INTRINSIC TRANSVERSE MOMENTUM AND PARTON CORRELATIONS FROM NONPERTURBATIVE SHORT-RANGE INTERACTIONS*

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We summarize recent progress in understanding the effects of nonperturbative short-range interactions in QCD on the nucleon's partonic structure at a low scale: (a) Sea quarks have intrinsic transverse momenta up to the chiral symmetry-breaking scale $\rho^{-1} \sim 0.6$ GeV, much larger than those of valence quarks. (b) Sea quarks in the nucleon light-cone wave function exist partly in correlated pairs of transverse size ρ with sigma and pi-like quantum numbers and a distinctive spin structure ($L = 1$ components). The effects are demonstrated in an effective model of the low-energy dynamics resulting from chiral symmetry breaking in QCD. They have numerous implications for the P_{T} distribution of hadrons in semi-inclusive DIS and multiparton processes in high-energy pp collisions.

Describing the transition between the short-distance regime of asymptotic freedom and long-distance hadronic structure is perhaps the main challenge in practical applications of QCD. A basic observation is that nonperturbative effects become important already at distances much smaller than the typical hadronic size $R \sim 1$ fm. In the usual approach to QCD based

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on equal-time quantization and Euclidean correlation functions, these effects lead to a non-trivial ground state and are often referred to as "vacuum structure;" however, their significance really lies in the existence of short-range nonperturbative interactions which can manifest themselves in hadronic structure in multiple ways. Specifically, dynamical chiral symmetry breaking in QCD is caused by nonperturbative interactions over a range $\rho \sim 0.3$ fm (see Fig. 1), defined by the typical size of the topological gauge field fluctuations creating the chiral condensate. The existence of this nonperturbative short-distance scale has far-reaching consequences for hadron structure. It is the foundation of the "constituent quark" picture explaining many aspects of static nucleon properties and low-energy interactions. An outstanding question is what the chiral symmetry-breaking interactions at the scale ρ imply for the nucleon's partonic structure, *i.e.*, the light-cone momentum distributions of quarks, antiquarks and gluons measured in deep-inelastic scattering (DIS) and other high momentum-transfer processes. A recent study [1] found two striking manifestations:

(a) Sea (or non-valence) quarks in the nucleon at a low scale have transverse momenta extending up to the inverse chiral symmetry-breaking scale, $p_T \sim \rho^{-1}$, much larger than those of valence quarks, which are of the order of the inverse hadronic size R^{-1}.

(b) Sea quarks in the nucleon's light-cone wave function are partly correlated in pairs of transverse size $\rho \ll R$ with sigma and pi-like quantum numbers and a distinctive spin structure (including $L = 1$ components), amounting to nonperturbative short-range correlations of partons at a low scale.

These effects were demonstrated in a dynamical model using chiral constituent quarks as effective degrees of freedom; because they rely only on generic features of the nonperturbative dynamics ($\rho \ll R$) they are expected to hold also in QCD in a properly defined context. They have potential implications for the understanding of transverse nucleon structure (role of chiral symmetry breaking, valence *vs.* sea quarks), the effectiveness of QCD factorization in DIS with identified transverse momenta (natural scales, QCD
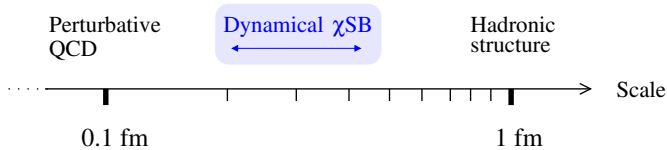

Fig. 1. Scale of dynamical chiral symmetry breaking in QCD.

evolution), and the phenomenology of scattering processes sensitive to intrinsic transverse momentum and parton correlations (semi-inclusive DIS, multiparton processes in pp collisions). In this note, we summarize the main points; for details we refer to the original article [1].

