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Exploring Skewed Parton Distributions with Polarized Targets

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Exploring skewed parton distributions with polarized targets * †

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Abstract

I briefly review the physics of skewed parton distributions. Special emphasis is put on the relevance of target polarization, and on the different roles of small and of intermediate x_B.

1 The physics of skewed parton distributions

In recent years much progress has been made in the theory of skewed parton distributions (SPDs). Unifying the concepts of parton distributions and of hadronic form factors, they contain a wealth of information about how quarks and gluons make up hadrons. Advances in experimental technology raise hope to study the exclusive processes where these functions appear.

While the usual parton distributions are matrix elements of quark or gluon operators for a given hadron state p, SPDs are obtained from the same operators sandwiched between two hadron states p and p' with different momenta, corresponding to the finite momentum transfer the hadron undergoes in an exclusive process. A good example for this is deeply virtual Compton scattering (DVCS). This is the process $\gamma^* p \to \gamma p$ (measured in electroproduction $ep \to ep\gamma$) in the kinematical regime where the photon virtuality $Q^2 = -q^2$ and the energy squared $W^2 = (p+q)^2$ are large, while the invariant momentum transfer $t = (p-p')^2$ to the proton is small. If Q^2 is large enough, the transition amplitude factorizes [1] into a perturbatively calculable subprocess at the level of quarks and gluons and an SPD, which encodes the nonperturbative dynamics relating the quarks or gluons with the proton states (Fig. 1a).

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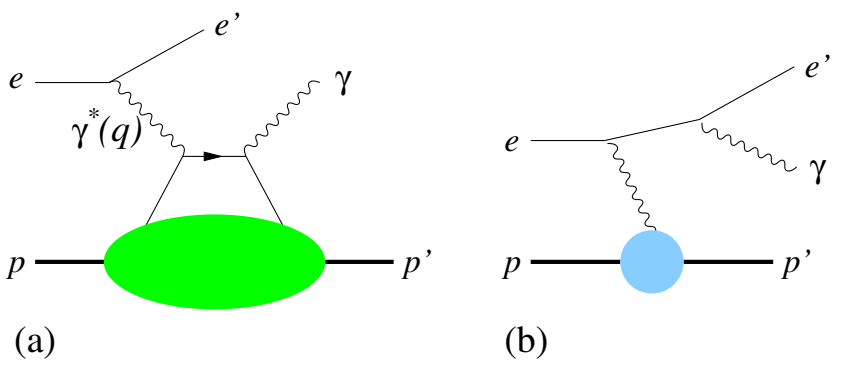

Figure 1: (a) A Born level diagram for DVCS. The blob represents a skewed quark distribution. (b) A diagram for the Bethe-Heitler process. The blob here stands for an elastic proton form factor.

The key difference between the usual parton distributions and their skewed counterparts can be seen by representing them in terms of the quark and gluon wave functions of the hadron [2]. The usual parton distributions are obtained from the squared wave functions for all partonic configurations containing a parton with specified polarization and longitudinal momentum fraction x in the fast moving hadron (Fig. 2a). This represents the probability for finding such a parton. In contrast, SPDs represent the *interference* of different wave functions, one where a parton has momentum fraction $x+\xi$ and one where this fraction is $x-\xi$ (Fig. 2b). SPDs thus correlate different parton configurations in the hadron at the quantum mechanical level. There is also a kinematical regime where the initial hadron emits a quark-antiquark or gluon pair (Fig. 2c). This has no counterpart in the usual parton distributions and carries information about $q\bar{q}$ and gg-components in the hadron wave function.

Apart from the momentum fraction variables x and ξ SPDs depend on the invariant momentum transfer t. This is an independent variable because the momenta p and p' may differ not only in their longitudinal but also in their transverse components. SPDs thus interrelate the longitudinal and transverse momentum structure of partons within a fast moving hadron.

