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The Diffractive Contribution to Deep Inelastic Lepton-Proton Scattering: Implications for QCD Momentum Sum Rules and Parton Distributions

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Abstract

The cross section for deep inelastic lepton-proton scattering (DIS) $\ell p \to \ell' X$ includes a diffractive deep inelastic (DDIS) contribution $\ell p \to \ell' p' X$, in which the proton remains intact with a large longitudinal momentum fraction x_F greater than 0.9 and small transverse momentum. The DDIS events, which can be identified with Pomeron exchange in the t-channel, account for approximately 10% of all of the DIS events. Thus, when one measures DIS, one automatically includes the leading-twist Bjorken-scaling DDIS events as a contribution to the DIS cross section, whether or not the final-state proton p' is detected. In such events, the missing momentum fraction $x_{p'} \sim 0.9$ carried by the final-state proton p' in the DDIS events could be misidentified with the light-front momentum fraction carried by sea quarks or gluons in the protons' Fock structure. As we shall show in this article, the underlying QCD Pomeron-exchange amplitude which produces the DDIS events does not obey the operator product expansion nor satisfy momentum sum rules. Thus we conclude that the quark and gluon distributions measured in DIS experiments will be misidentified, unless the measurements explicitly exclude the DDIS events and that a correct determination of the parton distribution functions (PDFs) derived from the DIS data requires the explicit subtraction of the DDIS contribution from the full DIS cross section.

Keywords:
Deep inelastic scattering, diffractive deep inelastic scattering, parton distribution functions, momentum sum rules

1. Diffractive Deep Inelastic Scattering

Deep inelastic lepton scattering (DIS) $\ell + p \to \ell' + X$ [1, 2] on the proton is the key experimental tool for extracting information about the fundamental quark and gluon structure of the proton, as encoded in its partonic distribution functions (PDFs).

A striking feature of DIS lepton-proton scattering is the large fraction of diffractive events $\ell + p \to \ell' + p' + X$, where the struck proton remains intact, with longitudinal Feynman momentum fraction x_F greater than 0.9, acquiring small

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momentum transfer, and being well-separated in rapidity from the other produced particles. As first discovered by the ZEUS Collaboration and rediscovered by the H1 Collaboration at DESY [3], approximately 10% of the conventional DIS events are diffractive. These diffractive deep inelastic scattering (DDIS) events are also observed to be leading twist; i.e., they satisfy Bjorken scaling [see Fig.4 in Ref. [3]].

Thus when one measures the DIS cross section, one automatically includes the DDIS contribution, even when the final-state proton p' is not detected nor measured. In such events, the missing momentum fraction $x_{p'} \sim 0.9$ carried by the final-state proton p' in the DDIS events could be misidentified with the light-front (LF) momentum fraction carried by sea quarks or gluons in the target proton's Fock structure. As we show in this article, the underlying QCD Pomeron-exchange mechanism which produces the DDIS events obeys leading-twist Bjorken scaling, but it does not obey the operator product expansion (OPE) nor satisfy momentum sum rules (MSRs). Therefore, the PDFs measured in DIS experiments will be misidentified if the DIS measurements do not exclude the DDIS events; the true extraction of PDFs from the data requires the explicit identification and subtraction of the DDIS contribution from the full DIS cross section. For a comprehensive discussion of diffractive Pomeron contributions and other nonlinear contributions to the sea quark and gluon distributions measured in DIS, see Ref. [5].

We shall begin with a simplified parton-model interpretation of DDIS $ep \to e'p'X$, as measured in an ep collider. For example, the electron can scatter on a sea quark q in an extrinsic five-quark Fock state $|(uud)_{8C}(Q\bar{Q})_{8C}>$ of the proton, a Fock state created from an internal virtual gluon exchange. The $eQ \to e'Q'$ collision produces a quark jet with high transverse momentum opposite the transverse momentum of the scattered electron, while the $\bar{Q}$ and the $(uud)_{8C}$ remain as spectators with momenta similar to that as the incident proton. Subsequently, after the electron-quark scattering $eQ \to e'Q'$ occurs, a final-state gluon can then be exchanged between the $\bar{q}$ and one of the $(uud)_{8C}$ valence quarks. This final-state soft gluon exchange neutralizes the color of the uud spectators to a $(uud)_{1C}$ color-singlet Fock state which can in turn overlaps with the eigenstate of a final-state proton p'. The produced p' will have a 4-momentum closely matching the initial proton's 4-momentum.

