The Deep Inelastic Scattering on the Polarized Nucleons at Electron-Ion Collider

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Abstract

The contributions the individual quark and antiquark flavors, the valence quarks in the nucleon spin are obtained in the deep inelastic scattering longitudinally polarized leptons off longitudinally polarized protons, neutrons and deuterons with charged current for the experiments at Electron-Ion Collider. The radiative corrections to the measurable asymmetries are discussed.

Understanding how the nucleon spin is built up from the spin of quarks and gluons and their orbital angular momentum is one of the most challenging goals in hadron physics [1–4].

We have two pictures about the nucleon spin:

1) Jaffe-Monahar (1990)

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

Here $\Delta\Sigma, \Delta G$ are the quark and the gluon helicity; L_q, L_g are the orbital momentum of the quarks and the gluons.

There is the simple parton picture for the longitudinal polarization.

2) X.Ji (1996)

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

where J_q, J_g are the total angular momentum of the quarks and the gluons respectively. This decomposition the nucleon spin relate to the partons in transverse polarized nucleon.

At present we know fairly well the quark contribution

$$\Delta\Sigma = \int\limits_0^1 dx \Big[\Delta u(x) + \Delta\overline{u}(x) + \Delta d(x) + \Delta\overline{d}(x) + \Delta s(x) + \Delta\overline{s}(x)\Big] \sim 30\%.$$

However, the details on the flavor and sea structure of the polarization are still necessary as and contribution from small x. We know with large uncertains about the gluon contribution $\Delta G = \int\limits_0^1 dx \quad g(x) \sim 20\%$ with RHIC data [5]. There not have direct information on the quark and gluon orbital angular momentum.

The calculations L_q in lattice QCD [6–8] and in model dependent way with the pretzelasity distribution [9] give agreement results that $L_u < 0, \quad L_d > 0$ and $L_u + L_d \sim 0$. Now we have new phenomenology to study nucleon structure – Generalized Parton Distributions (GPD) that provide access to orbital angular momentum in Deep Virtual Compton Scattering (DVCS) and Exclusive $J/\Psi, \rho, \varphi$ production. These studies will require high luminosity and polarized beams. The Electron-Ion Collider (EIC) proposed as a next generation facility for nuclear physics, would expand the opportunities for high-energy scattering on polarized protons, light nuclei ($D^3, He...$).

The machine designs are aimed to achive:

- Polarized ($\sim 70\%$) beams of electrons, protons and light nuclei.
- High luminosity $10^{33-34} cm^{-2} s^{-1}$.
- Low x regime $x \to 10^{-4}$.
- Center of mass energies $\sim 20-100$ GeV, upgradable $\sim 140-150$ GeV. An EIC can delineate with unprecedented precision the full helicity structure of the nucleon in terms of gluons, quarks and antiquarks and their flavor.
- At EIC can to explore.
- Sea gluon $x \sim 10^{-2} - 10^{-4}$ (inclusive DIS, SIDIS at low x), spin flavor decomposition of the light quark sea.

- GPD (DVCS, Exclusive meson production) $\Rightarrow$ angular momentum J_q, J_g:

$$J_q = \frac{1}{2}\lim_{t\to 0}\int\limits_{-1}^{1} dx \quad x\Big[\overbrace{H_q(x,\xi,t)+E_g}^{GPD}(x,\xi,t)\Big] = \frac{1}{2}\Delta\Sigma + L_q.$$

The first constraint on quark orbital contribution L_q to proton spin by combining the sea from EIC and valence quarks from JLab 12.

