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Transverse spin with high energy polarized beams at an EIC

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Future Electron Ion Collider at medium – high energy $\sqrt{s} \sim 20 \div 70$ GeV is discussed. This facility will be valuable for transverse spin physics studies. Wide range of Q^2 and P_{hT} will allow to study both QCD evolution and interplay among different QCD factorization formalisms. Three-dimentional distribution of partons inside polarised nucleon can be measured at EIC.

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Electron Ion Collider is a future high energy facility proposed by EIC Collaboration [1]. Electron Ion Collider at medium – high energy $\sqrt{s} \sim 20 \div 70$ GeV will operate with polarised proton and ion H, D, He^3, possibly Li beams. Luminosity up to $\mathscr{L} \simeq 10^{34}$ sm^{-2}s^{-1} will allow high precision measurements of underlying spin structure of the proton.

One of the obvious advantages of collider experiment is a possibility to reach high energy in the lab frame, $s = 4P_\ell P_P$, where P_ℓ, P_P are electron and proton beam momenta. Fixed target experiment are usually designed in such a way that only so called beam fragmentation region is covered, collider experiment can be designed in much more hermetic way, so that almost all particles after the interaction can be detected. This will allow to study both target and beam fragmentation regions.

A powerful tool to study the spin structure means is measurement of spin asymmetries in the SIDIS process $\ell P(S_P) \to \ell' hX$ or in Jet-SIDIS $\ell P(S_P) \to \ell' JetX$. A number of structures can be measured in DIS process $\ell P(S_P) \to \ell' X$ or in SIDIS with two detected hardons $\ell P(S_P) \to \ell' h_1 h_2 X$.

Applicability of QCD factorization theorems [2] at high values of photon's virtuality $Q^2 >> \Lambda^2_{QCD}$ allows to decompose unpolarised and polarised cross-sections of the process under consideration as convolution of universal parton distribution functions f_q and fragmentation functions $D_{q/h}$:

$$d\sigma^{\ell P(S_P)\to \ell' hX} \propto \sum_q e_q^2 f_q \otimes d\sigma^{\ell q(s_q)\to \ell' q'(s_{q'})} \otimes D_{q/h} \,. \tag{1}$$

In case of SIDIS $\ell P(S_P) \to \ell' hX$ process two scales exist: virtuality of the photon Q^2 and transverse momentum of the produced hadron P_{hT} with respect to the lepton scattering plane. Consequently two two distinct factorization theorems exist, if $Q^2 \simeq P^2_{hT} >> \Lambda^2_{QCD}$ collinear factorization theorem for unpolarised cross section [3] and Single Spin Asymmetries (SSA) [4] is valid, SSA is described as twist-3 quantum interference [5] of scattering amplitudes with different numbers of active partons. Partons are considered to be parallel to the parent hadron and small transverse intrinsic momentum of partons is neglected. If the produced hadron has low transverse momentum $Q^2 >> P^2_{hT} \geq \Lambda^2_{QCD}$ then so-called Transverse Momentum Dependent factorisation theorem [6] is valid. It describes the cross section as convolution of Transverse Momentum Dependent distribution and fragmentation functions (TMDs) that depend not only on fraction of hadron momentum carried by parton x but also on intrinsic transverse momentum of the parton $\mathbf{p}_T$.

The quark-quark distribution correlation function is defined as [7]

$$\Phi_{ij}(x, \mathbf{p}_T) = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3}\, e^{ip\cdot\xi}\, \langle P, S_P | \bar{\psi}_j(0)\, \mathscr{U}^{n_-}_{(0,+\infty)}\, \mathscr{U}^{n_-}_{(+\infty,\xi)}\, \psi_i(\xi) | P, S_P \rangle \Big|_{\xi^+=0} \tag{2}$$

with $p^+ = xP^+$, $P^+ = (P^0 + P^3)/\sqrt{2}$ is the big component of proton's momentum. $\mathscr{U}$ is the gauge link (Wilson line) that assures color gauge invariance of the correlator Φ_{ij}.

