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ON THE DISTRIBUTION OF PARTONS IN THE TRANSVERSE PLANE

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Elastic nucleon form factors constrain the spatial distribution of quarks in the impact parameter plane. A recent analysis found that the average impact parameter of quarks strongly depends on their longitudinal momentum, and obtained an estimate of the orbital angular momentum carried by valence quarks in the proton.

1. Generalized parton distributions

Parton densities are among the most important sources of information on hadron structure at the level of quarks and gluons. The conventional densities describe the distribution of longitudinal momentum and helicity carried by partons in a fast-moving hadron. Generalized parton distributions (GPDs) complement this essentially one-dimensional picture with information on the directions transverse to the one in which the hadron moves.[1,2] In this talk I present main results of a study of the interplay between transverse and longitudinal degrees of freedom.[3]

Thanks to short-distance factorization GPDs appear in exclusive scattering processes such as deeply virtual Compton scattering ($\gamma^* p \to \gamma p$) and hard meson production. In such processes a finite momentum is transferred to the proton. As a consequence, GPDs depend on two longitudinal parton momentum fractions and in addition on the invariant momentum transfer t to the proton. Understanding the interplay between the two longitudinal parton momenta remains an outstanding task, and in the following I consider the simpler case where they are equal. The so-called skewness parameter ξ is then zero, and the distributions depend on a single longitudinal momentum fraction x and on t.

At small x and not too large t, phenomenological experience from high-energy scattering suggests a simple parameterization[4]

$$H(x,t) \sim x^{-(\alpha+\alpha' t)} = x^{-\alpha} \exp[\, t\alpha' \log(1/x)\,] \tag{1}$$

of a generic GPD at $\xi = 0$. Literally, this form corresponds to the exchange of a single Regge trajectory linear in t, but in a broader sense it may be taken as an effective power-law valid in a limited range of small x and t. For $t = 0$ such a power behavior is indeed used in many parameterizations of conventional parton densities. It is well known that for sea quark and gluon distributions one finds effective exponents α that are very different from the corresponding values extracted

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for meson or Pomeron exchange in soft scattering processes.[5] In addition, analyses of J/Ψ production at HERA find α' significantly smaller than the corresponding value for Pomeron exchange in soft reactions like $pp \to pp$ or $\gamma p \to \rho p$.[6] On the other hand, the typical values $\alpha \approx 0.5$ for valence quark distributions at low momentum scale rather closely correspond to the leading meson trajectories in Regge phenomenology of soft interactions. There is presently no direct measurement of α' for valence quark distributions.

2. Impact parameter

At given longitudinal momenta one can trade the dependence of a GPD on t for the dependence on the transverse momentum transferred to the proton. A very intuitive picture is obtained by Fourier transforming the GPD with respect to this transverse momentum transfer.[1,7] The conjugate variable $\boldsymbol{b}$, called impact parameter, gives the transverse distance of the struck parton from the center of momentum (c.o.m.) of the proton. The c.o.m. of a system is the weighted average $\sum_i x_i \boldsymbol{b}_i / \sum_i x_i$ of the transverse positions $\boldsymbol{b}_i$ of its constituents, with the weights being their individual momentum fractions x_i.

For $\xi = 0$ the Fourier transformed GPDs give the probability to find a parton with specified momentum fraction x and impact parameter $\boldsymbol{b}$ in the proton. The average squared impact parameter at a given x is

$$\langle b^2 \rangle_x = 4 \frac{\partial}{\partial t} \log H(x,t) \Big|_{t=0} . \tag{2}$$

This average depends on the resolution scale μ and obeys an evolution equation similar to the one for conventional parton densities.[3] The form (1) translates into $\langle b^2 \rangle_x$ growing like $\log(1/x)$ in the small-x limit. In the opposite limit, the impact parameter of a parton with large x tends to coincide with the c.o.m. of the proton (see Fig. 1a). It is plausible to assume that, because of confinement, the distance $b/(1-x)$ of the struck parton from the c.o.m. of the remaining *spectator* partons on average remains finite for $x \to 1$.

3. Information from the electromagnetic Dirac form factors

Information on the valence combination $H_v^q = H^q - H^{\bar{q}}$ of unpolarized quark and antiquark GPDs can be obtained from the sum rule

$$F_1^p(t) = \int_0^1 dx \, \Big[\tfrac{2}{3} H_v^u(x,t) - \tfrac{1}{3} H_v^d(x,t) \Big] \tag{3}$$

relating them to the Dirac form factor of the proton, and from the analogous sum rule for the neutron. We fitted the measured form factors to an ansatz[3]

$$H_v^q(x,t) = q_v(x) \exp[\, t f_q(x) \,] \tag{4}$$

with valence quark densities q_v taken from the CTEQ6M parameterization at scale $\mu = 2$ GeV. We chose $f_q(x)$ to interpolate between limiting behaviors $\alpha' \log(1/x)$