A decomposition of J_g into spin and orbital components using gauge invariant local operators (as for J_q) is impossible. The total angular momentum of gluons J_g can, in principle, be accessed in exclusive deeply virtual meson production through the relation

$$J_g = \frac{1}{2}\lim_{t\to 0}\int\limits_{0}^{1} dx\Big[H_q(x,\xi,t)+E_g(x,\xi,t)\Big].$$

The deep inelastic scattering (DIS) with charged current (CC)

$$l + N \to \nu + X \tag{1}$$

can be studied only in high-energy lepton-nucleon collision, e.g. at EIC. Data from CC DIS experiments (1) with the polarized beams provide complementary information on the nucleon spin as they probe combinations of quark flavors different from those accessible in electromagnetic DIS. Here are two independent polarized structure functions (SF)

$$g_1 \sim \Delta q + \Delta\overline{q}$$

$$g_6 \sim \Delta q - \Delta\overline{q}$$

that provide flavor separation Δq and $\Delta\overline{q}$.

Now flavor-separated parton distribution functions Δq and $\Delta\overline{q}$ are obtained exclusively from semi-inclusive DIS (SIDIS) data. However, in contrast SIDIS the inclusive CC DIS (1) not have the fragmentation functions which carry in an essential uncertains to measurable quantities.

In this paper we study CC DIS (1) on polarized nucleons with goal to receive of an information about the spin structure of the nucleon in the experiments at EIC.

In the experiments with polarized beams the asymmetries are measured. The polarized asymmetries for CC DIS (1) in the Born approximation through SF are (the details see [10, 11]).

$$A_{l^-,l^+}(x,Q^2) = \frac{d^2\sigma^{\downarrow\uparrow,\uparrow\uparrow}_{l^-,l^+}/dxdy - d^2\sigma^{\downarrow\downarrow,\uparrow\downarrow}_{l^-,l^+}/dxdy}{d^2\sigma^{\downarrow\uparrow,\uparrow\uparrow}_{l^-,l^+}/dxdy + d^2\sigma^{\downarrow\downarrow,\uparrow\downarrow}_{l^-,l^+}/dxdy} = \\ = \frac{y_1^+ g_6^{l^-,l^+}(x,Q^2) \pm y_1^- g_1^{l^-,l^+}(x,Q^2)}{y_1^+ F_1^{l^-,l^+}(x,Q^2) \pm \frac{y_1^-}{2} F_3^{l^-,l^+}(x,Q^2)}$$

$$A_\pm(x,Q^2) = \frac{\left(d^2\sigma^{\downarrow\uparrow}_{l^-}/dxdy \pm d^2\sigma^{\uparrow\uparrow}_{l^+}/dxdy\right) - \left(d^2\sigma^{\downarrow\downarrow}_{l^-}/dxdy \pm d^2\sigma^{\uparrow\downarrow}_{l^+}/dxdy\right)}{\left(d^2\sigma^{\downarrow\uparrow}_{l^-}/dxdy \pm d^2\sigma^{\uparrow\uparrow}_{l^+}/dxdy\right) + \left(d^2\sigma^{\downarrow\downarrow}_{l^-}/dxdy \pm d^2\sigma^{\uparrow\downarrow}_{l^+}/dxdy\right)} \\ = \frac{y_1^+\left[g_6^{l^-}(x,Q^2) \pm g_6^{l^+}(x,Q^2)\right] + y_1^-\left[g_1^{l^-}(x,Q^2) \mp g_1^{l^+}(x,Q^2)\right]}{y_1^+\left[F_1^{l^-}(x,Q^2) \pm F_1^{l^+}(x,Q^2)\right] + \frac{y_1^-}{2}\left[F_3^{l^-}(x,Q^2) \mp F_3^{l^+}(x,Q^2)\right]}.$$

Here $F_{1,3}$ and $g_{1,6}$ are the spin-averaged and polarized SF; $y_1^\pm = 1 \pm y_1^2$, $y_1 = 1 - y$.

The polarized SF in leading order QCD (improved parton model) are

$$g_1(x,Q^2) = \sum_q \Delta q(x,Q^2) + \sum_{\overline{q}} \Delta\overline{q}(x,Q^2),$$
$$g_6(x,Q^2) = \sum_q \Delta q(x,Q^2) - \sum_{\overline{q}} \Delta\overline{q}(x,Q^2),$$

where $q = u, c, t$ $(q = d, s, b)$ and $\overline{q} = \overline{d}, \overline{s}, \overline{b}$ $(\overline{q} = \overline{u}, \overline{c}, \overline{t})$ for lepton (antilepton).