SPDs have a rich structure in the polarization of both the hadrons and the partons. For quarks four different combinations contribute to DVCS. The functions H_q and E_q are summed over the quark helicity, and $\tilde{H}_q$ and $\tilde{E}_q$ involve the difference between right and left handed quarks. H_q and $\tilde{H}_q$ conserve the helicity of the proton, whereas E_q and $\tilde{E}_q$ allow for the possibility that the proton helicity is flipped. In that case the overall helicity is not conserved: the proton changes helicity but the quarks do not, so that angular momentum conservation has to be ensured by a transfer of *orbital* angular momentum (Fig. 3a). This is only possible for nonzero transverse momentum transfer, and therefore cannot be observed with ordinary parton distributions, where the momenta p and p'

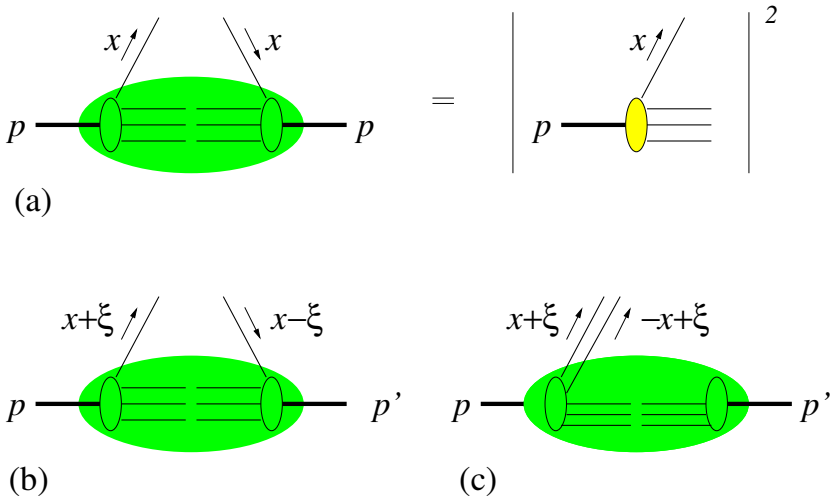

Figure 2: (a) Usual parton distribution, representing the probability to find a parton with momentum fraction x in the nucleon. All configurations of the spectator partons are summed over. (b) SPD in the region where it represents the emission of a parton with momentum fraction $x+\xi$ and its reabsorption with momentum fraction $x-\xi$. (c) SPD in the region where it represents the emission of a parton pair. Here $x+\xi > 0$ and $x-\xi < 0$.

are equal. That SPDs deeply involve the orbital angular momentum of the partons is epitomized in Ji's sum rule [3], which states that the second moment $\int dx\, x\, [H_q(x,\xi,t) + E_q(x,\xi,t)]$ is a form factor whose value at $t = 0$ gives the *total* angular momentum carried by quarks, both its spin and orbital part. For gluons there are corresponding distributions H_g, E_g, $\tilde{H}_g$, $\tilde{E}_g$, and an analogous sum rule exists.

There are SPDs with yet another spin structure [4]. Distributions flipping the quark helicity are the skewed counterparts of the usual quark transversity distribution, but no process is known at present where they contribute [5]. In the gluon sector there are distributions which change the gluon helicity by two units. Because of angular momentum conservation such a double helicity flip can be realized with ordinary parton distributions only for targets of spin 1 or higher [6], whereas the skewed distributions are accessible for nucleons if there is a finite transverse momentum transfer (Fig. 3b). These distributions appear in DVCS at the α_s level [4, 7, 8].

2 Phenomenology: the potential of polarization

The principal reactions where SPDs can be accessed are DVCS and exclusive meson electroproduction, $ep \to ep\,M$, where the meson M replaces the real

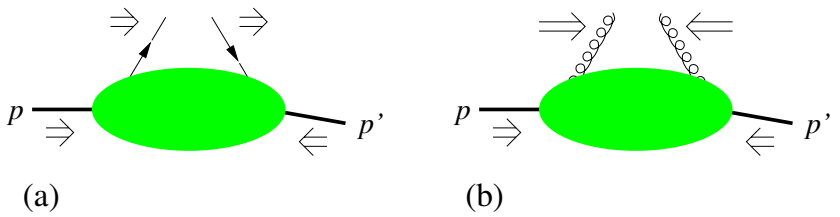

Figure 3: (a) SPD which flips the helicity of the proton but not of the quark. A unit of orbital angular momentum must be transferred. (b) SPD which flips the gluon helicity. Again there must be transfer of orbital angular momentum.

