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Violations of parton-hadron duality in Deep Inelastic Scattering

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Abstract. I present an overview of recent data on Deep Inelastic Scattering at large Bjorken x and low invariant mass, W^2, where parton-hadron duality was originally observed. I discuss the concept of parton-hadron duality from the perspective of perturbative QCD. Within this framework, I show that parton-hadron duality is broken for low values of W^2, in the Δ- and S_{11}-resonance production region. A model that accounts for the anomalous scale dependence ensuing from this situation is developed.

PACS. 13.60.-r Photon and charged-lepton interactions with hadrons – 13.60.Hb Total and inclusive cross-sections (including deep-inelastic processes)

1 Introduction

> "QCD nowadays has a split personality. It embodies "hard" and "soft" physics, both being hard subjects and the softer the harder." [1]

Studies of parton-hadron duality have been a key issue since the interpretation of hard processes in terms of QCD. It is in fact a fundamental goal of QCD to account for the structure of hadrons —the *observables* in both the initial and final stages of the hard processes used to investigate them— using quark and gluon (parton) degrees of freedom —that are *not observable*. The underlying idea is that at large enough momentum scales, Q^2, or at short distances, one explores hadronic structure independently of what might be observed at lower momentum scales (larger distances). Because of the property of asymptotic freedom, QCD is calculable at short distances $\approx 1/\sqrt{Q^2}$, where a hard probe sees hadrons as composed of quarks and gluons carrying fractions x of the hadron's momentum, with a given probability distribution described by the hadron's structure functions. The change in the quark's distribution, as increasingly shorter distances are probed, is calculated using perturbation theory —perturbative QCD (pQCD)— in the parameter α_S, the strong coupling constant. The outcome is a pattern of scaling violations which, along with predictions for infrared safe quantities such as total rates, direction of jets, ..., are among the striking successes of the theory. At large distances, $1/\sqrt{\Lambda^2} \approx R$, Λ being the parameter of QCD, and R being a hadronic size, the partonic structure is in principle no longer resolved, pQCD breaks down, and confinement sets in. Large-distance physics regulates a number of other observables such as hadron multiplicities in hadron-hadron scattering, and the x-dependence of the structure and fragmentation functions. The calculation of the "short-distance–type" observables (or, technically, the infrared safe ones) is independent of the values taken by the latter ones, this property being embodied by factorization theorems.

The separation and yet coexistence of long-distance and short-distance structure in QCD has by now become naturally accepted as part of a "common wisdom framework" underlying the interpretation of most experiments, from Deep Inelastic Scattering (DIS) to $e^+e^- \to$ hadrons, to hadron-hadron scattering. The concept of *duality* is implicitly used, somewhat in between the lines, meaning that hadronic observables are replaced by calculable partonic ones with little more going into the hadronic formation phase of the process (from partons to hadrons or vice versa). In a phenomenological context, duality purports to study how a number of properties defined from the beginning of the hard scattering process, are predetermined and persist in the non-perturbative stage.

With the advent of more detailed studies of soft scales and confinement, it is now becoming mandatory to investigate duality in QCD, *per se*. An illustrative example is given by the series of recent papers on local quark-hadron duality and its violations in semi-leptonic decays, and τ decays (see review in [2]). The outcome of these experiments and their possible impact on the experimental extraction of CKM matrix elements, depends on the ability to gauge violations of local duality. A similar urgent practical need to address duality exists in DIS where for large values of Bjorken $x > 0.5$ ($x = Q^2/2M\nu$, M being the proton mass and ν the energy transfer in the lab system), and for $Q^2 \approx 5$ GeV^2, a typical starting value for perturbative

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evolution, $W^2 \leq 5$ GeV^2 (with $W^2 = Q^2(1/x - 1) + M^2$), *i.e.* it lies mostly in the resonance region

In this paper, we discuss our program to address specifically DIS. Our starting point is similar to [2,3], in that the background of our model is the OPE within which we pursue a connection between the resonance region and the higher-twist operators. Crucial for the construction of our model is an accurate analysis of recent data conducted in [4], reviewed in sect. 2; in sect. 3 we present our model and in sect. 4 we draw our conclusions.

