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Novel QCD Phenomena in Deep Inelastic Lepton Scattering

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I discuss several novel phenomenological features of QCD which are observable in deep inelastic lepton-nucleon and lepton-nucleus scattering. Initial- and final-state interactions from gluon exchange, normally neglected in the parton model, have a profound effect on QCD hard-scattering reactions, leading to leading-twist single-spin asymmetries, the diffractive contribution to deep inelastic scattering, and the breakdown of the pQCD Lam-Tung relation in Drell-Yan reactions. Leading-twist diffractive processes in turn lead to nuclear shadowing and non-universal antishadowing– physics not incorporated in the light-front wavefunctions of the nucleus computed in isolation.

1 Introduction

Quantum Chromodynamics has many remarkably novel and interesting features. Experiments at HERMES [2] have confirmed QCD expectations [3] for leading-twist single-spin asymmetries which require both the presence of quark orbital angular momentum in the proton wavefunction and novel final-state QCD phases. Experiments at HERA [4] have shown that diffractive deep inelastic scattering, where the proton target remains intact, constitutes a remarkably large percentage of the deep inelastic cross section, again showing the importance of QCD final-state interactions. Intrinsic contributions to structure functions lead to the production of heavy hadrons at large x_F in the hadron fragmentation region physics not generated by DGLAP evolution. Color transparency [5], a key feature of the gauge theoretic description of hadron interactions, has now been experimentally established at FermiLab [6] in diffractive dijet production. More recently, it has been possible to use light-front holography [7] to compute nonperturbative boost invariant light-front hadron wavefunctions from the fifth dimension of Anti-de Sitter space, the amplitudes which underly structure functions, form factors, and exclusive amplitudes such as generalized parton distributions.

2 Diffractive Deep Inelastic Scattering

A remarkable feature of deep inelastic lepton-proton scattering at HERA is that approximately 10% events are diffractive [8, 9]: the target proton remains intact, and there is a large rapidity gap between the proton and the other hadrons in the final state. These diffractive deep inelastic scattering (DDIS) events can be understood most simply from the perspective of the color-dipole model: the $q\bar{q}$ Fock state of the high-energy virtual photon diffractively dissociates into a diffractive dijet system. The exchange of multiple gluons between the

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color dipole of the $q\bar{q}$ and the quarks of the target proton neutralizes the color separation and leads to the diffractive final state. The same multiple gluon exchange also controls diffractive vector meson electroproduction at large photon virtuality [10]. This observation presents a paradox: if one chooses the conventional parton model frame where the photon light-front momentum is negative $q+ = q^0 + q^z < 0$, the virtual photon interacts with a quark constituent with light-cone momentum fraction $x = k^+/p^+ = x_{bj}$. Furthermore, the gauge link associated with the struck quark (the Wilson line) becomes unity in light-cone gauge $A^+ = 0$. Thus the struck "current" quark apparently experiences no final-state interactions. Since the light-front wavefunctions $\psi_n(x_i, k_{\perp i})$ of a stable hadron are real, it appears impossible to generate the required imaginary phase associated with pomeron exchange, let alone large rapidity gaps. This paradox was resolved by Hoyer, Marchal, Peigne, Sannino and myself [11]. Consider the case where the virtual photon interacts with a strange quark—the $s\bar{s}$ pair is assumed to be produced in the target by gluon splitting. In the case of Feynman gauge, the struck s quark continues to interact in the final state via gluon exchange as described by the Wilson line. The final-state interactions occur at a light-cone time $\Delta\tau \simeq 1/\nu$ shortly after the virtual photon interacts with the struck quark. When one integrates over the nearly-on-shell intermediate state, the amplitude acquires an imaginary part. Thus the rescattering of the quark produces a separated color-singlet $s\bar{s}$ and an imaginary phase. In the case of the light-cone gauge $A^+ = \eta \cdot A = 0$, one must also consider the final-state interactions of the (unstruck) $\bar{s}$ quark. The gluon propagator in light-cone gauge $d^{\mu\nu}_{LC}(k) = (i/k^2 + i\epsilon)\left[-g^{\mu\nu} + (\eta^\mu k^\nu + k^\mu \eta^\nu/\eta \cdot k)\right]$ is singular at $k^+ = \eta \cdot k = 0$. The momentum of the exchanged gluon k^+ is of $\mathcal{O}(1/\nu)$; thus rescattering contributes at leading twist even in light-cone gauge. The net result is gauge invariant and is identical to the color dipole model calculation.