The first moments polarized SF give access to the quark and antiquark contributions in the nucleon spin

$$\Gamma_{1,6}(Q^2) = \int_0^1 g_{1,6}(x,Q^2)dx = \sum_{q,\overline{q}} (\Delta q \pm \Delta\overline{q}),$$

where $\Delta q(\Delta\overline{q}) = \int_0^1 \Delta q(x)\big(\Delta\overline{q}(x)\big)dx$ is the quark (antiquark) contribution to the nucleon spin.

The proton

$$
\begin{aligned}
\Gamma_6^{l^-p} - \Gamma_6^{l^+p} &= (\Delta u + \Delta\overline{u}) - (\Delta d + \Delta\overline{d}) - (\Delta s + \Delta\overline{s}),\\
\Gamma_6^{l^-p} + \Gamma_6^{l^+p} &= \Delta u_V + \Delta d_V = \Delta q_V,
\end{aligned}
$$

where $\Delta u_V = \Delta u - \Delta\overline{u}, \quad \Delta d_V = \Delta d - \Delta\overline{d}.$

$$
\begin{aligned}
\Gamma_1^{l^-p} + \Gamma_1^{l^+p} &= (\Delta u + \Delta\overline{u}) + (\Delta d + \Delta\overline{d}) + (\Delta s + \Delta\overline{s}),\\
\Gamma_1^{l^-p} - \Gamma_1^{l^+p} &= \Delta u_V - \Delta d_V.
\end{aligned}
$$

We use also the measurable quantity – the axial charge $a_3 = F + D = 1.2670 \pm 0.0035$ that in parton model: $a_3 = (\Delta u + \Delta\overline{u}) - (\Delta d + \Delta\overline{d})$.

The quark contributions to the nucleon spin:

The quark flavors

$$
\begin{aligned}
\Delta u + \Delta\overline{u} &= \frac{1}{2}\Big(\Gamma_1^{l^-p} + \Gamma_1^{l^+p} - \Gamma_6^{l^+p} + \Gamma_6^{l^-p}\Big),\\
\Delta d + \Delta\overline{d} &= \frac{1}{2}\Big(\Gamma_1^{l^-p} + \Gamma_1^{l^+p} - \Gamma_6^{l^+p} + \Gamma_6^{l^-p} - 2a_3\Big),\\
\Delta s + \Delta\overline{s} &= \Gamma_6^{l^+p} - \Gamma_6^{l^-p} + a_3.
\end{aligned}
$$

The valence quarks

$$
\begin{aligned}
\Delta u_V &= \frac{1}{2}\Big(\Gamma_6^{l^-p} + \Gamma_6^{l^+p} - \Gamma_1^{l^-p} + \Gamma_1^{l^+p}\Big),\\
\Delta d_V &= \frac{1}{2}\Big(\Gamma_1^{l^+p} - \Gamma_1^{l^-p} + \Gamma_6^{l^-p} + \Gamma_6^{l^+p}\Big).
\end{aligned}
$$

The sea quarks

$$
\begin{aligned}
\Delta\overline{u} &= \frac{1}{2}\Big(\Gamma_1^{l^+p} - \Gamma_6^{l^+p}\Big),\\
\Delta\overline{d} &= \frac{1}{2}\Big(\Gamma_1^{l^-p} - \Gamma_6^{l^+p} - a_3\Big),\\
\Delta\overline{s} &= \frac{1}{2}\Big(\Gamma_6^{l^+p} - \Gamma_6^{l^-p} + a_3\Big).
\end{aligned}
$$

We have obtained the quark contributions for neutron and deuteron.