photon in the final state of Compton scattering. DVCS is special in its phenomenology, because it interferes with the Bethe-Heitler process, where the real photon is radiated from the lepton (Fig. 1b). In kinematics where the Bethe-Heitler contribution is large compared with the Compton process, one can use their interference term to study the latter, because the former can be calculated given knowledge of the Dirac and Pauli form factors $F_1(t)$ and $F_2(t)$ of the proton. This offers the unique possibility to study Compton scattering at the amplitude level, including its phase. The even larger pure Bethe-Heitler contribution can be removed from the cross section by various asymmetries. Different information on the interference term is obtained by reversing the lepton beam charge and by various asymmetries of the lepton and the proton polarizations.

To fully explore the physics of SPDs one will want to disentangle the contributions from the various spin and flavor combinations. For flavor the combined information from DVCS and from the production of mesons with different quantum numbers will be necessary. As for the spin degrees of freedom, the functions H and E appear for vector mesons, $\tilde{H}$ and $\tilde{E}$ for pseudoscalar mesons, and all of them for DVCS. To make further progress (and for instance to obtain the combination $H + E$ occurring in Ji's sum rule) it is mandatory to perform measurements with polarized protons. While it is true that one can access polarization dependent SPDs in unpolarized collisions, one *needs polarization* in order to disentangle the different distributions.

With some exceptions, the unpolarized cross section and the different polarization asymmetries in DVCS involve all four distributions H, E, $\tilde{H}$, $\tilde{E}$ [9]. Typically, however, some of them are suppressed by kinematical prefactors. The unpolarized DVCS cross section is dominated by

$$H \cdot H + \tilde{H} \cdot \tilde{H},$$

whereas with longitudinal target polarization one is mostly sensitive to $H \cdot \tilde{H}$. This provides a handle to separate H and $\tilde{H}$, with smaller contributions from E and $\tilde{E}$. The same is possible with the interference between DVCS and Bethe-Heitler, where with an unpolarized target one mainly looks at

$$F_1 \cdot H + (F_1 + F_2) \cdot \xi \tilde{H},$$

and with longitudinal target polarization mainly at

$$F_1 \cdot \tilde{H} + (F_1 + F_2) \cdot \xi H.$$

A way to access E and $\tilde{E}$ without a large contribution from H and $\tilde{H}$ is the transverse target polarization asymmetry in the DVCS cross section, which is a sum of terms where E or $\tilde{E}$ are multiplied with H or $\tilde{H}$. The same type of separation can be made in exclusive meson production [10].

The gluon helicity flip distributions discussed above can be isolated in the DVCS cross section through the angular distribution of the final state [7]. This can be done without target polarization, but target polarization enhances the possibilities of extraction. With a longitudinally polarized target one generates a $\sin 3\varphi$ dependence in the interference between the Compton and Bethe-Heitler processes that is otherwise absent [8], and target polarization is again required for separating the different helicity flip SPDs.

3 Small x or not small x

The momentum fraction variables x and ξ of the skewed distributions play different roles in the amplitude of physical processes: x parameterizes a loop momentum and is always integrated over, whereas ξ is fixed to $x_B/(2-x_B)$ by external kinematics, where $x_B = Q^2/(2p \cdot q)$ is the Bjorken variable as defined for deep inelastic scattering. Broadly speaking, the loop integrals will however probe smaller values of x when ξ becomes small.

The physics questions one aims to study with SPDs typically change with the value of ξ. At moderate or large ξ one expects to be most sensitive to the effect of the skewed kinematics, and to learn about the interference between different wave functions, including the regime $-\xi < x < \xi$ where one probes quark-antiquark and gluon pairs in the target wave function.