In this simple picture, two gluons are exchanged in the $t-$ channel between the $\gamma^* \to Q\bar{Q}$ and $p \to p'$ systems, as in the Low-Nussinov model [6, 7]. The final state of the DDIS events is thus characterized by a $q + \bar{q}$ dijet, plus a final state p' close in rapidity and momentum to the rapidity and momentum of the initial proton. Since the second final state gluon exchange happens after the electron scatters, the scattering amplitude has a propagating intermediate state with a phase i corresponding to a Glauber cut. Thus DDIS is in effect Pomeron exchange. Since they are diffractive, the DDIS events can be characterized as due to soft Pomeron exchange between the sea quark pair, which is produced by the virtual photon $\gamma^*(q^2) \to Q\bar{Q}$ and the target proton. Therefore, in this Pomeron based-picture, the DDIS amplitude $\gamma^* + p \to Q\bar{Q} + p'$ has the energy and phase dependence $M(s, t, q^2) \sim is\beta(t)$ of Pomeron exchange. One should stress that our analysis also applies for scattering amplitudes where the Pomeron exchange corresponds to two hard gluons.

One can also use Regge phenomenology and extend the class of diffractive events to $C = -$ Odderon exchange, as well as Reggeon quark interchange events with isospin exchange, such as $\gamma^* + p \to n + X^+$. In addition, the final state p' in DDIS events can also be an excited proton state or a nucleon resonance. DDIS events can also occur in lepton-ion collisions $\gamma^* + A \to A + X$, where the nucleus A remains intact in its ground state.

It is also possible to still tag the flavor of the struck sea quark Q' in DDIS events, by measuring the leading hadron in the jet recoiling opposite to the lepton. For example, one can tag strange quark events by measuring a leading strange hadron at high z in the jet; this measures the strange quark distribution $s(x, Q^2)$ or $\bar{s}(x, Q^2)$ in the proton where its LF momentum $x = x_{Bj}$ is determined by the lepton kinematics.

2. Light-Front Description of DDIS

How can the distinction between the conventional DIS $\gamma^* p \to X$ and DDIS events $\gamma^* p \to p'X$ be understood in terms of the underlying quark and gluon degrees of freedom of QCD ? In the standard, frame-independent description based on the light-front (LF) Hamiltonian formulation of QCD, the DIS $\gamma^* p \to X$ events are due to the interaction of a virtual photon $\gamma^*(q)$, emitted by the incident lepton scattering on a quark or antiquark on one of the Fock states of the proton eigenstate $H^{\rm QCD_{LF}}|\Psi_p\rangle = M_p^2|\Psi_p\rangle$ of QCD, via the free quark current $j^+(0)$. The standard LF kinematics for DIS are: $p^\mu = (P^+, \vec{0}_\perp, \frac{M^2}{P^+})$, $q^\mu = (0, \vec{q}_\perp, q^-)$, $\vec{q}_\perp^{\,2} = Q^2 = -q^2$. Therefore, $(q + p)^2 = q^- P^+ = W^2$ and $q^- = \frac{W^2}{P^+}$. The quark and gluon constituents in each Fock state of the proton have kinematics $k^\mu = (xp^+, \vec{k}_\perp, \frac{m^2+k_\perp^2}{x})$, where $\sum_i x_i = 1$

and $\sum_i \vec{k}_{\perp i} = \vec{0}_\perp$. Notice that this LF formulation is invariant under both longitudinal and transverse boosts, and that the struck quark or antiquark has the LF momentum fraction $x = x_{Bj} = \frac{Q^2}{2p\cdot Q}$.

The probability amplitude for a given Fock state $|n\rangle$ in the target proton is given by its light-front wavefunction (LFWF) $\phi_n^p(x_i, \vec{k}_{\perp i}, \lambda_i)$, which is the projection $\langle n|\Psi_P\rangle$ of the proton eigenstate on the quark and gluon Fock state $|n\rangle$ of the free Hamiltonian. The structure functions, transverse momentum distributions and their evolution measured in DIS can thus be predicted from the square of the LFWFs, summed over the contributing Fock states.

