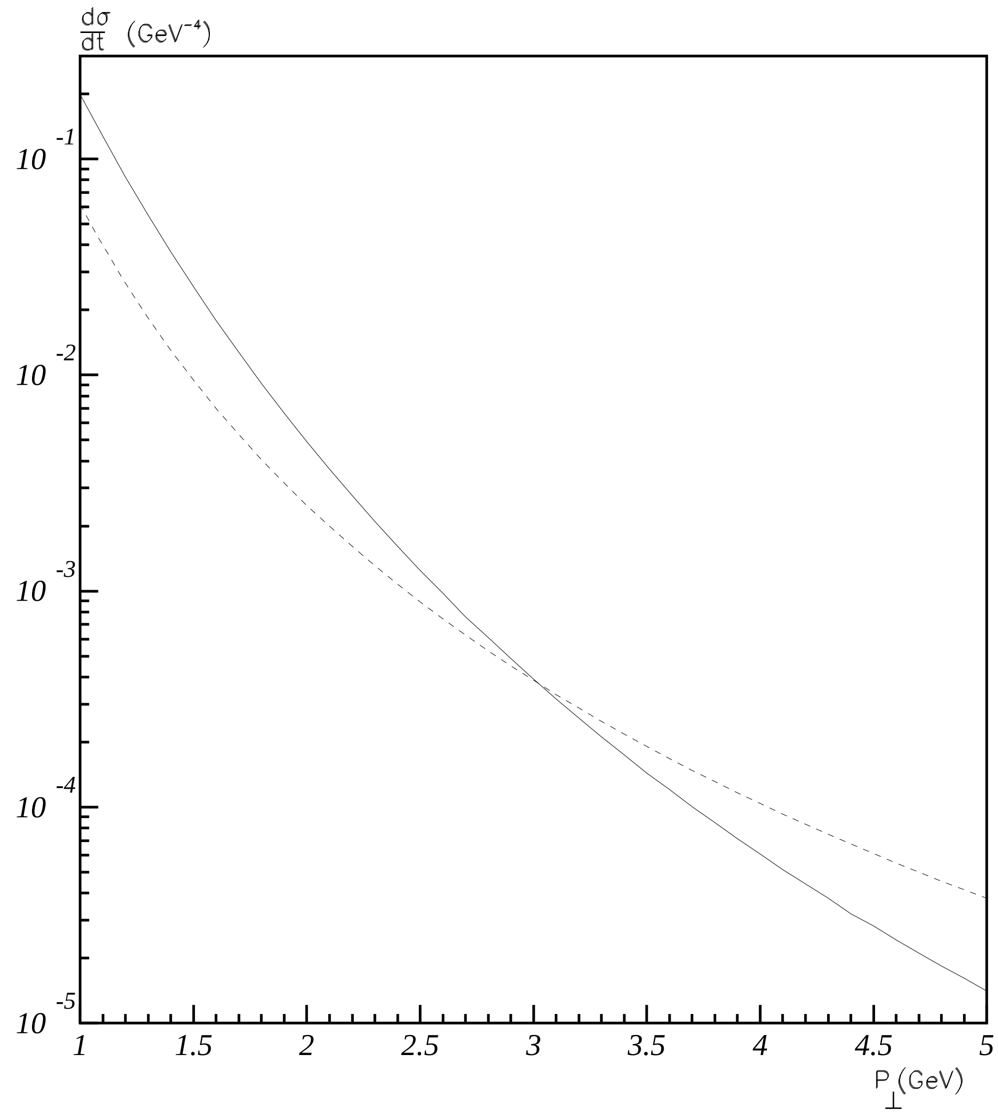


Figure 3: Perturbative (dashed) and nonperturbative (solid) quark-quark differential cross sections versus transverse momentum.