As ξ becomes very small, the relative difference of momentum fractions in the SPD is small over an increasingly important region of x. The hope here is that the measurement of SPDs can help constrain the usual parton distributions. Most studies have so far focused on vector meson production at small x_B, which is dominated by the square of the skewed gluon distribution H_g. Data from the HERA collider have already been used in an attempt to get information on the gluon density $g(x)$ at small x [11]. It is not a trivial task to relate a function $H_g(x,\xi,t)$ of three variables to $g(x)$, but theoretical arguments [12] building on the QCD evolution equations for SPDs suggest that at small enough x_B this can be done within reasonable uncertainties. There have been efforts to find a similar way to constrain the polarized gluon density $\Delta g(x)$ from $\tilde{H}_g(x,\xi,t)$ [13], but it turns out that for vector meson production this is not possible at the leading-twist level [14]. Beyond leading twist theory is plagued with large contributions from infrared regions if the meson is made from light quarks [15]. The only known process where $\tilde{H}_g$ comes in is DVCS, where it appears at the level of α_s corrections (as $\Delta g(x)$ does in polarized deep inelastic scattering). No studies have yet been made of whether this might help in pinning down $\Delta g(x)$.

Where the transition is between "large" values of ξ, where one hopes to learn from the effect of the longitudinal momentum asymmetry, and "small" values, where one expects this effect to be sufficiently under control to provide handles on the usual parton densities, is not known. This will probably have to be explored in the data. Many studies will not need to go to very small ξ (note for example that Ji's sum rule involves $x(H_q+E_q)$ where small x is suppressed), and others will aim to get ξ as small as possible. As far as spin is concerned, one expects that the parton helicity independent distributions will become more and more dominant at small x, just as happens with ordinary distributions.

Whereas moderate or large values of x_B are kinematically accessible for a wide range of collision energies (although with different counting rates that need to be studied), small x_B is of course the realm of high-energy machines. A specific feature of DVCS is that at given ep collision energy and Q^2 the interference term with Bethe-Heitler favors the smallest available x_B, whereas the DVCS cross section reaches out to higher values, in a similar way as inclusive deep inelastic scattering. Given the rather complex structure of the interference term and the various combinations of polarization, it is difficult without detailed numerical studies to determine the "optimal" machine energy for studies of SPDs, even in a given range of ξ.

4 Experimental challenges (a theorist's view)

The experimental study of SPDs faces several tasks:

1. Luminosity: some of the interesting channels have relatively small cross sections. This includes DVCS, whose cross section goes like $\alpha_{\rm em}^3$. For a quantitative study of SPDs, event statistics must be sufficient to allow binning in the different variables, Q^2, x_B, t, and to study angular correlations.

2. Large Q^2: in order to be in the regime where the QCD factorization theorems hold, one needs sufficiently large Q^2. What "sufficient" is has to be determined experimentally for each channel, by testing the predicted power-law behavior in Q^2 and the predicted pattern of angular distributions. This requires lever arm in Q^2, and to be on safe ground one will want to achieve large Q^2. For given x_B it imposes both kinematical constraints on the machine (not very serious at high energies) and requires again good luminosity, because of the expected decrease of cross sections as a power-law in $1/Q$.

3. Exclusivity: For quantitative studies it is paramount that one knows the final state of the reaction. The processes $\gamma^* p \to \gamma p$ and $\gamma^* p \to Mp$ compete with the cases where the proton dissociates into a low-mass system, say a Δ or the $N\pi$ continuum. Interesting in themselves, these reactions involve SPDs for the transition from the target proton to the hadronic system in question. In order to extract specific SPDs it is of course necessary

to separate the corresponding channel. This is especially crucial for spin studies, since the spin structure of the transitions $p \to \Delta$ and $p \to p$ is different. In the case of DVCS one also finds that with proton dissociation polarization asymmetries no longer remove the Bethe-Heitler contribution to the cross section (only the lepton charge asymmetry still does).

Detection and identification of the scattered proton (or hadronic system) is therefore necessary, unless the resolution in energy and momentum is sufficient to use the missing-mass technique with an accuracy of the order of the pion mass.

In addition to these requirements there is the strong physical motivation to have a polarized lepton beam and a polarized proton target. Given the boundary conditions 1. and 3. just discussed, it is not clear at present whether this can be achieved with fixed targets, and a polarized collider may be the most promising option. The wealth of physics to be learned about by studying skewed parton distribution goes with formidable challenges for experiment.

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