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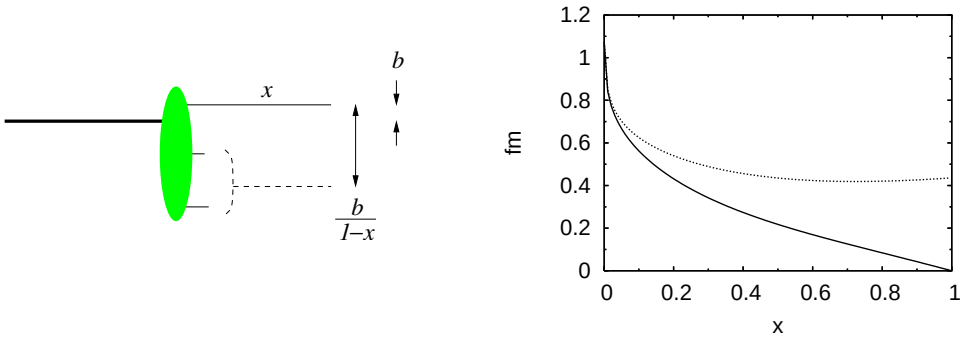

Fig. 1. (a) Three-quark configuration with one fast quark in the proton. The thick line denotes the c.o.m. of the proton and the dashed line the c.o.m. of the two spectator quarks. (b) Average impact parameter $[\langle b^2\rangle_x]^{1/2}$ for valence u quarks (lower curve) and the corresponding distance $(1-x)^{-1}\,[\langle b^2\rangle_x]^{1/2}$ of the struck quark from the c.o.m. of the spectators (upper curve).

at small x and $A^q(1-x)^2$ at large x, respectively corresponding to the form (1) for $x \to 0$ and to a finite size of the proton for $x \to 1$. A good description of proton and neutron form factors can be achieved, with a parameter $\alpha' \approx 0.9$ GeV^{-2} consistent with expectations from soft Regge phenomenology. A key result of our analysis is the strong change of the average impact parameter over the entire x range, shown in Fig. 1b.

4. Spin and the electromagnetic Pauli form factors

An analog of (3) relates the valence combination $E_v^q = E^q - E^{\bar q}$ of proton helicity-flip GPDs to the Pauli form factor. Transformed to impact parameter space, a combination of H^q and E^q describes the density of unpolarized quarks in a transversely polarized proton.[1] Positivity of the density for arbitrary quark and proton polarization implies a bound[9]

$$\Big[E^q(x,t=0)\Big]^2 \le m^2\Big[q(x)+\Delta q(x)\Big]\Big[q(x)-\Delta q(x)\Big] \times 4\,\frac{\partial}{\partial t}\log\Big[H^q(x,t)\pm\tilde H^q(x,t)\Big]_{t=0} \qquad (5)$$

in terms of the parton densities $q \pm \Delta q$ of right and left handed quarks and the average impact parameter of quarks with either helicity. The strong decrease with x of the right-hand side puts strong constraints on E^q. We fitted the data of proton and neutron Pauli form factors to a parameterization

$$E_v^q(x,t) = \mathcal{N}_q\, x^{-\alpha}(1-x)^{\beta_q}\,\exp[\,t g_q(x)\,], \qquad (6)$$

with g_q constructed as f_q in (4) and normalization factors $\mathcal{N}_q$ determined by the magnetic moments of proton and neutron. Good fits to the data are obtained with $\alpha \approx 0.5$, again corresponding to expectations from soft Regge phenomenology, and for a wide range of β_u and β_d restricted mainly by the positivity constraints on E^q.

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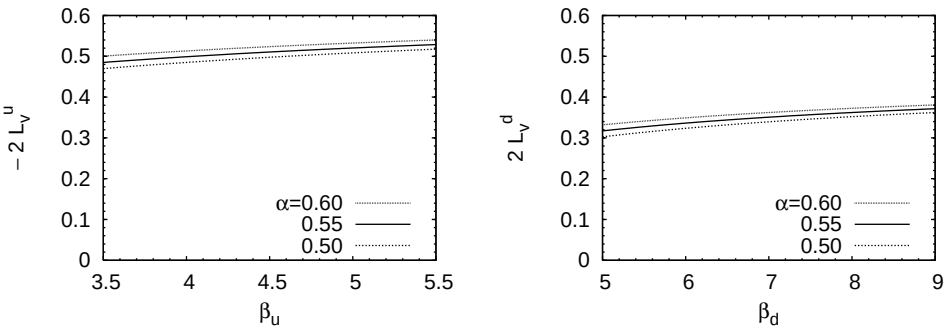

Fig. 2. The orbital angular momentum carried by valence quarks at scale $\mu = 2$ GeV, obtained in the range of parameters for which we obtain a good fit to the Pauli form factors.[3]

Quite remarkably, the uncertainties on the parameters in our fit result in very little variation of the orbital angular momentum of valence quarks, given by Ji's sum rule as[10]

$$L_v^q = \tfrac{1}{2} \int_0^1 dx \, \Big[x E_v^q(x, t=0) + x q_v(x) - \Delta q_v(x) \Big]. \tag{7}$$

The results shown in Fig. 2 correspond to a range $L_v^u - L_v^d = -\frac{1}{2}\,(0.77 \div 0.92)$. The combination $L_v^u + L_v^d = -\frac{1}{2}\,(0.11 \div 0.22)$ has large errors and is rather small due to partial cancellation between the two quark flavors.

Electromagnetic form factors can only constrain the difference of quark and antiquark distributions. In this they are complementary to hard scattering processes like deeply virtual Compton scattering, which provide access to the sea quark sector.

Acknowledgments

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