Single Spin Asymmetries in Semi-Inclusive Deep-Inelastic Scattering

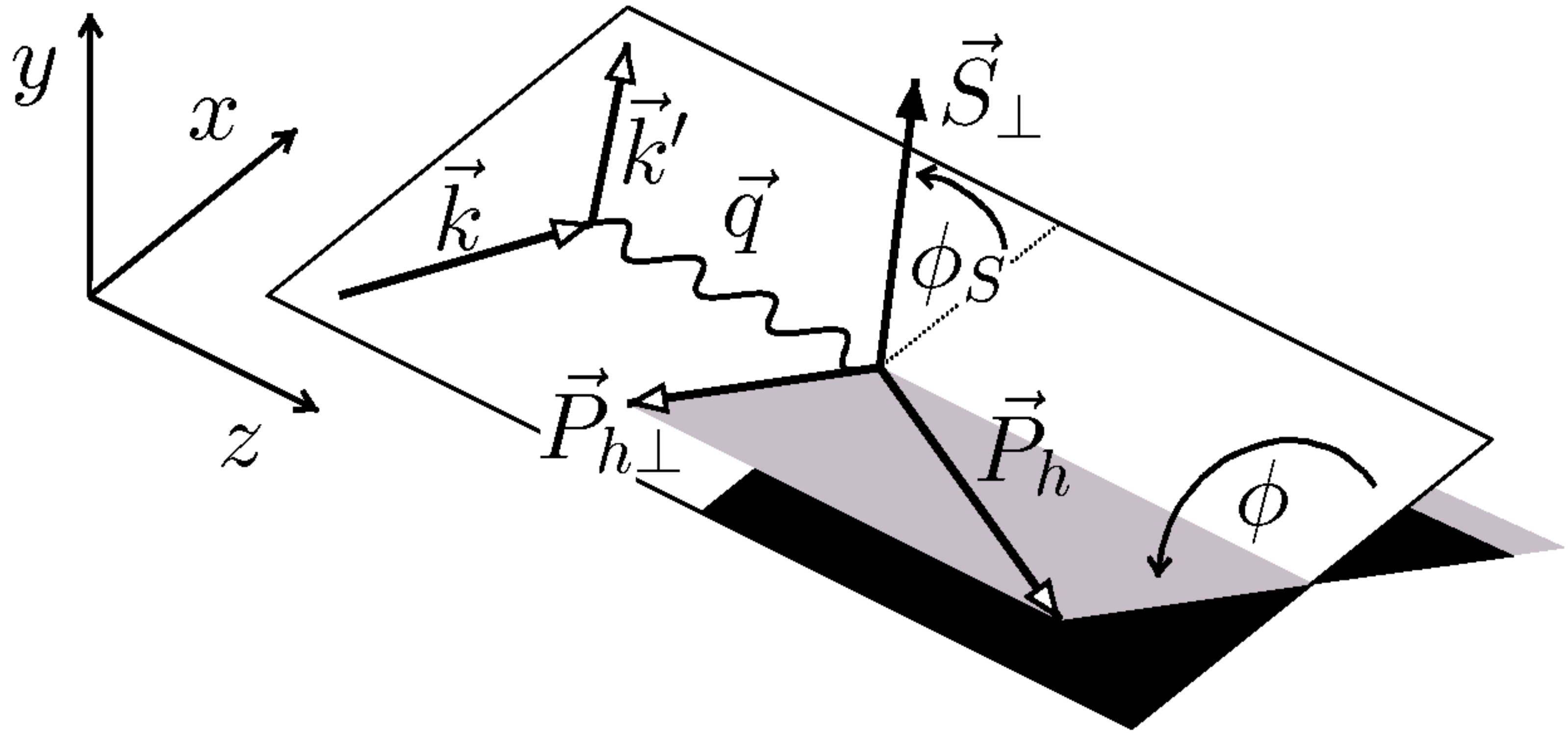


Figure 4: SIDIS kinematics.