The neutron

$$\begin{aligned}
\Delta u + \Delta \overline{u} &= \frac{1}{2}\Big(\Gamma_6^{l^-n} - \Gamma_6^{l^+n} + \Gamma_1^{l^-n} + \Gamma_1^{l^+n}\Big) + a_3,\\
\Delta d + \Delta \overline{d} &= \frac{1}{2}\Big(\Gamma_1^{l^-n} + \Gamma_1^{l^+n} + \Gamma_6^{l^-n} - \Gamma_6^{l^+n}\Big),\\
\Delta s + \Delta \overline{s} &= -a_3 - \Gamma_6^{l^-n} + \Gamma_6^{l^+n}.
\end{aligned}$$

$$\begin{aligned}
\Delta d_V &= \frac{1}{2}\Big(\Gamma_1^{l^-n} - \Gamma_1^{l^+n} + \Gamma_6^{l^-n} + \Gamma_6^{l^+n}\Big),\\
\Delta u_V &= \frac{1}{2}\Big(\Gamma_6^{l^-n} + \Gamma_6^{l^+n} - \Gamma_1^{l^-n} + \Gamma_1^{l^+n}\Big).
\end{aligned}$$

$$\begin{aligned}
\Delta \overline{s} &= \frac{1}{2}\Big(-a_3 - \Gamma_6^{l^-n} + \Gamma_6^{l^+n}\Big),\\
\Delta \overline{d} &= \frac{1}{2}\Big(\Gamma_1^{l^+n} - \Gamma_6^{l^+n}\Big),\\
\Delta \overline{u} &= \frac{1}{2}\Big(\Gamma_1^{l^-n} - \Gamma_6^{l^+n} + a3\Big).
\end{aligned}$$

The deuteron

$$\begin{aligned}
\Delta s + \Delta \overline{s} &= \frac{\Gamma_6^{l^+d} - \Gamma_6^{l^-d}}{1 - 1,5\omega},\\
\Delta u_V + \Delta d_V &= \frac{\Gamma_6^{l^-d} + \Gamma_6^{l^+d}}{1 - 1,5\omega},\\
\Delta \Sigma &= \frac{\Gamma_1^{l^-d} + \Gamma_1^{l^+d}}{1 - 1,5\omega},
\end{aligned}$$

where $\omega = 0.05$ is the probability D-state in the wave function of the deuteron.

Obviously, this approach to obtain the quark polarization requires a knowledge of SF g_1, g_6. These SF can be extracted from the measurable asymmetries A_{l^-,l^+} and $A_\pm$. In contrast electromagnetic DIS processes an extraction of polarized SF in DIS with CC (1) is a nontrivial problem, because the asymmetries A_{l^-,l^+}, $A_\pm$ include two independent SF g_1 and g_6. The ways to extract the SF g_1 and g_6 from asymmetries measured in experiments DIS with CC were proposed in our work [11, 12].

The numerical calculations the asymmetries were performed for DIS CC polarized electrons (positrons) off longitudinal polarized protons, neutrons and deuterons using parton distributions [13]. In Fig.1 we show the size of the asymmetries A_{e^-} for protons (top) and neutrons (bottom), but also $A_{e^\pm}$ for deuterons (Fig.3). As can be seen, the asymmetries are considerable and can to access more than 50% at $x \geq 0.7$.

We calculated the QED corrections to the asymmetries in Leading Log Approximation (LLA) [14, 15].

In Fig.5 and Fig.6 we show size QED corrections in LLA to the asymmetries $A^p_{e^-}$ and $A^n_{e^-}$ respectively. They are neglectly small at $x \gtrsim 0.5$ and get noticeable in regime small x accessing of value $10 - 15\%$ at small y.

The Next Leading Order QCD corrections to the asymmetries CC DIS are small and leading order accuracy is very good approximation [16].