Corresponding distribution functions can be obtained by projecting the correlator onto the full basis of γ matrices $\Phi^{[\Gamma]} = \frac{1}{2}\mathrm{Tr}[\Phi\Gamma]$. At leading twist (expansion in P^+) the spin structure of the proton can be described by 8 TMDs (see [7] and references therein):

$$\Phi^{[\gamma^+]}(x, p_T^2) \;=\; f_1(x, p_T^2) - \frac{\varepsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M}\, f_{1T}^\perp(x, p_T^2)\,, \tag{3}$$

$$\Phi^{[\gamma^+\gamma_5]}(x, p_T^2) \;=\; S_L\, g_{1L}(x, p_T^2) - \frac{p_T \cdot S_T}{M}\, g_{1T}(x, p_T^2)\,, \tag{4}$$

$$\Phi^{[i\sigma^{\alpha+}\gamma_5]}(x,p_T^2) \;=\; S_T^{\alpha}\, h_1(x,p_T^2) + S_L\,\frac{p_T^{\alpha}}{M}\, h_{1L}^{\perp}(x,p_T^2) - \frac{p_T^{\alpha}p_T^{\rho} - \frac{1}{2}\,p_T^2\, g_T^{\alpha\rho}}{M^2}\, S_{T\rho}\, h_{1T}^{\perp}(x,p_T^2) - \frac{\varepsilon_T^{\alpha\rho}\, p_{T\rho}}{M}\, h_1^{\perp}(x,p_T^2)\,, \tag{5}$$

here the projections are done with respect to the quark's polarisation, $\Phi^{[\gamma^+]}$ is distribution of unpolarised quarks, $\Phi^{[\gamma^+\gamma_5]}$ is distribution of longitudinally polarised quarks and $\Phi^{[i\sigma^{\alpha+}\gamma_5]}(x,p_T^2)$ is the distribution of transversely polarised quarks.

Let us describe some of those functions.

Transversity distribution $h_1(x,p_T^2)$ [9] describes distribution of transversely polarised quarks inside a transversely polarised nucleon. Tensor charge measures net transverse polarisation of quarks

$$\delta_T q = \int_0^1 dx(h_{1q}(x) - h_{1\bar{q}}(x)). \tag{6}$$

Lorentz boost and rotation do not commute thus transversity and helicity distribution (g_1 distribution of longitudinally polarised quarks inside a longitudinally polarised nucleon) are different, as soon as interaction with virtual photon takes place the preferred direction appear to exist. We may write transversity in so called helicity basis and obtain that $h_1 \propto \mathrm{Im}A_{+-,-+}$, here A is one of 16 helicity amplitudes describing spin structure of the spin-1/2 nucleon. $A_{\Lambda\lambda,\Lambda'\lambda'}$ where $\lambda\lambda',(\Lambda\Lambda')$ are quark (nucleon) helicities. Transversity is a chiral-odd quantity and thus cannot be measured in DIS (observables should be chiral-even) and it requires helicity flip of 1 unit of angular momentum thus gluon helicity distribution does not exist. Experimentally spin distributions can be measured using SSA on transversely polarised target defined as

$$A_{UT} \propto \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \tag{7}$$

The "golden" channel to measure transversity is double spin asymmetry in Drell-Yan experiment with polarised proton and anti-proton beams, product of transversities can be measured [8]:

$$A_{NN} \propto \sum_q e_q^2 h_{1q/P} h_{1\bar{q}/\bar{P}} \tag{8}$$

In SIDIS transversity can be measured together with chiral-odd fragmentation function $H_{1q}^{\perp}(z,k_T^2)$ so-called Collins fragmentation function [10]

$$A_{UT}^{\sin(\Phi_h+\Phi_S)} \propto \sum_q e_q^2 h_{1q} \otimes H_{1q}^{\perp} \tag{9}$$

Experimental data from HERMES, COMPASS and BELLE collaborations [11, 12, 13] allow extraction of transversity.

In Fig. 1 we plot tensor charge and transversity distributions compared to models. As can be seen from Fig. 1 the experimental precision is still not good enough to discriminate among models. Apart from that still there is no information on anti-quark transversity distributions and Q^2 dependence of asymmetry was not measured experimentally. EIC will be able to shed light on both anti-quark distributions and Q^2 dependence.