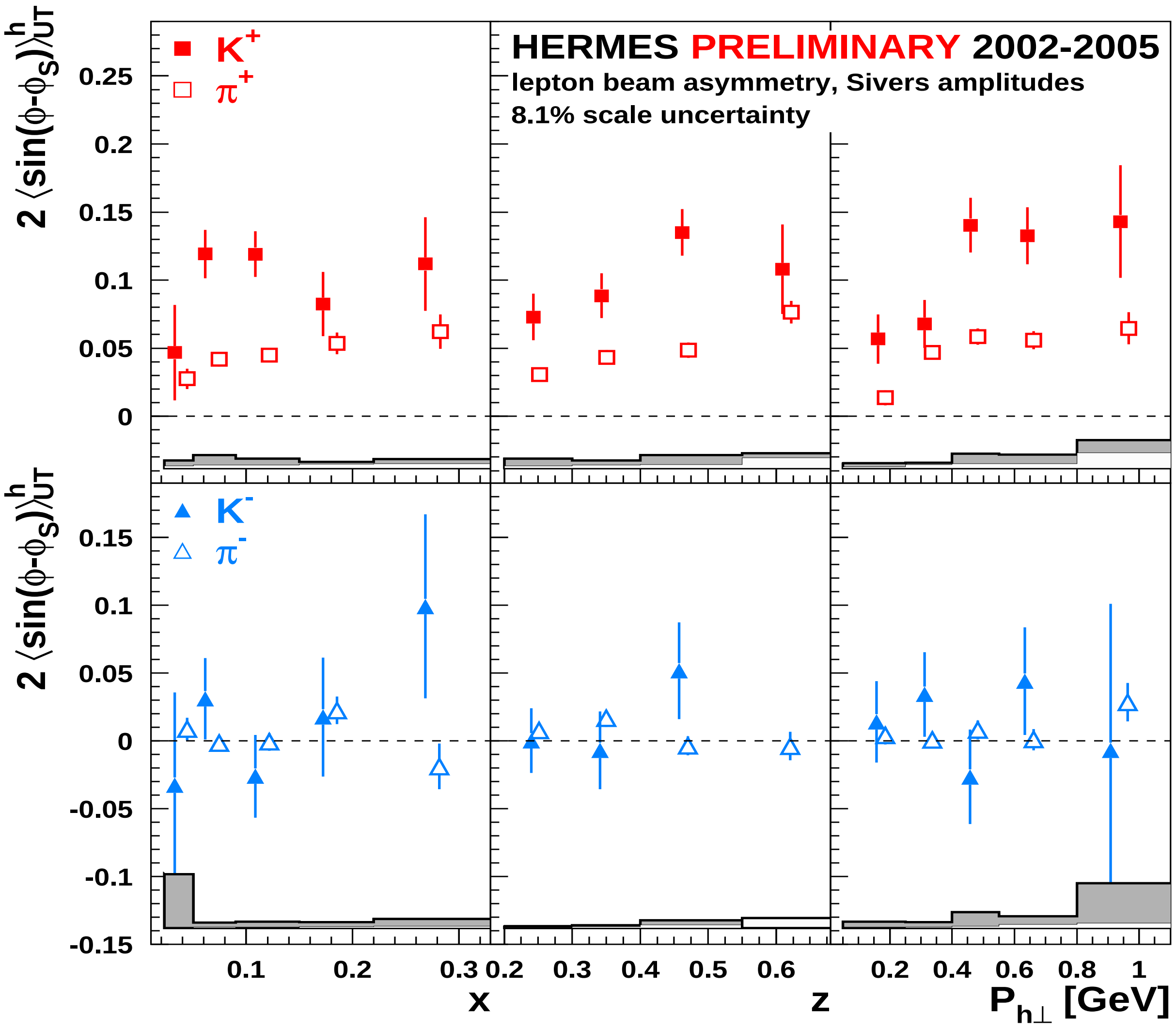


Figure 5: HERMES data on Sivers SSA in SIDIS (preliminary).

One-gluon exchange based mechanism to explain single spin asymmetry in SIDIS

(review was given in Oleg Teryaev talk)

- M. Anselmino *et al.*, "Sivers Effect for Pion and Kaon Production in Semi-Inclusive Deep Inelastic Scattering," arXiv:0805.2677 [hep-ph].

- S. Arnold, A. V. Efremov, K. Goeke, M. Schlegel and P. Schweitzer, "Sivers effect at Hermes, Compass and Clas12, arXiv:0805.2137 [hep-ph].

- S. J. Brodsky, D. S. Hwang and I. Schmidt, "Final-state interactions and single-spin asymmetries in semi-inclusive deep inelastic scattering," Phys. Lett. **B530** (2002) 99

Model calculation of Sivers function

F. Yuan, (Sivers function in the MIT bag model) Phys. Lett. B **575**, 45 (2003).

O. Cherednikov, U. D'Alesio, N. I. Kochelev and F. Murgia, (Chromomagnetic quark-gluon interaction contribution to the Sivers function) Phys. Lett. B **642**, 39 (2006).

A. Courtoy, F. Fratini, S. Scopetta and V. Vento, (A quark model analysis of the Sivers function) arXiv:0801.4347 [hep-ph].

- Problem is to explain a large Sivers asymmetry for K^+ observed at HERMES.

