

Large x Physics

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Abstract.

The large x_{bj} domain of deep inelastic lepton-proton scattering provides essential information on the structure of the proton when the struck quark is far off-shell and one must take into account inter-quark correlations, higher twist effects, and the breakdown of standard DGLAP evolution. I briefly review predictions from PQCD and AdS/CFT. I also discuss how intrinsic heavy quark Fock states lead to novel production mechanisms for heavy hadrons.

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THE FAR OFF-SHELL BEHAVIOR OF QCD WAVEFUNCTIONS

One of the most important arenas for testing QCD at a fundamental level is the large x_{bj} domain of deep inelastic structure functions as measured in inclusive lepton-proton scattering and other hard inclusive reactions. Predictions for the quark and gluon distributions at $x_{bj} \simeq 1$ can be made directly from the structure of the hadronic light-front wavefunctions from the near conformal behavior of QCD at short distances, using either perturbative expansions [1, 2, 3] or the AdS/CFT correspondence principle [4, 5] which maps conformal transformations to the behavior of hadronic wavefunctions in the fifth dimension of AdS space. These first-principle predictions depend in detail on flavor, spin, and angular momentum composition of the target hadron. Other issues include (a) the quenching of DGLAP evolution when the struck quark is off-shell; (b) duality between hard exclusive and inclusive channels; (c) the effects of dynamical higher-twist contributions from quark correlations within the hadron wavefunction. In addition, the distributions of intrinsic heavy quarks arising from the hadron bound state are peaked at high x_{bj} .

At leading twist $x_{bj} = Q^2/2p \cdot q$ can be equated to the light-cone momentum fraction $x = k^+/P^+ = (k^0 + k^z)/(P^0 + P^z)$ carried by the struck quark in the target hadron's light-front Fock state wavefunction $\Psi_n(x_i, k_{\perp i})$. The mathematical limit $x \rightarrow 1$ at leading twist requires all of the light-cone momentum of the target to be carried by just one quark. Since $\sum_i^n x_i = 1$, all of the other (spectator) constituents are forced kinematically to have $x_i \rightarrow 0$, and the valence Fock state dominates. In fact, the requirement $k_i^+ = k_i^0 + k_i^z \rightarrow 0$ demands that $k_i^z \rightarrow -\infty$ for each spectator with nonzero mass or transverse momentum. Furthermore, the invariant mass of the Fock state $\mathcal{M}_n^2 = \sum_i^n ((k_{\perp i}^2 + m_i^2)/x_i)$ becomes infinitely large. If one uses a covariant formulation of bound states, such as the Bethe-Salpeter formalism, one sees that the Feynman virtuality of the struck quark: $k_F^2 - m_q^2 = x_q(M^2 - \mathcal{M}_n^2)$ becomes infinitely spacelike. Thus measurements at the limit $x_{bj} \rightarrow 1$ test the extreme kinematics of the hadron bound state. It is thus not

surprising that, given asymptotic freedom, one can make first-principle predictions for the behavior of the parton distributions of hadrons at large x from the short-distance properties of QCD [6, 1, 2, 3]. The main power-law dependence at $x \sim 1$ is given by the minimal number of (vertical) gluon exchanges required to stop the hadronic spectator; *i.e.*, one iterates the interaction kernel of the hadron wavefunction to obtain the connected tree graphs, thus providing the minimal path for the momentum to flow to the struck constituent. For the case of the nucleon, the leading Fock state component is the $|qqq\rangle$ state, and two gluon exchanges with virtuality $k^2 \sim O\left((\vec{k}_\perp^2 + \tilde{m}^2)/(1-x)\right)$ are required. The same basic QCD interactions which yield DGLAP evolution thus also predict the $x \rightarrow 1$ behavior. More generally, the nominal power-law prediction for the large x behavior for constituent a in hadron H is [7] $f_{a/H}(x) \sim (1-x)^{2n_s-1+2|\Delta S^z|}$, where n_s is the number of spectator constituents and $\Delta S^z = S_a^z - S_H^z$ is the difference of spin projections for the struck parton a and the hadron H . For example, for the valence quarks of the proton, $q_p^\uparrow(x) \sim (1-x)^3$ and $q_p^\downarrow(x) \sim (1-x)^5$ since $n_s = 2$ and $\Delta S^z = 0, 1$, respectively, whereas for the pion $q_\pi(x) \sim (1-x)^2$ since $n_s = 1$ and $2\Delta S^z = 1$. The power law must be even when one measures a fermion in a boson in order to have consistent crossing to the fragmentation functions at large z . The gluon distributions fall at least one power of $(1-x)$ faster than the valence quark distributions. The suppression of the antiparallel quarks reflects the fact that the internal orbital angular momentum of the quark is required for J_z angular momentum conservation. Helicity-flip terms from quark mass insertions are subleading at large x . The nominal powers for structure functions at large x can also be derived from the AdS/CFT approach [4, 5] without perturbation theory—reflecting the underlying conformal features of QCD. In general one predicts logarithmic corrections from the nonzero QCD β function as well as higher order diagrams.

