

# Dynamic versus Static Hadronic Structure Functions <sup>★</sup>

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## Abstract

“Static” structure functions are the probabilistic distributions computed from the square of the light-front wavefunctions of the target hadron. In contrast, the “dynamic” structure functions measured in deep inelastic lepton-hadron scattering include the effects of rescattering associated with the Wilson line. Initial- and final-state rescattering, neglected in the parton model, can have a profound effect in QCD hard-scattering reactions, producing single-spin asymmetries, diffractive deep inelastic scattering, diffractive hard hadronic reactions, the breakdown of the Lam-Tung relation in Drell-Yan reactions, nuclear shadowing, and non-universal nuclear antishadowing—novel leading-twist physics not incorporated in the light-front wavefunctions of the target computed in isolation. I also review how “direct” higher-twist processes – where a proton is produced in the hard subprocess itself – can explain the anomalous proton-to-pion ratio seen in high centrality heavy ion collisions.

*Key words:* Diffraction, QCD, Light-Front Wavefunctions, Hadronization, Multiple Scattering, Heavy-Ion Collisions

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## 1. Introduction

It is important to distinguish “static” structure functions which are computed directly from the light-front wavefunctions of a target hadron from the nonuniversal “dynamic” empirical structure functions which take into account rescattering of the struck quark in deep inelastic lepton scattering. [See fig. 1. ] The real wavefunctions underlying static structure functions cannot describe diffractive deep inelastic scattering nor single-spin asymmetries, since such phenomena involve the complex phase structure of the  $\gamma^*p$  amplitude. One can augment the light-front wavefunctions with a gauge link corresponding

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to an external field created by the virtual photon  $q\bar{q}$  pair current [1,2], but such a gauge link is process dependent [3], so the resulting augmented wavefunctions are not universal. [4,1,5].

A remarkable feature of deep inelastic lepton-proton scattering at HERA is that approximately 10% events are diffractive [6,7]: the target proton remains intact, and there is a large rapidity gap between the proton and the other hadrons in the final state. 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 soft rescattering. 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 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 [4]; the leading-twist contribution to DIS from rescattering of a quark in the target is thus a coherent effect which is not included in the light-front wavefunctions computed in isolation.

The shadowing of nuclear structure functions arises from destructive interference between multi-nucleon amplitudes involving diffractive DIS and on-shell intermediate states with a complex phase. The physics of rescattering and nuclear shadowing is not included in the nuclear light-front wavefunctions, and a probabilistic interpretation of the nuclear DIS cross section is precluded.

Antishadowing of nuclear structure functions is also observed in deep inelastic lepton-nucleus scattering. Empirically, one finds  $R_A(x, Q^2) \equiv (F_{2A}(x, Q^2)/(A/2)F_d(x, Q^2)) > 1$  in the domain  $0.1 < x < 0.2$ ; *i.e.*, the measured nuclear structure function (referenced to the deuteron) is larger than than the scattering on a set of  $A$  independent nucleons. Ivan Schmidt, Jian-Jun Yang, and I [8] have extended the analysis of nuclear shadowing to the shadowing and antishadowing of the electroweak structure functions. We note that there are leading-twist diffractive contributions  $\gamma^* N_1 \rightarrow (q\bar{q})N_1$  arising from Reggeon exchanges in the  $t$ -channel [9]. For example, isospin-non-singlet  $C = +$  Reggeons contribute to the difference of proton and neutron structure functions, giving the characteristic Kutiv Weisskopf  $F_{2p} - F_{2n} \sim x^{1-\alpha_R(0)} \sim x^{0.5}$  behavior at small  $x$ . The  $x$  dependence of the structure functions reflects the Regge behavior  $\nu^{\alpha_R(0)}$  of the virtual Compton amplitude at fixed  $Q^2$  and  $t = 0$ . The phase of the diffractive amplitude is determined by analyticity and crossing to be proportional to  $-1 + i$  for  $\alpha_R = 0.5$ , which together with the phase from the Glauber cut, leads to *constructive* interference of the diffractive and nondiffractive multi-step nuclear amplitudes. The nuclear structure function is predicted to be enhanced precisely in the domain  $0.1 < x < 0.2$  where antishadowing is empirically observed. The strength of the Reggeon amplitudes is fixed by the fits to the nucleon structure functions, so there is little model dependence. Quarks of different flavors will couple to different Reggeons; this leads to the remarkable prediction that nuclear antishadowing is not universal; it depends on the quantum numbers of the struck quark. This picture implies substantially different antishadowing for charged and neutral current reactions, thus affecting the extraction of the weak-mixing angle  $\theta_W$ . We find that part of the anomalous NuTeV result [10] for  $\theta_W$  could be due to the non-universality of nuclear antishadowing for charged and neutral currents. In fact, Schienbein et al. [11] have recently given a comprehensive analysis of charged current deep inelastic neutrino-iron scattering, finding significant differences with the nuclear corrections for electron-iron scattering.