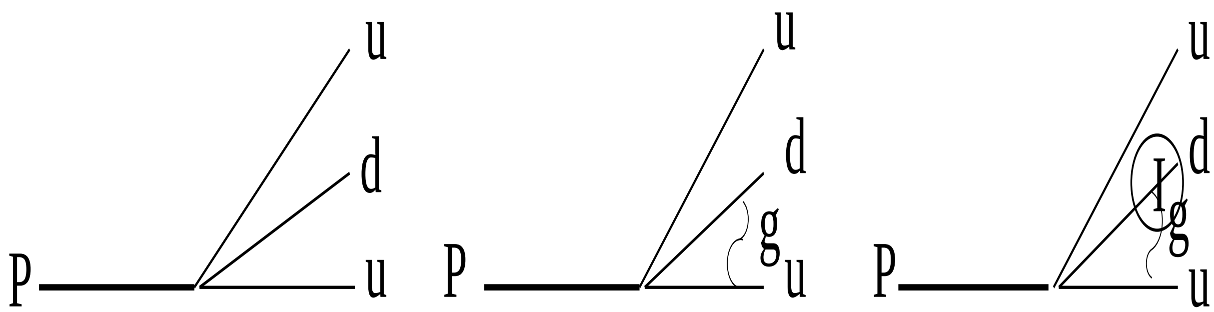


Figure 6: Model calculation of Sivers function.

Quark-exchange mechanism for single spin asymmetry of hadrons in SIDIS

in the collaboration with Bystritskiy, Kuraev and Nowak

We assume:

- Quark(u) -scalar diquark(ud) model for proton

Therefore suppress color indices we assume that proton-diquark-quark vertex has the following form

$$\mathcal{L}_{PDu} = g_{PDu}\bar{P}uD \tag{2}$$

- Quark-K-meson vertex has the form:

$$\mathcal{L}_{usK} = ig_{Kus}\bar{u}\gamma_5 sK^+ \tag{3}$$

- Six-quark t'Hooft instanton induced interaction should lead to the effective ud-diquark-s-quark interaction:

$$\mathcal{L}_{Ds} = g_{Ds} \bar{s} s \bar{D} D, \tag{4}$$

where in mean-field approximation the coupling is

$$g_{DS} = \frac{m_D^2}{2 < 0|\bar{s}s|0 >}, \tag{5}$$

with mass of diquark $m_D \approx m_u = m_d \approx 350$ MeV and strange quark condensate is $< 0|\bar{s}s|0 >= 0.8 < 0|\bar{q}q|0 >$.

- Different from flavor blind Brodsky et al FSI mechanism for SSA

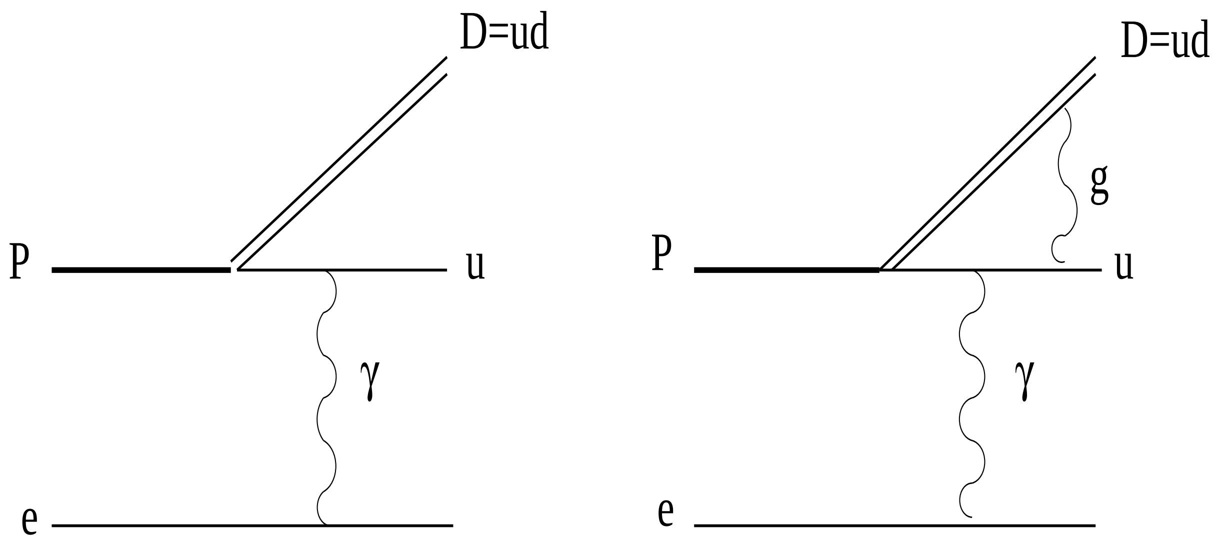


Figure 7: Final state interaction induced by pQCD one gluon exchange by Brodsky et al.