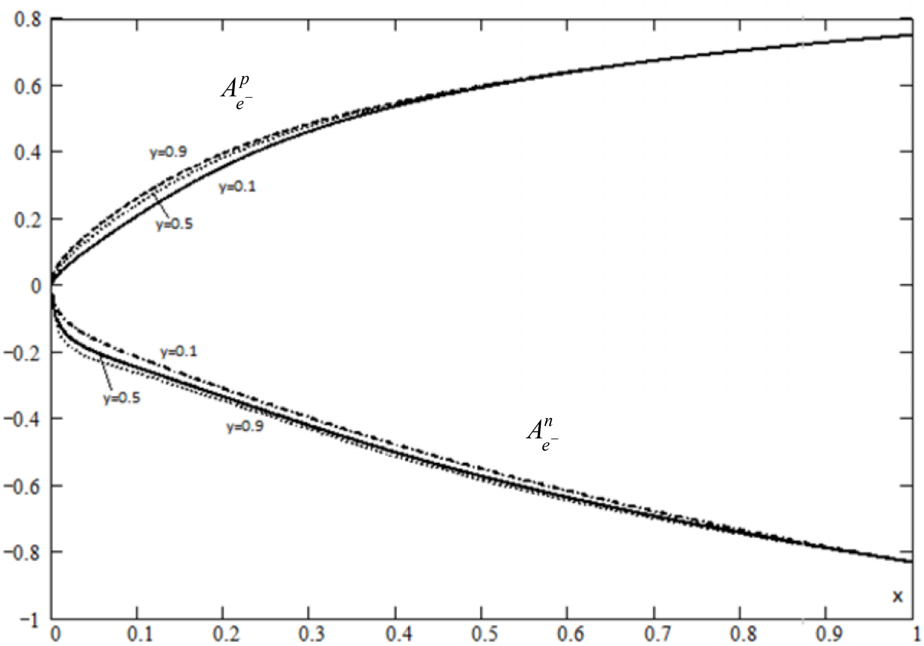

Figure 1. The asymmetries $A^p_{e^-}$ and $A^n_{e^-}$

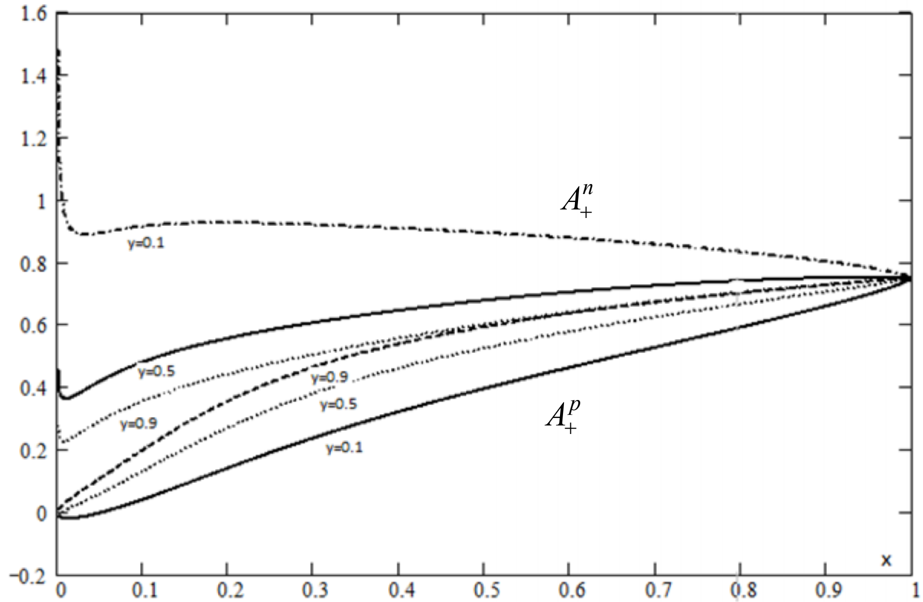

Figure 2. The asymmetries A_+^p and A_+^n

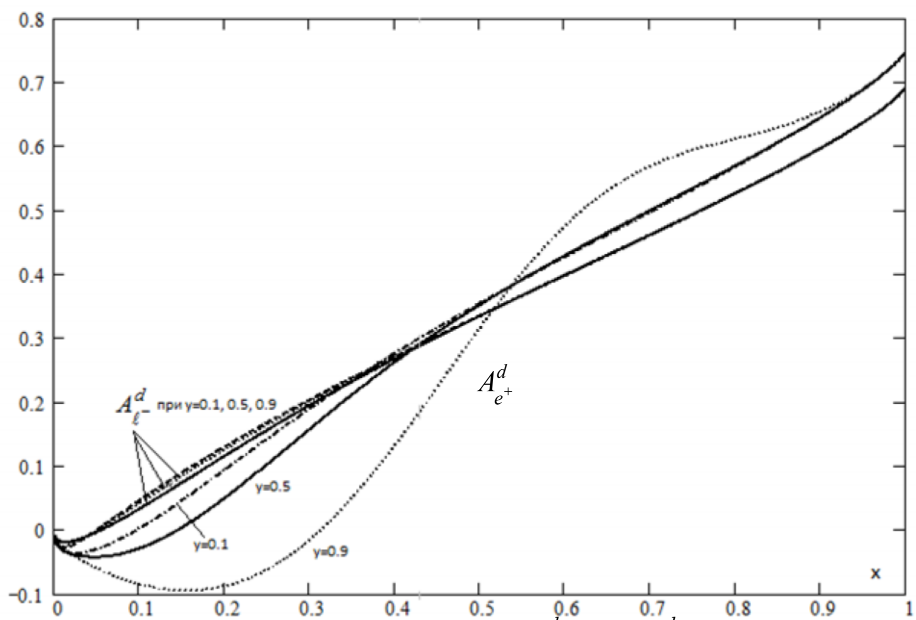

Figure 3. The asymmetries $A^d_{e^-}$ and $A^d_{e^+}$

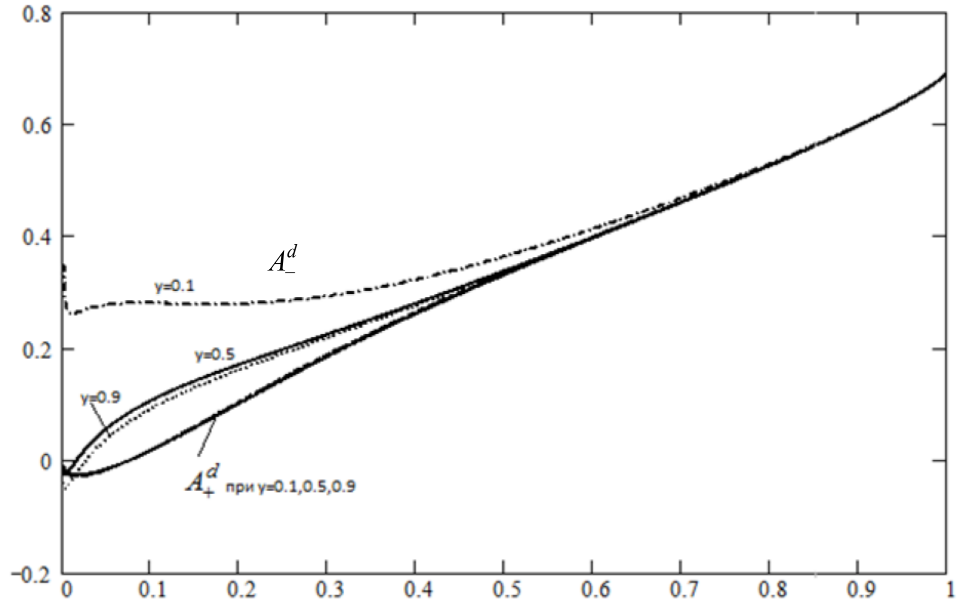

Figure 4. The asymmetries A_+^d and A_-^d

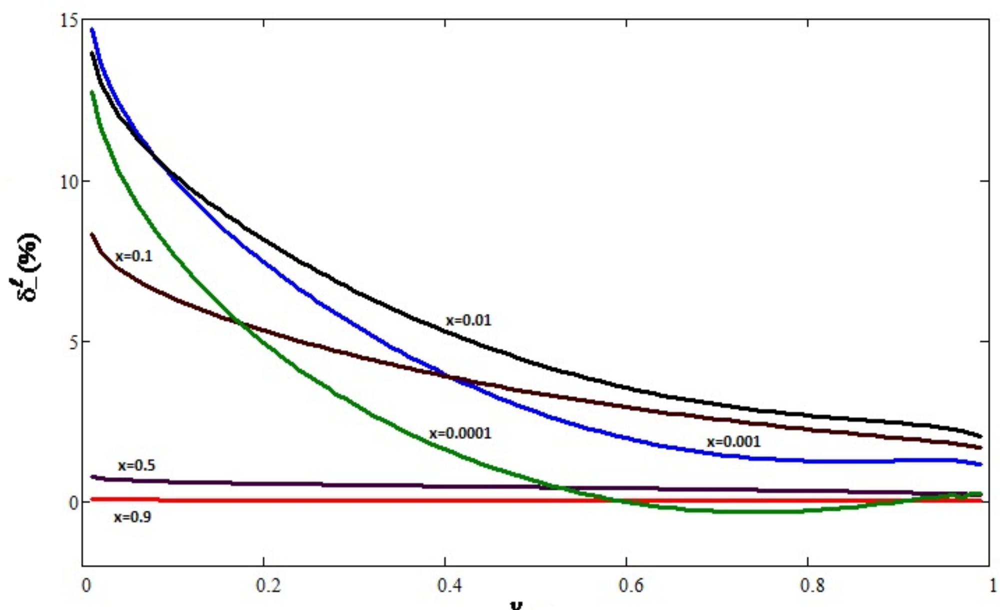