A new understanding of the role of final-state interactions in deep inelastic scattering has thus emerged. The multiple scattering of the struck parton via instantaneous interactions in the target generates dominantly imaginary diffractive amplitudes, giving rise to an effective "hard pomeron" exchange. The presence of a rapidity gap between the target and diffractive system requires that the target remnant emerges in a color-singlet state; this is made possible in any gauge by the soft rescattering. The resulting diffractive contributions leave the target intact and do not resolve its quark structure; thus there are contributions to the DIS structure functions which cannot be interpreted as parton probabilities [11]; the leading-twist contribution to DIS from rescattering of a quark in the target is a coherent effect which is not included in the light-front wave functions computed in isolation. One can augment the light-front wave functions with a gauge link corresponding to an external field created by the virtual photon $q\bar{q}$ pair current [12, 13]. Such a gauge link is process dependent [14], so the resulting augmented LFWFs are not universal [11, 12, 15]. We also note that the shadowing of nuclear structure functions is due to the destructive interference between multi-nucleon amplitudes involving diffractive DIS and on-shell intermediate states with a complex phase. The physics of rescattering and shadowing is thus not included in the nuclear light-front wave functions, and a probabilistic interpretation of the nuclear DIS cross section is precluded. The same analysis shows that antishadowing is *not universal*, but it depends in detail on the flavor of the quark or antiquark constituent [16]. Rikard Enberg, Paul Hoyer, Gunnar Ingelman and I [17] have shown that the quark structure function of the effective hard pomeron has the same form as the quark contribution of the gluon structure function. The hard pomeron is not an intrinsic part of the proton; rather it must be considered as a dynamical effect of the lepton-proton interaction. It is important to investigate in detail at

HERA the composition of the final state X in $ep \to eXp$, as well as the balance between σ_L and σ_T in DDIS events.

3 Single-Spin Asymmetries from Final-State Interactions

Among the most interesting polarization effects are single-spin azimuthal asymmetries in semi-inclusive deep inelastic scattering, representing the correlation of the spin of the proton target and the virtual photon to hadron production plane: $\vec{S}_p \cdot \vec{q} \times \vec{p}_H$. Such asymmetries are time-reversal odd, but they can arise in QCD through phase differences in different spin amplitudes. In fact, final-state interactions from gluon exchange between the outgoing quarks and the target spectator system lead to single-spin asymmetries in semi-inclusive deep inelastic lepton-proton scattering which are not power-law suppressed at large photon virtuality Q^2 at fixed x_{bj} [3]. In contrast to the SSAs arising from transversity and the Collins fragmentation function, the fragmentation of the quark into hadrons is not necessary; one predicts a correlation with the production plane of the quark jet itself. Physically, the final-state interaction phase arises as the infrared-finite difference of QCD Coulomb phases for hadron wave functions with differing orbital angular momentum. The same proton matrix element which determines the spin-orbit correlation $\vec{S} \cdot \vec{L}$ also produces the anomalous magnetic moment of the proton, the Pauli form factor, and the generalized parton distribution E which is measured in deeply virtual Compton scattering. Thus the contribution of each quark current to the SSA is proportional to the contribution $\kappa_{q/p}$ of that quark to the proton target's anomalous magnetic moment $\kappa_p = \sum_q e_q \kappa_{q/p}$ [3, 18]. The HERMES collaboration has recently measured the SSA in pion electroproduction using transverse target polarization [2]. A related analysis also predicts that the initial-state interactions from gluon exchange between the incoming quark and the target spectator system lead to leading-twist single-spin asymmetries in the Drell-Yan process $H_1 H_2^{\updownarrow} \to \ell^+ \ell^- X$ [14, 19]. The SSA in the Drell-Yan process is the same as that obtained in SIDIS, with the appropriate identification of variables, but with the opposite sign. There is no Sivers effect in charged-current reactions since the W only couples to left-handed quarks [20]. If both the quark and antiquark in the initial state of the Drell-Yan subprocess $q\bar{q} \to \mu^+ \mu^-$ interact with the spectators of the other incident hadron, one finds a breakdown of the Lam-Tung relation, which was formerly believed to be a general prediction of leading-twist QCD. These double initial-state interactions also lead to a $\cos 2\phi$ planar correlation in unpolarized Drell-Yan reactions [21].