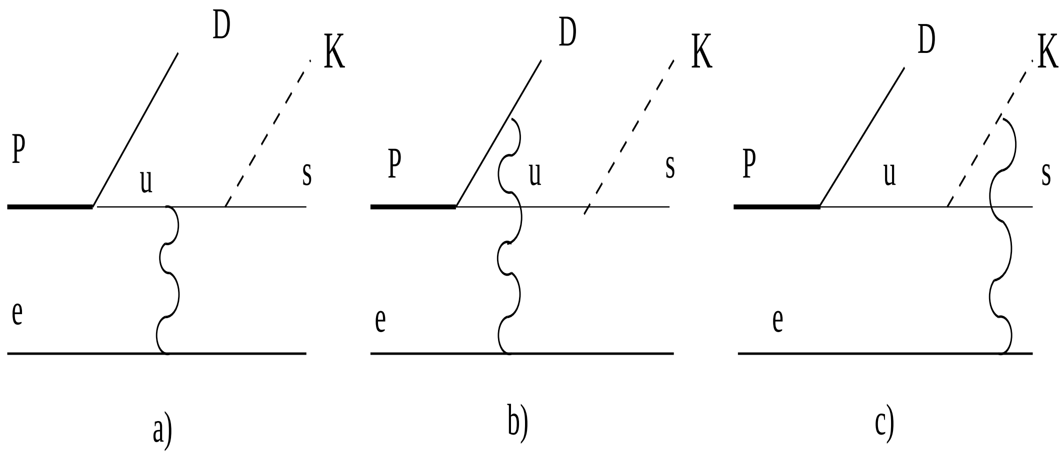


Figure 8: Tree level diagrams for K meson production in SIDIS.

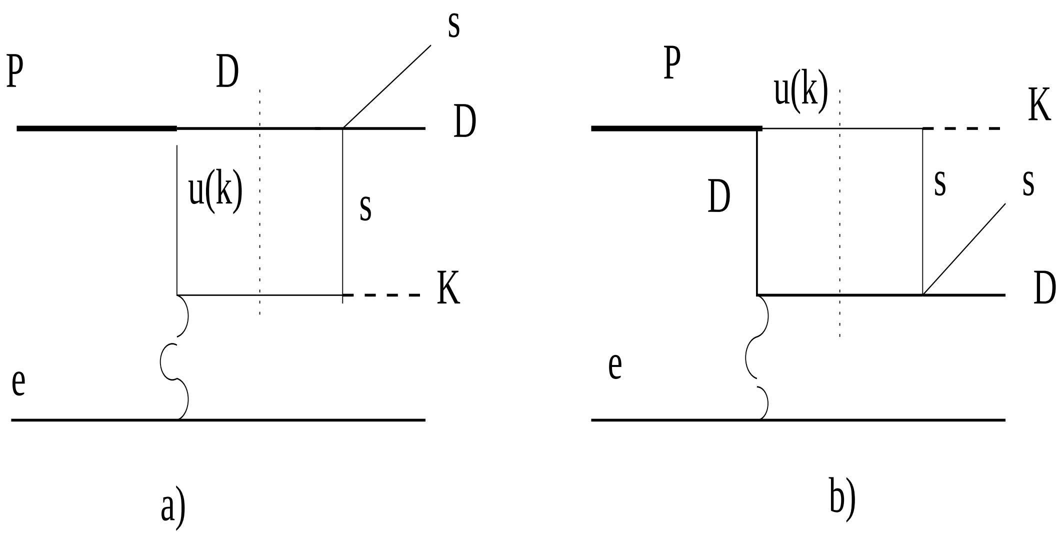


Figure 9: Loop diagrams for K meson production in SIDIS. The dotted line indicated the imaginary part of amplitude. The k is momentum of u-quark in the loop.