The kinematics of the lepton-proton collision is chosen such that the virtual photon $\gamma^*(q^\mu)$ has $q^+ = 0$. This choice of kinematics eliminates events where the virtual photon creates a $Q\bar{Q}$ pair in the lepton-proton collision, since the LF momentum k^+ of each particle in LF Hamiltonian theory is positive, and the + momentum is conserved. The virtual photon has therefore no quantum fluctuations and acts as a classical probe of the proton's structure. For example, extrinsic heavy quark production in lepton-proton collisions is solely associated with the proton's structure. (This is the LF equivalent of Feynman's choice of the infinite momentum frame $P^z \to \infty$ in ordinary instant-form Hamiltonian theory.) The LF formulation thus provides a rigorous foundation for the parton model.

As noted above, the DDIS $\gamma^* p \to p' X$ events begin with the γ^* interacting with a non-valence quark Q or $\bar{Q}$ in any LF extrinsic Fock state of the proton, which contains sea quarks, such as $|(uud)_{8C}(Q\bar{Q})_{8C}\rangle$. Such an five-particle extrinsic Fock state can originate from a virtual color-octet gluon creating the color octet $Q\bar{Q}$ pair.

We can now follow the evolution of the event in LF time $\tau = t + z/c$, after the $\ell Q \to \ell' Q'$ interaction. See Fig. 1. The struck quark Q' acquires large transverse momentum $\vec{q}_\perp$, with kinematics $\left(xP^+, \vec{q}_\perp, \frac{m_Q^2+\vec{q}_\perp^2}{xP^+}\right)$. The Q' and its partner $\bar{Q}$ then propagate as a massive $(Q'\bar{Q})_{8C}$ color octet, and the remaining spectator valence quarks $(uud)_{8C}$ propagates as a color-octet along the proton direction. As the LF time τ progresses, a soft gluon exchange can be exchanged between the $\bar{Q}$ of the propagating $(Q'\bar{Q})_{8C}$ and the $(uud)_{8C}$. This produces a color-singlet $(Q\bar{Q})_{1C}$ dijet system and a final-state color-singlet cluster $(uud)_{1C}$ which can materialize as the final state proton $|p'\rangle$ thus giving the observed $\gamma^* p \to p' X$ DDIS event. The final state X can thus be a $Q\bar{Q}$ dijet isolated in rapidity from the remnant forward moving p'.

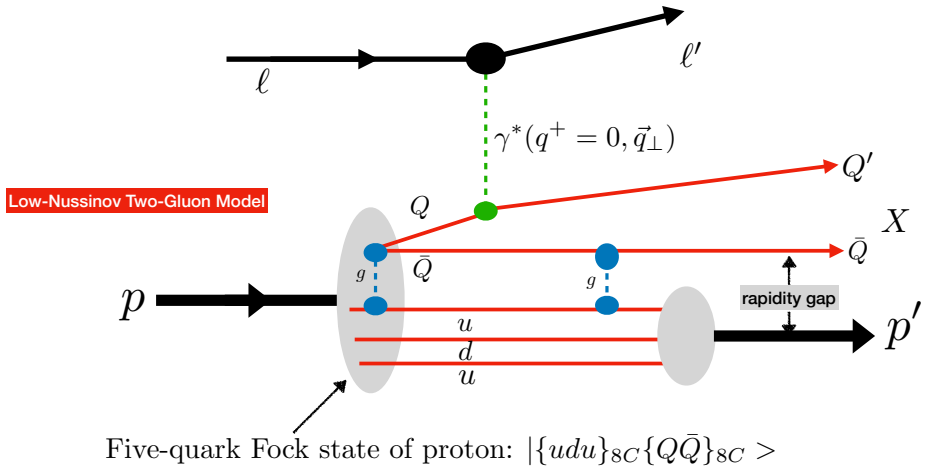

Figure 1. Simplified description of the DDIS event $\gamma^* + p_{|uduQ\bar{Q}\rangle} \to p' + X +$ rapgap from the simplified two-gluon Low-Nussinov model of Pomeron exchange in the LF framework. Multiple gluons can also propagate between the initial and final gluons. The five-quark Fock state of proton $|\{udu\}_{8C}\{Q\bar{Q}\}_{8C}\rangle$ produces the rapidity gap.