Chiral symmetry breaking from short-range interactions. The short-range character of the nonperturbative interactions causing the dynamical breaking of chiral symmetry is seen in numerous theoretical and phenomenological observations. The most direct theoretical evidence comes from studies of the size distribution of chirality-flipping topological gauge fields in lattice simulations of Euclidean QCD (see Fig. 2 (a)) [2]. The instanton vacuum, an approximate realization of this mechanism, uses an average size $\rho \sim 0.3$ fm [2]. Other evidence comes from the large value of the "average quark virtuality" in the chiral condensate, $m_0^2 = 2\langle\bar{\psi}\nabla^2\psi\rangle/\langle\bar{\psi}\psi\rangle \gtrsim 1\,\mathrm{GeV}^2$, obtained in lattice QCD and the instanton vacuum [3]. Phenomenologically, the short range of chiral symmetry-breaking interactions is seen in the success of the constituent quark picture of hadron structure [4]. The "superconducting" quark model [5] and models based on Dyson–Schwinger equations of QCD [6] describe chiral symmetry breaking as the generation of a dynamical quark mass of 0.3–0.4 GeV from effective interactions with a range $\ll 1$ fm (this aspect is not often emphasized).
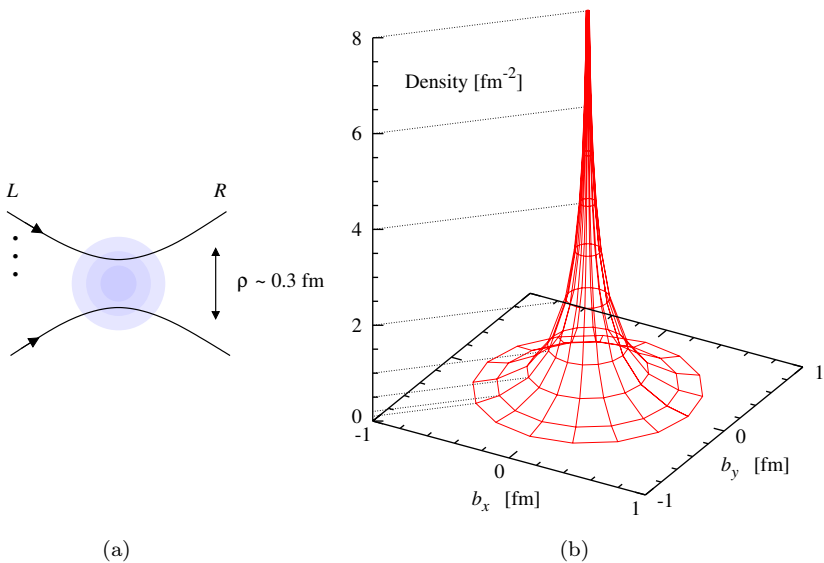

(a)   (b)

Fig. 2. (a) Chiral symmetry breaking by topological gauge fields in Euclidean QCD. (b) Transverse charge density in the pion obtained from e^+e^- data [7]. The large density at $b \ll 1$ fm is due to small-size configurations likely generated by short-range nonperturbative interactions.

Pion structure as example. Besides generating a dynamical quark mass, the short-range interactions associated with chiral symmetry-breaking induce dynamical correlations which manifest themselves when probing hadron structure at distance scales $\sim \rho$. Particularly interesting is the structure of the pion, the Goldstone boson of chiral symmetry breaking. A recent dispersion analysis using time-like form factor data from e^+e^- annihilation experiments found a large transverse charge density in the pion at distances $b \ll 1$ fm (see Fig. 2 (b)) [7]. Interpreted in the context of light-cone wave functions it directly attests to the presence of small-size configurations in the pion, as would be produced by chiral symmetry-breaking interactions with a range $\rho \ll R$; it cannot be explained by end-point configurations ($x \to 1$) at any reasonable normalization point.

Chiral quark–soliton model of nucleon. The effect of the nonperturbative short-range interactions on the nucleon's partonic structure at a low scale can be studied in a schematic model of the effective dynamics resulting from chiral symmetry-breaking [1]. It uses "constituent" quarks with a dynamically generated mass $M \sim 0.3$–0.4 GeV as effective degrees of freedom below the chiral symmetry-breaking scale. The quark mass is accompanied by a coupling to a Goldstone boson (or chiral) field with strength $M/f_\pi \sim 3$–4, resulting in a strongly coupled field theory that is solved nonperturbatively in a $1/N_c$ expansion. The nucleon in this model develops a classical chiral field with a radius of the order $\sim M^{-1}$, which acts in two ways: it binds the valence quarks and creates quark–antiquark pairs out of the vacuum, which can interact further with the chiral field (chiral quark–soliton model, see Fig. 3) [8]. The resulting description is fully relativistic and can be studied either in the rest frame, where the classical chiral field and the quark orbitals are spherically symmetric ("hedgehog"), or in the infinite-momentum frame, where the fields can be projected on partonic quanta. The light-cone wave function of the nucleon in this model is built up from two types of configurations:
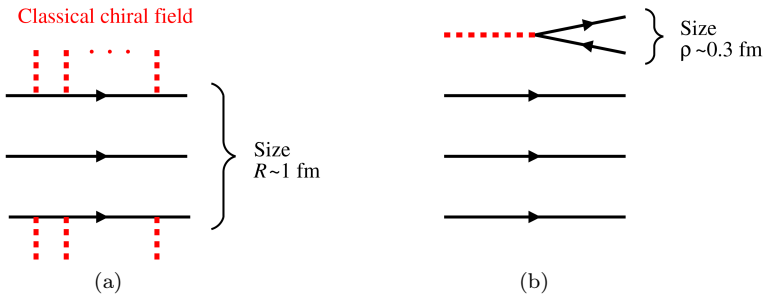

Fig. 3. Chiral quark–soliton model of nucleon. The classical chiral field (a) binds the valence quarks; (b) creates quark–antiquark pairs.

(a) Valence quarks in configurations of transverse size $R \sim M^{-1}$;

(b) Quark–antiquark pairs in configurations with sizes ranging from the chiral symmetry-breaking scale $\rho \ll R$ to the nucleon size R.