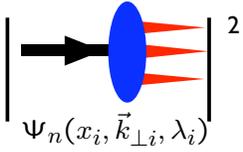
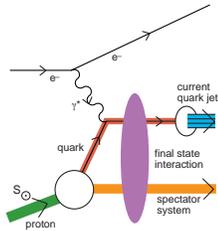
<b>Static</b>	<b>Dynamic</b>
<ul style="list-style-type: none"> <li>• Square of Target LFWFs</li> <li>• No Wilson Line</li> <li>• Probability Distributions</li> <li>• Process-Independent</li> <li>• T-even Observables</li> <li>• No Shadowing, Anti-Shadowing</li> <li>• Sum Rules: Momentum and <math>J^z</math></li> <li>• DGLAP Evolution; mod. at large <math>x</math></li> <li>• No Diffractive DIS</li> </ul>	<ul style="list-style-type: none"> <li>Modified by Rescattering: ISI &amp; FSI</li> <li>Contains Wilson Line, Phases</li> <li>No Probabilistic Interpretation</li> <li>Process-Dependent - From Collision</li> <li>T-Odd (Sivers, Boer-Mulders, etc.)</li> <li>Shadowing, Anti-Shadowing, Saturation</li> <li>Sum Rules Not Proven</li> <li>DGLAP Evolution</li> <li>Hard Pomeron and Odderon Diffractive DIS</li> </ul>
	

Fig. 1. Static versus dynamic structure functions

Diffractive multi-jet production in heavy nuclei provides a novel way to resolve the shape of light-front Fock state wavefunctions and test color transparency [12]. For example, consider the reaction [13,14].  $\pi A \rightarrow \text{Jet}_1 + \text{Jet}_2 + A'$  at high energy where the nucleus  $A'$  is left intact in its ground state. The transverse momenta of the jets balance so that  $\vec{k}_{\perp 1} + \vec{k}_{\perp 2} = \vec{q}_{\perp} < R^{-1} A$ . Because of color transparency, the valence wavefunction of the pion with small impact separation will penetrate the nucleus with minimal interactions, diffracting into jet pairs [13]. The  $x_1 = x$  and  $x_2 = 1 - x$  dependence of the dijet distributions thus reflects the shape of the pion valence light-cone wavefunction in  $x$ ; similarly, the  $\vec{k}_{\perp 1} - \vec{k}_{\perp 2}$  relative transverse momenta of the jets gives key information on the second transverse momentum derivative of the underlying shape of the valence pion wavefunction [14]. The diffractive nuclear amplitude extrapolated to  $t = 0$  will be linear in nuclear number  $A$  if color transparency is correct. The integrated diffractive rate will then scale as  $A^2/R_A^2 \sim A^{4/3}$ . This is in fact what has been observed by the E791 collaboration at FermiLab for 500 GeV incident pions on nuclear targets [15].

## 2. Single-Spin Asymmetries and Other Leading-Twist Rescattering Effects

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 (SSAs) in semi-inclusive deep inelastic lepton-proton scattering which are not power-law suppressed at large photon virtuality  $Q^2$  at fixed  $x_{bj}$  [16]. 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 wavefunctions 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  $\kappa_p = \sum_q e_q \kappa_{q/p}$  [16,17]. 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. If both the quark and antiquark in the initial state of the Drell-Yan subprocess  $q\bar{q} \rightarrow \mu^+\mu^-$  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 [18]. As noted by Collins and Qiu [19], the traditional factorization formalism of perturbative QCD for high transverse momentum hadron production fails in detail even at the LHC because of initial- and final-state rescattering. An important signal for factorization breakdown is a  $\cos 2\phi$  planar correlation in dijet production.

### 3. Novel Intrinsic Heavy Quark Phenomena

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 [20,21]. The relevant matrix element is the cube of the QCD field strength  $G_{\mu\nu}^3$ , in contrast to QED where the relevant operator is  $F_{\mu\nu}^4$  and the probability of intrinsic heavy leptons in an atomic state is suppressed as  $1/m_\ell^4$ . The maximum probability occurs at  $x_i = m_\perp^i / \sum_{j=1}^n m_\perp^j$  where  $m_{\perp i} = \sqrt{k_{\perp i}^2 + m_i^2}$ ; *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 [22]; this is in agreement with the EMC measurements [23]. Intrinsic charm can also explain the  $J/\psi \rightarrow \rho\pi$  puzzle [24]. It also affects the extraction of suppressed CKM matrix elements in  $B$  decays [25]. The dissociation of the intrinsic charm  $|uudc\bar{c}\rangle$  Fock state of the proton can produce a leading heavy quarkonium state at high  $x_F = x_c + x_{\bar{c}}$  in  $pN \rightarrow J/\psi XA'$  since the  $c$  and  $\bar{c}$  can readily coalesce into the charmonium state. Since the constituents of a given intrinsic heavy-quark Fock state tend to have the same rapidity, coalescence of multiple partons from the projectile Fock state into charmed hadrons and mesons is also favored. For example, one can produce a leading  $\Lambda_c$  at high  $x_F$  and low  $p_T$  from the coalescence of the  $udc$  constituents of the projectile  $|uudc\bar{c}\rangle$  Fock state. In the case of a nuclear target, the charmonium state will be produced at small transverse momentum and high  $x_F$  with a