The DDIS event is leading-twist, Bjorken-scaling in q^2, since the only hard interaction occurring is the hard scattering of the lepton on the Q of the initial proton $|uudQ\bar{Q}\rangle$ Fock state. This DDIS event mimics the exchange of the Low-Nussinov model in the t channel. The initial exchanged soft gluon in the proton Fock state produces the $|(uud)_{8C}(Q\bar{Q})_{8C}\rangle$ configuration in the initial state; the final-state exchange of the second soft gluon produces the isolated color singlet $Q\bar{Q}$, and the final-state color singlet $|uud\rangle$ produces the intact proton p' with small momentum transfer t. One can also have multiple gluons propagating between the initial and final gluons, thus resembling a

model of the Pomeron with the exchange of two interacting gluon strings in the t channel.

3. Application of the OPE to DIS

The application of the OPE to DIS utilizes the properties of deep inelastic forward virtual Compton scattering (DVCS) $\gamma^* p \to \gamma^* p$, since the imaginary part of its amplitude gives the DIS cross section $\gamma^* p \to X$ by unitarity. In the case of a simple DIS reaction $\gamma^* + Q \to Q'$, where the lepton scatters on a quark Q, the DVCS amplitude has the form of the *handbag diagram*, since there are no interactions occurring in LF time which will interrupt the propagation of the struck quark Q. See Fig. 2.

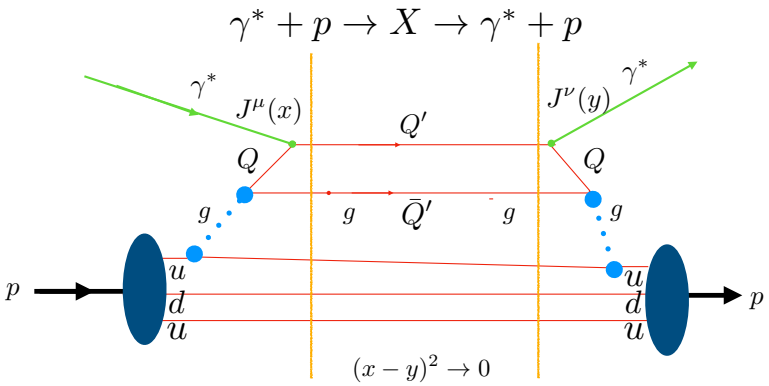

Figure 2. Forward DVCS for a DIS event $\gamma^* + p \to X \to \gamma^* + p$. Vanishing LF time between currents of virtual photons at high q^2 allows the application of the OPE to DIS.

In DIS at large q^2, the amplitude $\gamma^* + Q \to \gamma^* + Q$ contracts to an effective seagull operator of the local product of quark currents $j^+(0)j^+(0)$, which in the OPE can be replaced by the gravitational energy-momentum tensor $T^{++}(0)$. The graviton coupling is proportional to the LF momentum fraction $x = \frac{k^+}{P^+}$ carried by the struck quark, while the resulting matrix element $\langle p|T^{++}(0)|p\rangle$ is given by square of the proton's LFWF integrated over the quark, antiquark and gluon x_i and $\vec{k}_{\perp i}$ kinematics. In Fig. 2, the sequence in LF time is marked by the vertical orange bars. This procedure underlies the OPE derivation of the MSR for structure functions. One thus obtains the total LF momentum carried by the charged quarks in the proton.

The MSR is a property of the LFWF of the target proton; i.e., it is a property of the eigenfunction of the QCD light-front Hamiltonian. The square of the proton's LFWF defines the proton structure function at an initial scale, which then evolves by DGLAP evolution. The momentum sum rule is maintained by the pQCD subprocesses described by DGLAP evolution such as $q \to qg$ and $g \to q\bar{q}$. However, the diffractive contribution due to soft gluon exchange in the final state, which keeps the proton intact at low momentum transfer, is not due to the subprocesses which underly DGLAP evolution. Moreover, the DDIS amplitude acquires the complex phase of t-channel Pomeron exchange, physics which is not described by the usual leading-twist pQCD contributions. The diffractive DIS contribution from Pomeron exchange is thus a distinct contribution to the DIS cross section which does not obey the momentum and other sum rules. Note also that diffractive processes underlie the shadowing and anti-shadowing of the nuclear cross sections. Thus, as discussed in Ref. [7], nuclear parton distribution functions are not constrained by the momentum or other sum rules. Note that the measurements by the H1 Collaboration [4] for the diffractive F2 structure function satisfied the MSR within uncertainties; the MSR was not imposed in the fit. However, the NuTeV measurement of charged current DDIS contradicts the expectation that anti-shadowing compensates shadowing to restore the MSR for nuclear structure functions.