4 Intrinsic Heavy Quarks

The probability for Fock states of a light hadron such as the proton to have an extra heavy quark pair decreases as $1/m_Q^2$ in non-Abelian gauge theory [22, 23]. The relevant matrix element is the cube of the QCD field strength $G^3_{\mu\nu}$. This is in contrast to abelian gauge theory where the relevant operator is $F^4_{\mu\nu}$ and the probability of intrinsic heavy leptons in QED bound state is suppressed as $1/m_\ell^4$. The intrinsic Fock state probability is maximized at minimal off-shellness; *i.e.*, when the constituents have minimal invariant mass and equal rapidity. Thus the heaviest constituents have the highest momentum fractions and the highest x_i. Intrinsic charm thus predicts that the charm structure function has support at large x_{bj} in excess of DGLAP extrapolations [24]; this is in agreement with the EMC measurements [25]. Intrinsic charm can also explain the $J/\psi \to \rho\pi$ puzzle [26]. It also affects the extraction of suppressed CKM matrix elements in B decays [27]. The SELEX [28] discovery of ccd and ccu double-charm baryons at large x_F reinforces other signals for the presence of heavy quarks at large momentum fractions in hadronic wavefunctions, which is a novel feature of intrinsic heavy quark Fock states [24] As emphasized by Lai, Tung, and Pumplin [29], there are strong indications that the structure functions used to model charm and bottom quarks in the proton at large x_{bj} have been severely underestimated, since they ignore intrinsic heavy quark fluctuations of hadron wavefunctions. This has strong consequences for the production of heavy hadrons, heavy quarkonia, and even the Higgs at the LHC. Intrinsic charm and bottom leads to substantial rates for heavy hadron production at high x_F [30], as well as anomalous nuclear effects. Although HERA measurements of charm and bottom cross sections have been mainly at small x_{bj}, it is possible that the final data set can reach high x_{bj} and thus test the intrinsic component of heavy quark distributions.

5 Other Topics

Hidden-Color Fock States QCD predicts that a nucleus cannot be described solely as nucleonic bound states. In the case of the deuteron, the six-quark wavefunction has five color-singlet components, only one of which can be identified with the pn state at long distances. These "hidden color" components [31] play an essential role in nuclear dynamics at short distances. Hidden-Color configurations in the deuteron can be observed in $ed \to epX$ where the proton emerges from the target at high p_T and $ed \to e\Delta^{++}X$ reactions.

Higher-Twist Contributions to Semi-Inclusive DIS Reactions Although the contributions of higher twist processes are nominally power-law suppressed at high transverse momentum, there are phenomenological examples where they play a dominant role. For example, hadrons can interact directly within a hard subprocess, leading to higher twist contributions which can actually dominate over leading twist processes [32, 33]. A classic example is the reaction $\pi q \to \ell^+\ell^- q'$ which, despite its relative $1/Q^2$ fall-off, dominates the leading twist contribution to the Drell-Yan reaction $\pi N \to \ell^+\ell^- X$ at high x_F, producing longitudinally polarized lepton pairs. Crossing predicts that one also has reactions where the final-state hadron appears directly in the subprocess such as $e^+e^- \to \pi X$ at $z = 1$. It is interesting and important to look for duch direct-higher twist processes at HERA in $ep \to HX$.

Imaging the Proton in Deeply Virtual Compton Scattering The deeply virtual Compton amplitude $\gamma^* p \to \gamma p$ can be Fourier transformed to $b_\perp$ and $\sigma = x^- P^+/2$ space providing new insights into QCD distributions [34, 35, 36, 37]. The distributions in the LF direction σ typically display diffraction patterns arising from the interference of the initial and final state LFWFs [36, 38]. Measurements of DVCS can thus provide a detailed test of AdS/CFT predictions for hadronic light-front wavefunctions.

References

[1] Slides:
`http://indico.cern.ch/getFile.py/access?contribId=153&sessionId=24&resId=1&materialId=slides&confId=24657`

[2] A. Airapetian *et al.* [HERMES Collaboration], Phys. Rev. Lett. **94**, 012002 (2005) [arXiv:hep-ex/0408013].

[3] S. J. Brodsky, D. S. Hwang and I. Schmidt, Phys. Lett. B **530**, 99 (2002) [arXiv:hep-ph/0201296].

[4] M. Derrick *et al.* [ZEUS Collaboration], Phys. Lett. B **315**, 481 (1993).

[5] S. J. Brodsky and A. H. Mueller, Phys. Lett. B **206**, 685 (1988).

[6] E. M. Aitala *et al.* [E791 Collaboration], Phys. Rev. Lett. **86**, 4768 (2001) [arXiv:hep-ex/0010043].

[7] S. J. Brodsky and G. F. de Teramond, arXiv:0802.0514 [hep-ph].

[8] C. Adloff *et al.* [H1 Collaboration], Z. Phys. C **76**, 613 (1997) [arXiv:hep-ex/9708016].