characteristic  $A^{2/3}$  nuclear dependence since the color-octet color-octet  $|(uud)_{8C}(c\bar{c})_{8C} >$  Fock state interacts on the front surface of the nuclear target [26]. This forward contribution is in addition to the  $A^1$  contribution derived from the usual perturbative QCD fusion contribution at small  $x_F$ . Because of these two components, the cross section violates perturbative QCD factorization for hard inclusive reactions [27]. This is consistent with the observed two-component cross section for charmonium production observed by the NA3 collaboration at CERN [28] and more recent experiments [29]. The diffractive dissociation of the intrinsic charm Fock state leads to leading charm hadron production and fast charmonium production in agreement with measurements [30]. The hadroproduction cross sections for double-charm  $\Xi_{cc}^+$  baryons at SELEX [31] and the production of  $J/\psi$  pairs at NA3 are consistent with the diffractive dissociation and coalescence of double IC Fock states [32]. These observations provide compelling evidence for the diffractive dissociation of complex off-shell Fock states of the projectile and contradict the traditional view that sea quarks and gluons are always produced perturbatively via DGLAP evolution. It is also conceivable that the observations [33] of  $\Lambda_b$  at high  $x_F$  at the ISR in high energy  $pp$  collisions could be due to the dissociation and coalescence of the “intrinsic bottom”  $|uudb\bar{b} >$  Fock states of the proton. As emphasized by Lai, Tung, and Pumplin [34], there are indications that the structure functions used to model charm and bottom quarks in the proton at large  $x_{bj}$  have been underestimated, since they ignore intrinsic heavy quark fluctuations of hadron wavefunctions.

Goldhaber, Kopeliovich, Schmidt, Soffer, and I [26,35] have proposed a novel mechanism for exclusive diffractive Higgs production  $pp \rightarrow pHp$  and nondiffractive Higgs production in which the Higgs boson carries a significant fraction of the projectile proton momentum. The production mechanism is based on the subprocess  $(Q\bar{Q})g \rightarrow H$  where the  $Q\bar{Q}$  in the  $|uudQ\bar{Q} >$  intrinsic heavy quark Fock state has up to 80% of the projectile proton momentum. This mechanism provides a clear experimental signal for Higgs production at the LHC due to the small background in this kinematic region.

#### 4. Color Transparency and the RHIC Baryon Anomaly

It is conventional to assume that leading-twist subprocesses dominate measurements of high  $p_T$  hadron production at RHIC energies. Indeed the measured cross section for direct photon fragmentation  $E d\sigma/d^3p(pp \rightarrow \gamma X) = F(x_T, \theta_{cm})/p_T^{n_{eff}}$  is consistent with  $n_{eff}(pp \rightarrow \gamma X) = 5$ , as expected for the fixed- $x_T$  scaling of the  $gq \rightarrow \gamma q$  leading-twist subprocess [36]. However, the measured fixed- $x_T$  scaling for proton production at RHIC is anomalous: PHENIX reports  $n_{eff}(pp \rightarrow pX) \simeq 8$ . A review of this data is given by Tannenbaum [37]. One can understand the anomalous scaling if a higher-twist subprocess [38] where the proton is made *directly* within the hard reaction, such as  $uu \rightarrow p\bar{d}$  and  $(uud)u \rightarrow pu$ , dominates the reaction  $pp \rightarrow pX$  at RHIC energies. The dominance of direct subprocesses is possible since the fragmentation of gluon or quark jets to baryons requires that the 2 to 2 subprocess occurs at much higher transverse momentum than the  $p_T$  of observed proton because of the fast-falling  $(1-z)^3$  quark-to-proton fragmentation function. Thus the initial quark and gluon distributions have to be evaluated at higher  $x$  in leading twist fragmentation reactions compared to direct processes. Such “direct” reactions can readily explain the fast-falling power-law falloff observed at fixed  $x_T$  and fixed- $\theta_{cm}$  observed at the ISR, FermiLab and RHIC. Furthermore, the protons produced

directly within the hard subprocess emerge as small-size color-transparent colored states which are not absorbed in the nuclear target. In contrast, pions produced from jet fragmentation have the normal cross section. This provides a plausible explanation of the RHIC data, [39] which shows a dramatic rise of the  $p/\pi$  ratio at high  $p_T$  and a higher value for  $n_{eff}$  at fixed  $x_T$  when one compares peripheral with central (full overlap) heavy ion collisions. The directly produced protons are not absorbed, but the pions are diminished in the nuclear medium.

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