Figure 5. QED correction $\delta_-^l(\%)$ to asymmetry $A_{e^-}^p$ in leading log approximation (LLA)

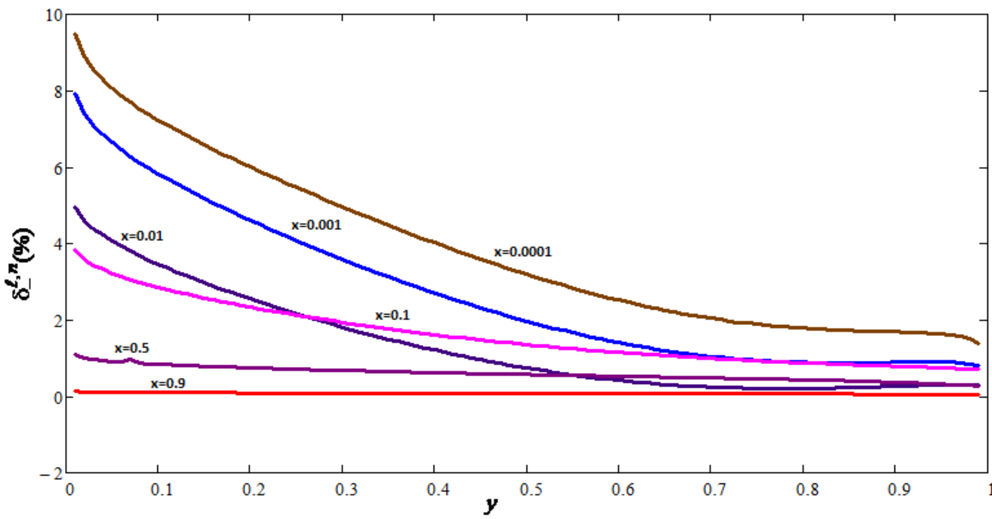

Figure 6. QED correction $\delta_-^{l,n}(\%)$ to asymmetry $A^n_{e^-}$ in LLA

Conclusion

- Data from CC DIS experiments provide complementary information on the spin structure nucleon as they probe combinations of quark flavors different from those accessible in purely electromagnetic DIS.
- CC DIS can be studied only in high-energy lepton-nucleon collisions (e.g. EIC).
- The quark contributions to the nucleon spin are obtained through the first moments of the polarized SF g_1, g_6 that can be to extract from the measurable asymmetries CC DIS.

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