2 What we learned from the data

The advent of new experimental data [5] has changed the nature of studies of parton-hadron duality. Initial studies started from the qualitative observation first reported for DIS by Bloom and Gilman [6] of an equivalence between the smooth function describing the inclusive structure functions x-dependence at large Q^2 and the average curve going through the nucleon resonances measured at lower Q^2. This was insightfully interpreted using partonic ideas [7,8] as a "correspondence" between exclusive and inclusive reactions at high energies. It is now possible to elaborate quantitative approaches within QCD [2,3].

It is for this reason that we first present the somewhat unexepected results obtained from a careful pQCD study of DIS data at large x [4], including recent accurate JLab data on F_2 in the resonance region [5]. In QCD, contributions from different operators to F_2 are ordered according to their twist, $\tau = 2, 4, \ldots$, leading to the expansion in inverse powers of Q^2:

$$F_2(x,Q^2) = F_2^{\rm LT}(x,Q^2) + \frac{H_2(x,Q^2)}{Q^2} + \mathcal{O}\left(1/Q^4\right) . \quad (1)$$

The first term is the leading twist, LT, $\tau = 2$, contribution. The terms of order $1/Q^{\tau-2}$, $\tau \geq 4$, in eq. (1) arise from higher-order terms in the twist expansion. Additional power corrections of kinematical origin are present, due to the finite mass of the initial nucleon (target mass corrections, TMCs), and they are included in the twist-2 part of F_2. At large x the proton structure function is dominated by non-partonic components —the nucleon resonances— up to relatively large Q^2 ($Q^2 \leq 20$ GeV^2). Based on earlier work [9] where the average of the resonance spectrum was expressed in terms of Mellin moments, it was conjectured that duality, or the equivalence of the resonance moments with Mellin moments of F_2 at much larger Q^2, resulted from a cancellation among terms of higher twist that would otherwise be expected to dominate the cross-section at $x \to 1$, or as more exclusive states are produced. This view has been adopted since —possible reasons for the cancellation are still a matter of debate [10]. Moreover, as pointed out in [11], the usage of moments at low Q^2 can give rise to ambiguities, such as the ones due to a rather large contribution of elastic scattering to the structure function.

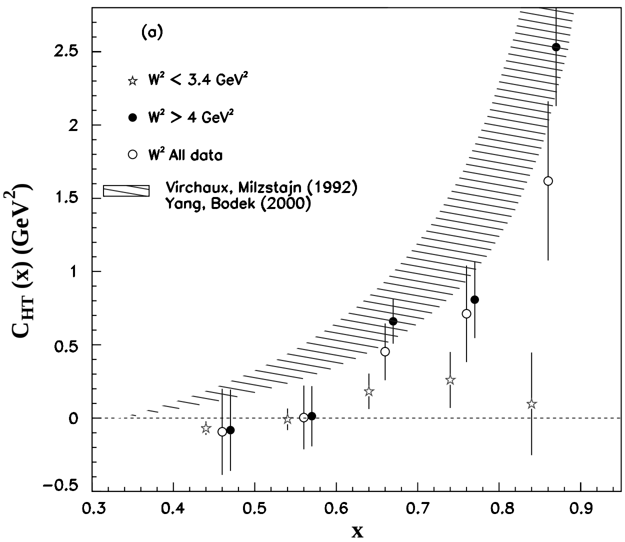

Fig. 1. Higher-twist coefficient from eq. (2).

The highly accurate data that are now available in the resonance region [5] allow one to fit them to a smooth curve going through the resonance peaks, with a $\chi^2 \approx$ 0.8–1.1 [4]. This curve, once evolved according to pQCD, can be compared with the DIS data. Such an analysis was performed in [4] by considering a number of steps similar to recent extractions of power corrections from DIS data [12,13]. In particular, uncertainties due to the treatment of TMCs and to large-x resummation had to be evaluated. A much richer structure of the Q^2-dependence behind the apparent cancellation among higher-twist terms was uncovered. The twist-4 contribution is summarized in fig. 1, where its coefficient is parametrized, consistently with current literature [12], as

$$C_{\rm HT}(x) = H(x,Q^2)/F_2^{\rm LT}(x,Q^2). \quad (2)$$

$C_{\rm HT}$ was extracted from: DIS data with $W^2 \geq 4$ GeV^2, from the resonance region ($W^2 < 4$ GeV^2), and over the entire range of W^2. While the large-W^2 data track a curve in agreement with the $1/W^2$ behavior expected from most models, the low-W^2 data yield a much smaller value for $C_{\rm HT}$ and they show a bend-over of the slope *vs.* x.