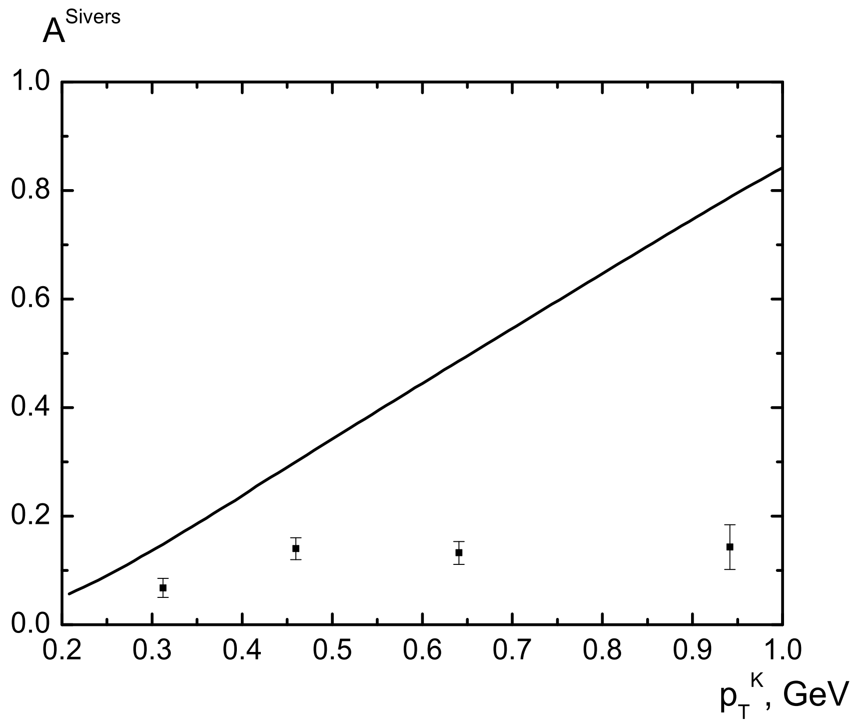


Figure 10: Sivers asymmetry for K^+ as the function of p_t without taking into account form factor effect in s-quark-diquark and s-quark-u quark vertex in loop diagram.

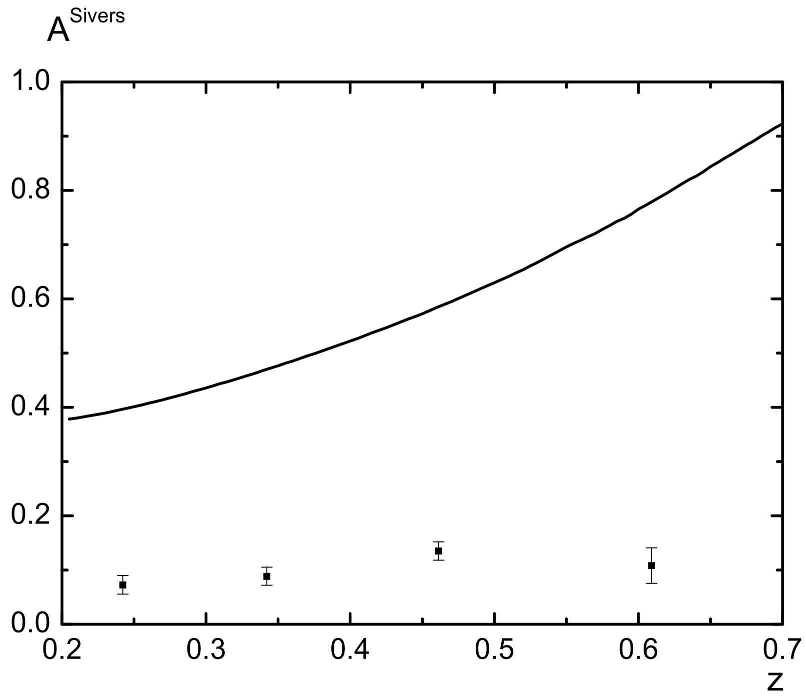


Figure 11: Sivers asymmetry for K^+ as the function of z_K without taking into account form factor effect.