Fig. 3 shows the corresponding contribution to forward DVCS $\gamma^*+p \to \{Q\bar{Q}\}+p' \to \gamma^*+p$ from the DDIS channel. In this case, the imaginary part of the forward DVCS amplitude gives the DDIS cross section and thus its contribution

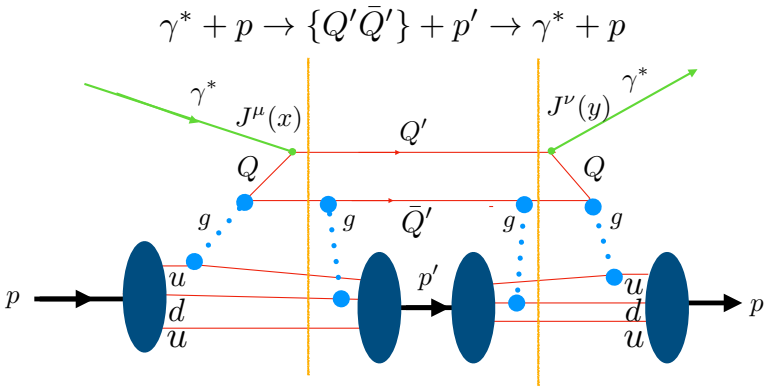

Figure 3. Forward DVCS for a DDIS event. Nonzero LF propagation time between virtual photons cannot be reduced to a local seagull interaction, thus preventing the application of OPE.

to the DDIS structure function. The sequence in LF time is again marked by the vertical orange bars. However, because of the final-state interaction (FSI) of the virtual gluon between the struck sea quark Q and the valence quarks, which restores the proton intact in its ground state in DDIS, the LF time $\Delta\tau = x^+ - y^+$ between the currents $J^\mu(x)$ and $J^\nu(y)$ in the DVCS amplitude is interrupted. The interactions of the two currents on the quark propagator in the DVCS amplitude cannot be reduced to a local seagull interaction, thus preventing the usual application of the OPE. We stress that the forward DVCS process shown in Fig. 3 represents the standard leading-twist two-gluon Low-Nussinov contribution to DDIS, where the proton stays intact and isolated. The extra $1/Q^2$ factors in the forward virtual Compton amplitude from the two extra denominators are compensated by the gluon couplings.

Our analysis is also supported by the results of Ref. [8], where the importance of absorptive correction at low x are noted. These authors use the knowledge of diffractive deep inelastic scattering to exclude the absorptive effect from conventional DIS data. Gluon recombination at low x leading to saturation of the gluon density is a rather well known phenomena. The authors of Ref. [8] use the known diffractive part of the DIS cross section " to remove the absorptive corrections from the inclusive data. The MSR is therefore inapplicable for the fraction of DIS events which are leading-twist DDIS events.

A key point is that only the final-state quarks which are scattered out with high transverse momentum opposite to the final-state lepton are measured in the DIS measurement. In the standard parton model picture, one assumes that all (100%) of the momentum of the incident proton in DIS events is carried off in the final state by quarks, antiquarks, and gluons. The MSR $\sum_{i=q,\bar{q},g} x_i = 1$ is then used to obtain the gluon momentum fraction $\langle x_g \rangle$.

If one sums the contributions $\sum_i x_{qi}$ to the LF MSR from the outgoing scattered quarks, the LF momentum fraction $x'_p \sim 0.9$ which is carried off by p' in the DDIS events is not counted. In this case, the spectators include the final-state intact proton; the scattered quarks thus cannot give accurate information about the parton momentum distribution inside the proton. Then substantial LF momentum x'_p which is carried off by p' in DDIS events is misinterpreted as the gluon LF momentum fraction $\langle x_g \rangle$. The value for $\langle x_g \rangle$ – which has been obtained by misapplying the MSR – has thus been overestimated – perhaps by $0.15 \times 0.9 \sim 0.13$. This overestimate of $\langle x_g \rangle$ can also have logarithmic dependence on Q^2.