The chiral quark–soliton model has been used extensively to study the nucleon's parton densities at the scale $\mu^2 \sim \rho^{-2}$ [9]. It predicts a non-trivial antiquark content at this scale as a consequence of dynamical chiral symmetry breaking, in agreement with results of fits to DIS and other data. The model describes the light-cone momentum distributions of constituent quarks and antiquarks — effective degrees of freedom which are to be matched with QCD quarks, antiquarks and gluons at the chiral symmetry-breaking scale $\mu^2 \sim \rho^{-2} \gg M^2$. The fits show that at this scale $\sim 30\%$ of the nucleon's light-cone momentum is carried by gluons; exactly how these appear out of the effective degrees of freedom is the subject of on-going study and requires detailed information on the embedding of the effective model in QCD.

Transverse momentum distributions. The effective model allows us to study also the transverse momentum distributions of constituent quarks and antiquarks in the nucleon. Fig. 4 shows the flavor-singlet unpolarized distribution $f_1^{u+d}(x, p_{\mathrm{T}})$ of valence and sea quarks at a representative value of $x = 0.1$. The valence quark distribution is concentrated at values $p_{\mathrm{T}}^2 \sim$ few M^2. The sea quark distribution is qualitatively different and exhibits a power-like "tail" that extends up to the chiral symmetry-breaking
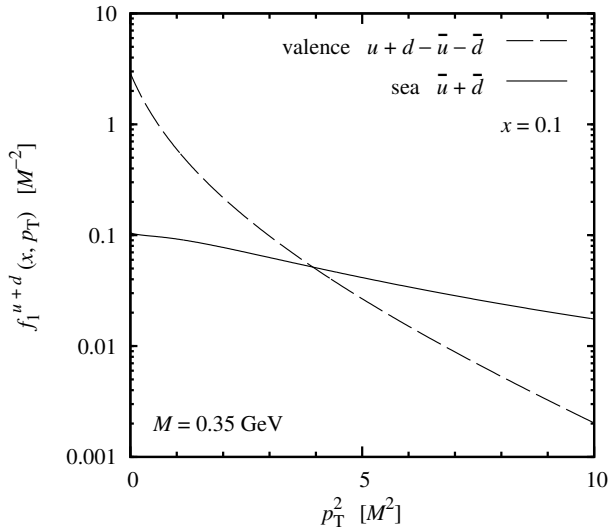

Fig. 4. Transverse momentum distribution of valence quarks (dashed line) and sea quarks (solid line) in the chiral quark–soliton model [1].

scale ρ^{-2} (for details see Ref. [1]). Similar behavior is found in the flavor-nonsinglet polarized distribution $g_1^{u-d}(x, p_\mathrm{T})$. These features follow from the basic properties of the configurations in the light-cone wave function (see Fig. 3) and represent a direct imprint of chiral symmetry breaking on the nucleon's partonic structure. They have many potential consequences for the modeling of transverse momentum-dependent (TMD) distributions in QCD and the role of QCD evolution in processes with identified soft transverse momenta. We note that the uncertainties in the matching of the model result with QCD presently preclude a fully quantitative interpretation. However, the qualitative difference between the valence and sea quark p_T distributions follows just from the existence of the two dynamical scales $\rho \ll R$ and should hold in QCD in a properly defined context.

Parton short-range correlations. Much more insight into the role of chiral symmetry breaking can be gained by going beyond the level of one-body densities and studying two-particle correlations in the partonic structure. The effective model predicts short-range correlations between constituent quarks and antiquarks in the nucleon's light-cone wave function as a direct result of the dynamical mechanism by which quark–antiquark pairs are created by the classical field (see Fig. 3 (b)). The correlated pairs have either scalar–isoscalar (Σ) or pseudoscalar–isovector (Π) quantum numbers; the pair's internal light-cone wave function involves components with $L = 1$ which dominate at $p_\mathrm{T}^2 \gg M^2$ and generate the "tail" in the sea quark p_T distribution (see Fig. 4). A very gratifying result is that at $p_\mathrm{T}^2 \gg M^2$ the wave functions of the Σ- and Π-type pairs become identical, $|\Psi_\Sigma|^2 = |\Psi_\Pi|^2$, amounting to "restoration of chiral symmetry" at the scale ρ^{-2}. These parton short-range correlations exibit many similarities with short-range NN correlations in nuclei [10]. Note that the fraction of sea quarks in the nucleon with momenta $p_\mathrm{T}^2 \gg M^2$ is not small, as can be seen from Fig. 4.

Experimental tests. The nonperturbative effects in the nucleon's partonic structure could potentially be tested in (a) semi-inclusive DIS discriminating between hadrons produced in scattering from quarks and antiquarks; (b) correlations between hadrons in the current and target fragmentation regions sensitive to intrinsic p_T. Realistic projections require detailed modeling of pQCD radiation, final-state interactions, and quark fragmentation, and are the object of on-going study. Other processes potentially affected by nonperturbative parton correlations are exclusive meson production at $W \sim$ few GeV and multiparton processes in high-energy pp scattering.

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