Transverse Spin Densities of Quarks in the Nucleon from Lattice QCD ◇

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The distribution of transverse quark spin in the nucleon received a lot of attention in recent years from both theory and experiment as it provides a new perspective on hadron structure and QCD evolution. Of central interest is the quark transversity distribution $\delta q(x) = h_1(x)$, which represents the probability to find a transversely polarized quark with longitudinal momentum fraction x in a transversely polarized nucleon [1]. Substantial progress has been made with respect to so-called transverse momentum dependent PDFs like the Sivers $f_{1T}^{\perp}(x, k_{\perp}^2)$ and Boer-Mulders $h_1^{\perp}(x, k_{\perp}^2)$ function [2], which measure correlations of the intrinsic quark transverse momentum $k_{\perp}$ with the transverse nucleon spin $S_{\perp}$ and the transverse quark spin $s_{\perp}$, respectively. Here, we report on another particularly promising approach to the transverse spin structure of hadrons which is based on the 3-dimensional density $\rho(x, b_{\perp}, s_{\perp}, S_{\perp})$ [3], representing the probability to find a quark with momentum fraction x and transverse spin $s_{\perp}$ at distance $b_{\perp}$ from the center-of-momentum of the nucleon with transverse spin $S_{\perp}$. Moreover, the density is directly related to the Sivers- and Boer-Mulders-functions [4]. Lattice QCD calculations give access to x^{n-1}-moments of transverse quark spin densities $\rho^n(b_{\perp}, s_{\perp}, S_{\perp})$ [3]. The moments ρ^n can be written in form of a multipole expansion with a monopole term, two dipole structures $\propto b_{\perp}^j \epsilon^{ji} s_{\perp}^i$ and $\propto b_{\perp}^j \epsilon^{ji} S_{\perp}^i$, and a quadrupole term. The strength of the dipole and quadrupole terms is determined by three different types of $b_{\perp}$-dependent nucleon generalized form factors (GFFs), $B_{n0}(b_{\perp}^2)$, $\overline{B}_{Tn0}(b_{\perp}^2)$ and $\widetilde{A}_{Tn0}(b_{\perp}^2)$, which are related to GFFs in momentum space $B_{n0}(\Delta_{\perp}^2)$, $\overline{B}_{Tn0}(\Delta_{\perp}^2), \ldots$ by a Fourier transformation with respect to the transverse momentum transfer $\Delta_{\perp}$. Our lattice calculation [5] of these GFFs is based on $N_f = 2$ dynamical non-perturbatively improved Wilson fermions and Wilson gluons. Simulations have been performed at lattice spacings as low as 0.07 fm, for pion masses down to 400 MeV and in spatial volumes as large as $(2.1\ \text{fm})^3$.

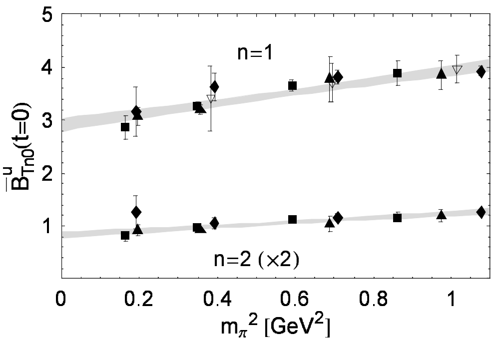

Figure 1: Chiral extrapolation of generalized form factors.

In Fig. 1, we show as an example the pion mass dependence of the GFF $\overline{B}_{T(n=1,2)0}^u(t = \Delta_{\perp}^2 = 0)$ as obtained from the lattice simulation. Since most of our pion masses are still rather large, we cannot expect recent chiral perturbation theory predictions [6] to be applicable. We therefore extrapolate our results to the physical pion mass using an ansatz linear in m_π^2, shown as shaded error bands in Fig. 1. We find $\overline{B}_{T10}^u(0) = 2.93(13)$, $\overline{B}_{T10}^d(0) = 1.90(9)$ and $\overline{B}_{T20}^u(0) = 0.420(31)$, $\overline{B}_{T20}^d(0) = 0.260(23)$. These comparatively large values already indicate a significant impact of this GFF on the transverse spin structure of the nucleon.

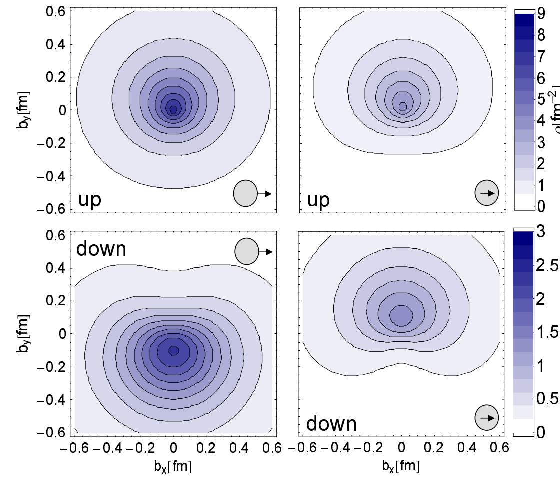

Figure 2: Transverse spin densities for $n = 1$.

In Fig. 2, we show the lowest moment $n = 1$ of spin densities for up and down quarks in the nucleon. We find strong distortions for unpolarized quarks in transversely polarized nucleons (left part of figure). This has already been discussed in [4] and can serve as a dynamical explanation of the experimentally observed Sivers-effect. Remarkably, we find even stronger distortions for transversely polarized quarks $s_{\perp} = (s_x, 0)$ in an unpolarized nucleon, shown on the right hand side of Fig. 2. The densities for up and for down quarks in this case are both deformed in positive b_y direction due to the large positive values for the GFFs $\overline{B}_{T10}^{u,d}$. This allows for the prediction of a sizeable, negative Boer-Mulders function for both up and down quarks, leading to significant azimuthal asymmetries in semi-inclusive deep ineleastic scattering, which may be confirmed in experiments at e.g. JLab [7], HERMES/DESY and COMPASS/CERN.

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