The FSI interactions of the included DDIS events from gluon exchange severely distort the measured sea-quark and antiquark distributions. The DIS experimentalists will thus obtain a false determination of $\langle x_q \rangle$ and $\langle x_{\bar{q}} \rangle$, because they incorrectly include the DDIS events, and when the MSR is applied, one obtains a false determination of $\langle x_g \rangle$. The imaginary part (cut) gives the cross section for the DDIS event $\gamma^* p \to p' x$, and then the LF time interval between the two currents at x and y does not vanish at large Q^2, since it includes the nonzero time for the proton to propagate. One cannot relate the product of $J^\mu(x)$ and $J^\nu(y)$ to the local operator $T^{\mu\nu}$. Thus the OPE is invalid and the MSR cannot be derived.

The DDIS $\gamma^* p \to p' X$ events where the final-state proton p' is produced – with a rapidity gap separating it from the other final-state hadrons – are a substantial subset of the final states which contribute to the leading-twist $\gamma^* p \to X$ DIS cross section. However, as we have shown, the DDIS events should be excluded when evaluating the traditional DIS momentum and other sum rules. In fact, as indicated in Fig. 4, the DDIS events will be misinterpreted as contributions to the gluon momentum fraction.

The DDIS events also play a role in the theory of shadowing and antishadowing of nuclear cross sections and thus the application of the MSR to nuclei, as we have discussed in Ref. [9].

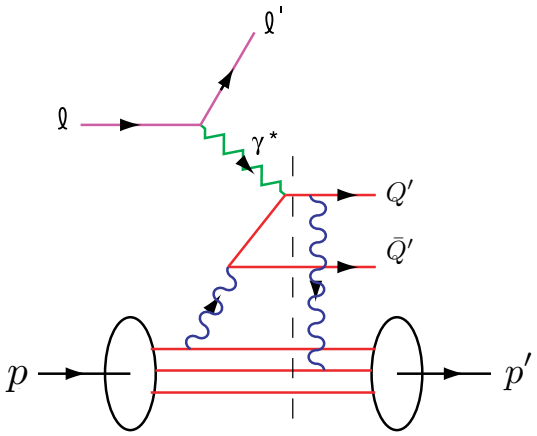

Figure 4. DDIS eventfinal-state interactions $\gamma^* + p \to p' + X$ with $Q'\bar{Q}'$ pair production. 90% of proton momentum carried off by final proton p' in 15% of events. Gluon momentum fraction misidentified. p' is produced in DDIS but escapes detection, and is misinterpreted as a DIS event.

The FSI occurring in DDIS phenomena has a similarity with the leading-twist Sivers' single-spin asymmetry (SSA), which is due to FSIs in semi-inclusive DIS [10], and which are not included in the proton's LFWFs. In particular, SSA does not factorize into a product of PDF and fragmentation function, and it is not related to the quark transversity PDF. As noted above, the DDIS cross section is also leading twist – Bjorken scaling. The numerator of the final-state gluon exchange amplitude compensates for the $1/Q^2$. In fact, the same gluon exchange interaction gives the leading-twist Sivers effect. The imaginary phase comes from the Glauber cut and contributes to both DDIS and the Sivers effect. In particular, the SSA does not factorize into a product of PDF and fragmentation function, and it is not related to the quark transversity PDF. Another example is the double Boer-Mulders effect in DY which breaks the Lam-Tung relation.

Thus the DDIS events do not actually measure the physics of the LFWF of the target proton since they arise from FSIs which are not in the eigensolution of the QCD LF Hamiltonian. The LFWF is a property of the hadronic eigenstate of the QCD LF Hamiltonian, and it obeys the MSR $\sum_{i=q,\bar{q},g} \langle x_i \rangle = 1$. The LFWF has no knowledge of events that occur after the electron quark scattering.