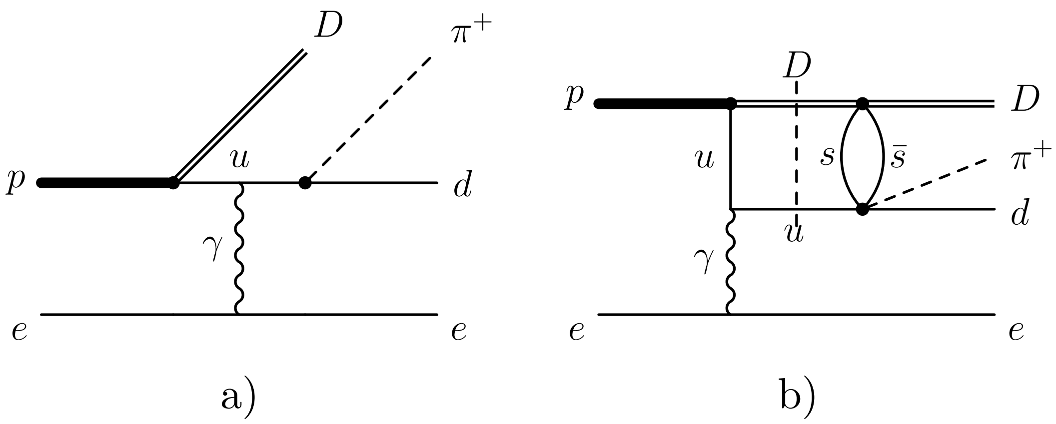


Figure 12: The diagrams contributed to π^+ Sivers asymmetry in SIDIS.

- It is needed to take into account formfactors in the nonperturbative vertices for detailed comparison with data!

Single Spin Asymmetry in hadron-hadron interaction

- Could pQCD based approach be applied to explain meson's SSA in hadron-hadron collisions?

- Twist-3 contribution
A. V. Efremov and O. V. Teryaev, The Transversal Polarization In Quantum Chromodynamics, Sov. J. Nucl. Phys. **39** (1984) 962

- The factorization approach based on the fitted from SIDIS Sivers distribution and Collin fragmentation functions (Efremov with collaborators, Anselmino with collaborators)