If one assumes $SU(6)$ spin-flavor symmetry, then the number of quarks in the $S^z = +1/2$ proton valence state is normalized to $u^\uparrow : u^\downarrow : d^\uparrow : d^\downarrow = 5/3 : 1/3 : 1/3 : 2/3$. Thus one predicts $d(x)/u(x) \rightarrow d^\uparrow(x)/u^\uparrow(x) \rightarrow 1/5$ and $F_{2n}(x)/F_{2p}(x) \rightarrow 3/7$, at large x [6]. In contrast, the scalar diquark model predicts $d(x)/u(x) \rightarrow 0$. The proton structure function data suggest that a smooth, power-law behavior of the u -quark distribution, $\sim (1-x)^3$, works very well at moderate to large x . Evidently the reason why $d(x)$ is far from the pQCD prediction at moderate x is that the ratio of spin-antiparallel to parallel d quarks is 2:1 in the proton (for a spin-flavor symmetric wave function), whereas the ratio is 1:5 in the case of the u quarks. Measurements of the neutron to proton structure function ratio as proposed at Jefferson Laboratory with the 12-GeV upgrade will provide essential tests of these predictions.

MODIFICATION OF DGLAP EVOLUTION AND THE INCLUSIVE-EXCLUSIVE CONNECTION

QCD evolution predicts structure functions at large x of the form $F_2(x, Q^2) \propto (1-x)^{V+\tilde{\xi}(Q^2, k^2)}$ where $(1-x)^V$ is the effective power-behavior at $Q^2 \sim O(k^2)$, and $\tilde{\xi}(Q^2, k^2) = \frac{C_F}{\pi} \int_{k^2}^{Q^2} \frac{d\ell^2}{\ell^2} \alpha_s(\ell^2) \sim O(\log \log Q^2)$. If one uses this form for fixed

$W^2 = \mathcal{M}^2 = \frac{1-x}{x} Q^2$, then one obtains transition form factors which fall faster than any power, in direct contradiction to PQCD predictions. Thus the standard application of DGLAP evolution to the deep inelastic structure functions appears inconsistent with Bloom-Gilman duality at fixed missing mass W . This conflict is resolved if one takes into account the fact that the struck quark is far-off shell in the $x \rightarrow 1$ domain [1, 2]. The virtuality of the struck quark k_F^2 in fact sets the lower limit of the ℓ^2 integration in $\tilde{\xi}$, severely truncating DGLAP evolution. One then finds that at fixed \mathcal{M}^2 , $\tilde{\xi} \rightarrow 0$, the inclusive and exclusive cross sections have the same fall-off. The “initial” or “starting” structure function is *no longer* unknown but is directly determined from QCD perturbation theory and distribution amplitude evolution in the large x domain. In a sense the most critical prediction from QCD is the nominal power law $(1-x)^3$ since the power 3 reflects the existence of a 3-quark Fock state as well as nearly scale-invariant QCD quark-quark interactions within the nucleon.