4. The "True", Non-Diffractive DIS Cross Section.

Now we turn to the master formulas which define the "true" non-diffractive DIS cross section (NDDIS) and true PDFs without DDIS events. The double-differential DIS cross section depending of x and Q^2 variables is expressed in terms of structure functions F_2 and $F_L = F_2 - 2xF_1$ as

$$\frac{d\sigma_{\rm DIS}}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\,\frac{1+(1-y)^2}{x}\left[F_2 - F_L\,\frac{y^2}{1+(1-y)^2}\right], \tag{1}$$

where $Q^2, \nu = p\cdot q \to \infty$. DDIS cross section is defined by analogy

$$\frac{d\sigma_{\rm DDIS}}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\,\frac{1+(1-y)^2}{x}\left[F_2^D - F_L^D\,\frac{y^2}{1+(1-y)^2}\right], \tag{2}$$

where F_2^D and $F_L^D = F_2^D - 2xF_1^D$ are the diffractive structure functions.

As we have shown the DIS differential cross section which obeys the OPE and the MSR requires that the DDIS events to be subtracted:

$$\frac{d\sigma_{\rm DIS_{true}}}{dxdQ^2} = \frac{d\sigma_{\rm DIS}}{dxdQ^2} - \frac{d\sigma_{\rm DDIS}}{dxdQ^2} \,. \tag{3}$$

for each scattered quark q'. Since the final states are different, this procedure reproduces the "true" quark distributions $q(x, Q)$ and $\bar{q}(x, Q)$, which specifically come from the proton LFWF, as in the parton model. Then the net result – after subtracting the DDIS events – is that the "true" sea quark and antiquark distributions obtained from $d\sigma_{\rm DIS_{true}}/dxdQ^2$ would appear at higher x. Applying the MSR for the partons in the proton LFWF $\sum\limits_{i=q,\bar{q},g} \langle x_i \rangle = 1$ then gives a decreased value for the "true" gluon momentum fraction $\langle x \rangle_g$.

According to the factorization theorem, in QCD the DIS and DDIS structure functions are written as convolution of PDFs $f_i(x)$ (nonperturbative part) of flavor i and hard scattering part (coefficient functions $C_{2,i}$)

$$F_{2/L}(x, Q^2) = \sum_i \int \frac{d\xi}{\xi} C^i_{2/L}\Big(\frac{x}{\xi}\Big) f_i(x, Q^2) \tag{4}$$

for DIS and

$$F^D_{2/L}(\beta, Q^2; x_{\mathbb{P}}, t) = \sum_i \int \frac{d\xi}{\xi} C^i_{2/L}\Big(\frac{\beta}{\xi}\Big) f^D_i(\xi, Q^2; x_{\mathbb{P}}, t) \tag{5}$$

for DDIS, where β is the diffractive exchange, $x_{\mathbb{P}} = x/\beta$ is the fraction of the momentum of proton carried by the diffractive exchange. Following Ref. [11, 12], we use the same coefficient functions $C_{2/L,i}$ for DIS and DDIS. In the Regge factorization scheme separating the Q^2 and $x_{\mathbb{P}}$ behavior of the PDFs, DDIS PDFs are splited into the Pomeron ($\mathbb{P}$) and Reggeon ($\mathbb{R}$) parts as:

$$f^D_i(\beta, Q^2; x_{\mathbb{P}}, t) = f_{\mathbb{P}/p}(x_{\mathbb{P}}, t)\, f_{i/\mathbb{P}}(\beta, Q^2) \,+\, f_{\mathbb{R}/p}(x_{\mathbb{P}}, t)\, f_{i/\mathbb{R}}(\beta, Q^2) \,, \tag{6}$$

where $f_{\mathbb{P}/p}$ and $f_{\mathbb{R}/p}$ are the Pomeron and Reggeon fluxes, $f_{i/\mathbb{P}}(\beta, Q^2)$ and $f_{i/\mathbb{R}}(\beta, Q^2)$ are the Pomeron and Reggeon PDFs. For $f_{\mathbb{P}/p}$ and $f_{\mathbb{R}/p}$ we use the same functional form [12]: $f_{\mathbb{P},\mathbb{R}/p} = A_{\mathbb{P},\mathbb{R}}\, e^{B_{\mathbb{P},\mathbb{R}} t}/x_{\mathbb{P}}^{2\alpha_{\mathbb{P},\mathbb{R}}(t)-1}$, where $A_{\mathbb{P},\mathbb{R}}$ is the Pomeron/Reggeon intercepts. $\alpha_{\mathbb{P},\mathbb{R}}$ is the linear Pomeron/Reggeon trajectories: $\alpha_{\mathbb{P},\mathbb{R}}(t) = \alpha_{\mathbb{P},\mathbb{R}}(0) + \alpha'_{\mathbb{P},\mathbb{R}} t$. For the DDIS PDFs $f_{i/\mathbb{R}}(\beta, Q^2)$ we use parameterizations extracted from world data analysis, which for quarks/antiquarks and gluon read: $f_i(z, Q_0^2) = \alpha_i\, z^{\beta_i}\, (1-z)^{\gamma_i}\, (1+\eta_i \sqrt{z})\,,\ i = q, g$. As commonly used, we assume that the quark and antiquark PDFs are equal. The sets of input parameters are listed, e.g., in [12].