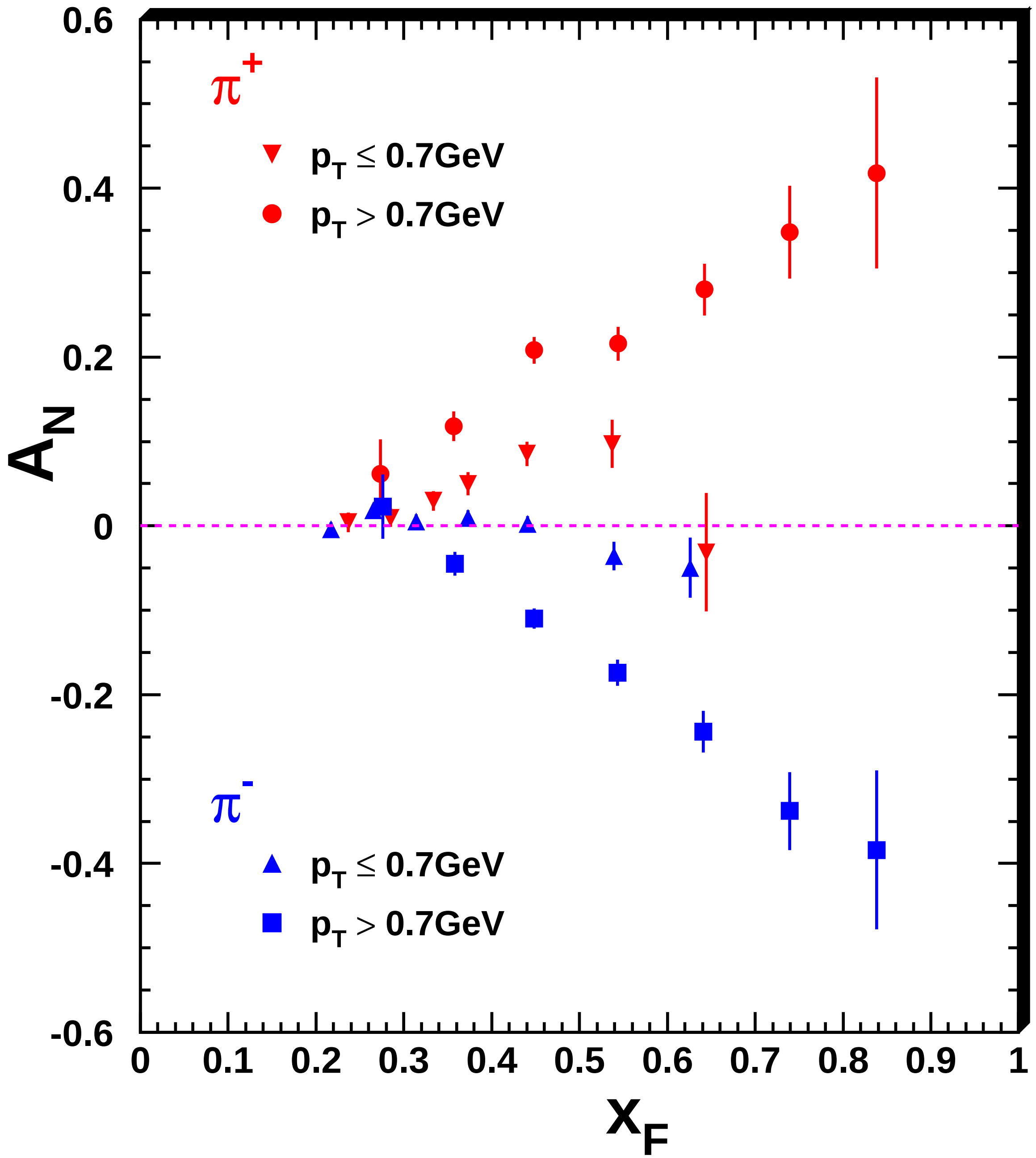


Figure 13: Fermilab E-704 Collaboration data on SSA for pions at $\sqrt{s} = 20$ GeV.

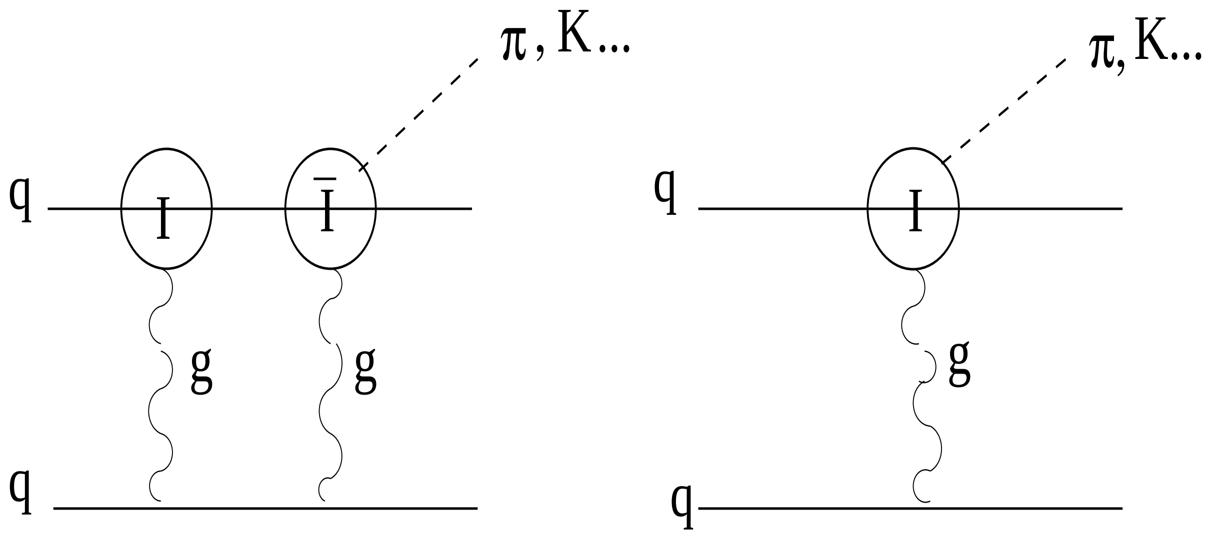


Figure 14: Instanton induced diagrams which contribute to SSA in hadron-hadron interaction

CONCLUSION

- Instantons induce very specific spin- and flavor-dependent quark-quark and quark-gluon interactions

- Inclusive meson production data at rather large energy and in few GeV transfer momentum region do not follow pQCD prediction. Nonperturbative instanton contribution is important

- The final state interaction induced by quark exchange may explain the anomalous single spin asymmetry in the K meson production in SIDIS

- For final answer it is needed to carry out more accurate calculation for SSA with formfactors including.