As one approaches the $x \rightarrow 1$ limit, dynamical higher-twist contributions from coherent scattering on more than one constituent becomes increasingly more probable [8]. For example, one can have subprocesses such as $qq\gamma^* \rightarrow qq$ where two quarks in the target are scattered coherently. These contributions are suppressed by powers of $1/Q^2$ but are enhanced at high x since the qq acts as a bosonic constituent with summed $x_{qq} = x_1 + x_2$. Such contributions, including the exclusive qqq subprocesses where all of the valence quarks scatter coherently, all contribute at leading order at fixed W^2 , in agreement with Bloom-Gilman duality. Sufficient kinematic range in Q^2 , as well as longitudinal-transverse separation, is required to cleanly separate the leading twist and higher twist contributions, all of which contribute to the measured structure functions.

INTRINSIC HEAVY QUARKS

It was originally suggested in Ref. [9] that there is a $\sim 1\%$ probability of IC Fock states in the nucleon; more recently, the operator product expansion has been used to show that the probability for Fock states in light hadron to have an extra heavy quark pair of mass M_Q decreases only as Λ_{QCD}^2/M_Q^2 in non-Abelian gauge theory [10]. In contrast, in the case of Abelian QED, the probability of an intrinsic heavy lepton pair in a light-atom such as positronium is suppressed by $\mu_{\text{bohr}}^4/M_\ell^4$ where μ_{bohr} is the Bohr momentum. The maximal probability for an intrinsic heavy quark Fock state occurs for minimal off-shellness; *i.e.*, at minimum invariant mass squared. Thus the dominant Fock state configuration is $x_i \propto m_{\perp i}$ where $m_{i\perp}^2 = m_i^2 + \vec{k}_{\perp i}^2$; *i.e.*, at equal rapidity, and the heaviest constituents carry the most momentum [9]. There are many experiments which confirm the presence of charm quarks at large x in the proton wavefunction beginning with the European Muon Collaboration (EMC) deep inelastic scattering experiment [11] which found a distinct excess of events in the charm quark distribution at $x_{bj} > 0.3$, at a rate at least an order of magnitude beyond lowest predictions based on gluon splitting and DGLAP evolution. The materialization of the intrinsic charm Fock state also leads to the production of open-charm states such as $\Lambda(cud)$ and $D^-(\bar{c}d)$ at large x_F through the coalescence of the valence and charm quarks which are co-moving with the same rapidity. The intrinsic charm model naturally accounts for the production of leading

charm hadrons as observed at the ISR and Fermilab. The existence of the rare double IC Fock state such as $|uudc\bar{c}c\bar{c}\rangle$ leads to the production of two J/ψ 's [12] or a double-charm baryon state at large x_F and small p_T . Double J/ψ events at a high combined $x_F \geq 0.8$ were in fact observed by NA3 [13]. The observation of the doubly-charmed baryon $\Xi_{cc}^+(3520)$ has been confirmed recently by SELEX at FNAL [14]; the presence of two charm quarks at large x_F thus has a natural interpretation within QCD. Another immediate consequence of intrinsic charm is the production of charmonium states at high $x_F = x_c + x_{\bar{c}}$ in a hadronic collision such as $pp \rightarrow J/\psi X$. The color octet $(c\bar{c})_{8_C}$ can be converted to a high x quarkonium state via gluon exchange with the target. Since the IC Fock state $|(uud)_{8_C}(c\bar{c})_{8_C}\rangle$ has a large color dipole moment which is strongly interacting, the production of quarkonium on a nucleus occurs at the front nuclear surface with an $A^{2/3}$ nuclear dependence. The IC mechanism also predicts that the strongest nuclear absorption appears when the J/ψ has minimum $p_T < 1$ GeV/c as well as large x_F . These features are precisely what has been observed by the NA3 Collaboration at CERN [15] in $pA \rightarrow J/\psi X$ and $\pi A \rightarrow J/\psi X$. Because of the existence of the IC plus usual A^1 contributions, the nuclear dependence of the total cross section is proportional to $A^{\alpha(x_F)}$ rather than the dependence predicted by leading-twist QCD $A^{\alpha(x_2)}$, where x_2 is the light-cone momentum fraction of the parton in the nucleus. This is in agreement with the NA3 and E866/NuSea [16] data which displays x_F shadowing, thus violating PQCD factorization, as emphasized in Ref. [17].

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