Upon the assumption on the same coefficient functions $C_{2/L,i}$ for DIS and DDIS, we can define the true PDF, as full PDF from which the diffractive PDF is subtracted:

$$f_i(x, Q^2)\Big|_{\rm true} = f_i(x, Q^2) - f^D_i(x, Q^2) \,, \tag{7}$$

where $f^D_i(x, Q^2) = f_{\mathbb{P}/p}(x_{\mathbb{P}}(0), 0)\, f_{i/\mathbb{P}}(\beta_0, Q^2) \,+\, f_{\mathbb{R}/p}(x_{\mathbb{P}}(0), 0)\, f_{i/\mathbb{R}}(\beta_0, Q^2)$, $f_{\mathbb{P},\mathbb{R}/p}(x_{\mathbb{P}}(0), 0) = A_{\mathbb{P},\mathbb{R}}/x_{\mathbb{P}}^{2\alpha_{\mathbb{P},\mathbb{R}}(0)-1}$, and $\beta_0 = x/x_{\mathbb{P}}(0)$. DDIS PDFs must be manifestly independent on $x_{\mathbb{P}}(0)$ [or $\beta_0 = x/x_{\mathbb{P}}(0)$ if they are expressed through β_0 instead of $x_{\mathbb{P}}(0)$] with taking into account of the constraint on a choice of the parametrization for DDIS PDFs:

$$\frac{\partial f^D_i(x, Q^2)}{\partial x_{\mathbb{P}}(0)} = \frac{\partial}{\partial x_{\mathbb{P}}(0)} \Big[f_{\mathbb{P}/p}(x_{\mathbb{P}}(0), 0)\, f_{i/\mathbb{P}}(x/x_{\mathbb{P}}(0), Q^2) \,+\, f_{\mathbb{R}/p}(x_{\mathbb{P}}(0), 0)\, f_{i/\mathbb{R}}(x/x_{\mathbb{P}}(0), Q^2) \Big] = 0 \,. \tag{8}$$

Therefore, the idea of extraction of realistic quark PDFs in proton from true DIS is simply reduced to the subtraction of PDF itself, following Eq. (7).

In conclusion, we propose a definition of the true NDDIS, which yields the true PDFs by subtracting the respective DDIS contribution. The DDIS contribution to the total DIS is not negligible, and therefore, its separation and subtraction is required in order to obtain an accurate determination of the quark and gluon PDFs, which play important role

in the description of hadron structure. Our paper provides new and important perspectives on the physics origin of the entire class of Bjorken-scaling diffractive events in deep inelastic lepton-proton scattering. Our analysis also has important implications for physics underlying the shadowing and antishadowing of nuclear structure functions. This point was discussed in Ref. [9].

Our main observation is that the quark and gluon parton distributions intrinsic to hadron structure will be misidentified, unless one excludes the DDIS events; for example, the correct determination of the PDFs for proton derived from the DIS data $\gamma^* p \to X$ requires the explicit subtraction of the leading-twist DDIS contribution $\gamma^* p \to p' X$ from the full DIS cross section. In particular, the light-front momentum carried by gluons in the proton will be misidentified since the final-state proton p' carries off LF momentum in the DDIS events. The modification of PDFs is expected to be of order 10%. This will also affect predictions for hadron production processes based on the standard factorization formalism. Clearly, a careful separation of non-diffractive and diffractive contributions to the measured deep inelastic cross section, as well as other hard-process cross sections is required.

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