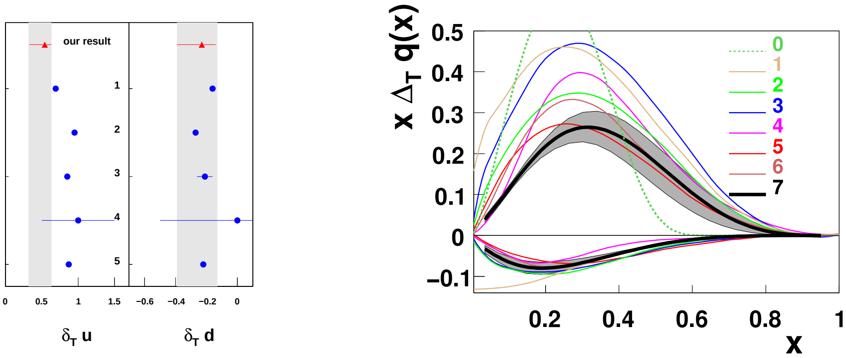

Figure 1: Left panel: extraction of tensor charge [14] compared to models [19]. Right panel: transversity for u and d quarks [14] compared to models [19]

$f_{1T}^{\perp}(x,p_T^2)$ is so-called Sivers function [15], it describes correlation between orbital angular motion of quarks and the spin of the proton $\varepsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}$. This function exists due to the presence of Final State Interactions of the struck quark and the remnant of the nucleon after the interaction.

This function obeys a modified universality, it changes sign from SIDIS to Drell-Yan [16]

$$f_{1T}^{\perp}(x,p_T^2)^{SIDIS} = -f_{1T}^{\perp}(x,p_T^2)^{DY}, \tag{10}$$

the prediction of change of sign based on color gauge symmetry and parity and time reversal invariance $\mathscr{P},\mathscr{T}$ of strong interactions. Experimental test of this relation is very important for our understanding of QCD.

EIC can contribute in unraveling the anti-quark contributions and will be able to measure Q^2 dependence of the asymmetry

$$A_{UT}^{\sin(\Phi_h-\Phi_S)} \propto \sum_q e_q^2 f_{1T}^{\perp} \otimes D_{1q}\,. \tag{11}$$

The first moment of Sivers function $f_{1T}^{\perp(1)}(x) = \int d^2k_\perp \frac{k_\perp^2}{M^2} f_{1T}^{\perp}(x,p_T^2)$ is related [17] to twist three Qiu-Sterman matrix element $T_F(x,x)$ [5]

$$T_F(x,x) = f_{1T}^{\perp(1)}(x)\,. \tag{12}$$

Twist three matrix elements are ingredients of collinear QCD to describe spin asymmetries and the formalism is valid at high $P_{hT} >> \Lambda_{QCD}$. The Sivers function describes the asymmetry at low values of $P_{hT} \sim \Lambda_{QCD}$. Interplay between two formalisms is very important check for EIC, the collider will be able to cover P_{hT} region up to 4 GeV.

In Fig. 2 we plot Sivers function extracted from the experimental data [18, 12] a three dimensional parton distribution at $x = 0.01$, as can be seen from Fig. 2 the distribution of partons in a transversely polarised hadron is not rotational symmetric, the distributions have dipole deformation with respect to the "center" of the hadron.

We conclude that EIC will be a valuable facility that will measure 3 dimensional distributions of partons in the nucleon. Q^2 range will allow to check evolution of asymmetries, wide P_{hT} range

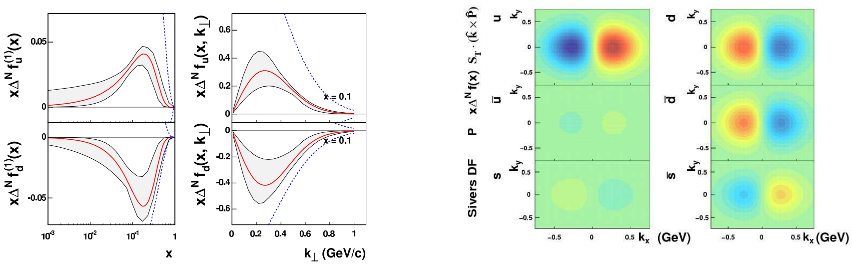

Figure 2: Left panel: extraction of Sivers function [20]. Right panel: three dimensional parton distribution.

will allow to measure asymmetries in both regions where TMD and collinear QCD factorizations are valid.

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