[9] J. Breitweg *et al.* [ZEUS Collaboration], Eur. Phys. J. C **6**, 43 (1999) [arXiv:hep-ex/9807010].

[10] S. J. Brodsky, L. Frankfurt, J. F. Gunion, A. H. Mueller and M. Strikman, Phys. Rev. D **50**, 3134 (1994) [arXiv:hep-ph/9402283].

[11] S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D **65**, 114025 (2002) [arXiv:hep-ph/0104291].

[12] A. V. Belitsky, X. Ji and F. Yuan, Nucl. Phys. B **656**, 165 (2003) [arXiv:hep-ph/0208038].

[13] J. C. Collins and A. Metz, Phys. Rev. Lett. **93**, 252001 (2004) [arXiv:hep-ph/0408249].

[14] J. C. Collins, Phys. Lett. B **536**, 43 (2002) [arXiv:hep-ph/0204004].

[15] J. C. Collins, Acta Phys. Polon. B **34**, 3103 (2003) [arXiv:hep-ph/0304122].

[16] S. J. Brodsky, I. Schmidt and J. J. Yang, Phys. Rev. D **70**, 116003 (2004) [arXiv:hep-ph/0409279].

[17] S. J. Brodsky, R. Enberg, P. Hoyer and G. Ingelman, Phys. Rev. D **71**, 074020 (2005) [arXiv:hep-ph/0409119].

[18] M. Burkardt, Nucl. Phys. Proc. Suppl. **141**, 86 (2005) [arXiv:hep-ph/0408009].

[19] S. J. Brodsky, D. S. Hwang and I. Schmidt, Nucl. Phys. B **642**, 344 (2002) [arXiv:hep-ph/0206259].

[20] S. J. Brodsky, D. S. Hwang and I. Schmidt, Phys. Lett. B **553**, 223 (2003) [arXiv:hep-ph/0211212].

[21] D. Boer, S. J. Brodsky and D. S. Hwang, Phys. Rev. D **67**, 054003 (2003) [arXiv:hep-ph/0211110].

[22] M. Franz, M. V. Polyakov and K. Goeke, Phys. Rev. D **62**, 074024 (2000) [arXiv:hep-ph/0002240].

[23] S. J. Brodsky, J. C. Collins, S. D. Ellis, J. F. Gunion and A. H. Mueller,

[24] S. J. Brodsky, P. Hoyer, C. Peterson and N. Sakai, Phys. Lett. B **93**, 451 (1980).

[25] B. W. Harris, J. Smith and R. Vogt, Nucl. Phys. B **461**, 181 (1996) [arXiv:hep-ph/9508403].

[26] S. J. Brodsky and M. Karliner, Phys. Rev. Lett. **78**, 4682 (1997) [arXiv:hep-ph/9704379].

[27] S. J. Brodsky and S. Gardner, Phys. Rev. D **65**, 054016 (2002) [arXiv:hep-ph/0108121].

[28] J. S. Russ, Int. J. Mod. Phys. A **21**, 5482 (2006).

[29] J. Pumplin, H. L. Lai and W. K. Tung, Phys. Rev. D **75**, 054029 (2007) [arXiv:hep-ph/0701220].

[30] S. J. Brodsky, B. Kopeliovich, I. Schmidt and J. Soffer, Phys. Rev. D **73**, 113005 (2006) [arXiv:hep-ph/0603238].

[31] S. J. Brodsky, C. R. Ji and G. P. Lepage, Phys. Rev. Lett. **51**, 83 (1983).

[32] E. L. Berger and S. J. Brodsky, Phys. Rev. Lett. **42**, 940 (1979).

[33] E. L. Berger and S. J. Brodsky, Phys. Rev. D **24**, 2428 (1981).

[34] M. Burkardt, Int. J. Mod. Phys. A **21**, 926 (2006) [arXiv:hep-ph/0509316].

[35] X. d. Ji, Phys. Rev. Lett. **91**, 062001 (2003) [arXiv:hep-ph/0304037].

[36] S. J. Brodsky, D. Chakrabarti, A. Harindranath, A. Mukherjee and J. P. Vary, Phys. Lett. B **641**, 440 (2006) [arXiv:hep-ph/0604262].

[37] P. Hoyer, AIP Conf. Proc. **904**, 65 (2007) [arXiv:hep-ph/0608295].

[38] S. J. Brodsky, D. Chakrabarti, A. Harindranath, A. Mukherjee and J. P. Vary, Phys. Rev. D **75**, 014003 (2007) [arXiv:hep-ph/0611159].

[39] S. J. Brodsky and A. Sickles, arXiv:0804.4608 [hep-ph]. (To be published in Physics Letters B)