Furthermore, the extension of our analysis to extract the $1/Q^4$ term (see [4] for details), confirms that this surprising effect is not a consequence of the interplay of higher-order corrections and the HT terms, but just of the extension of our detailed pQCD analysis to the large-x, low-W^2 kinematical region. In other words, we unraveled a Q^2-dependence that seems to deviate from the pioneering analysis of [9], or, in the language of [3], we observe a violation of *global* duality.

3 Large-N_c model of F_2 at low W^2

We propose a simple dynamical model for the structure function in the low-W^2 ($W^2 \leq 4$ GeV^2) and low-Q^2

($Q^2 < 10$ GeV^2) regime, where non-partonic configurations are expected to be dominant. In the standard approach to DIS the Q^2-dependence of F_2 is described by the pQCD evolution equations whose numerical solution requires parametrizing the input distributions at an initial scale Q_0^2 where pQCD is believed to be still applicable. Q_0^2 serves as a boundary between the perturbative and non-perturbative domains, although its value is somewhat arbitrary (reasonable values can be taken in the range: $Q_0^2 \approx 0.4$–10 GeV^2). We refer to this situation as the "fixed initial scale" description, and we write explicitely the dependence of the quark distributions, $q_i(x, Q^2, Q_0^2)$, $i = u, d, \ldots$, on Q_0^2. A simple kinematical argument shows that Q_0^2 is related to the invariant mass squared of the proton remnant after a parton is emitted, by $M_X^2 \approx Q_0^2/x$, *i.e.* valence quarks, whose distribution peaks at large x, can be considered as being emitted from an object with mass $\approx Q_0^2$.

In what follows, we explore this idea with a quantitative model. In our model partons are not emitted directly from the nucleon, but, before the pQCD radiative processes are initiated, a semi-hard phase occurs where the dominant degrees of freedom are color-neutral clusters with a mass distribution peaked at $\mu^2_{\rm peak} \approx Q_0^2$. As a result, the nucleon structure function is related to the quark distribution by a smearing of the initial Q_0^2, namely

$$F_2(x, Q^2) = x \sum_i e_i^2 \int_{\mu_0^2 > \Lambda^2}^{W^2} \frac{{\rm d}\mu^2}{\mu^2} P(\mu^2) q_i(x, Q^2, \mu^2), \quad (3)$$

where $P(\mu^2)$ ($P_{\rm peak}(\mu^2) \approx P(Q_0^2)$) is the clusters' mass distribution, and the sum is extended to valence quarks only since we are describing the large-x region. Equation (3) expresses the fact that the initial stage of pQCD evolution is characterized by color-neutral clusters of variable mass, from which the hard scattering parton will emerge, in a subsequent stage of the interaction.

Equation (3) is formally derived within the framework of the large-N_c approximation [14]. This approach is widely applied in cluster hadronization schemes implemented in QCD Monte Carlo simulations [15] where hadronization proceeds as prescribed by the pQCD property of preconfinement of color [14]: at the end of the parton's pQCD evolution, color singlets are formed with a Q^2-independent mass (and spatial) distribution. In practical implementations [15], all gluons left at the hadronization scale, are "forcibly", or non-perturbatively, split into $q\bar{q}$ pairs. It is this modification of the evolution equations that allows for the local parton-hadron conversion through preconfinement of color: each color line "color-connects" *e.g.* a quark to an anti-quark, forming a color singlet. The color singlet clusters are then fragmented into hadrons. In DIS the transiton hadrons → quarks → hadrons, is complicated both by initial-state radiation and by the presence of the beam cluster formed from the remnant of the initial hadron. This produces an additional rescattering term in eq. (3) [16]. The conversion of a hadron into a parton through a cluster stage in large-N_c approximation is described schematically in fig. 2.

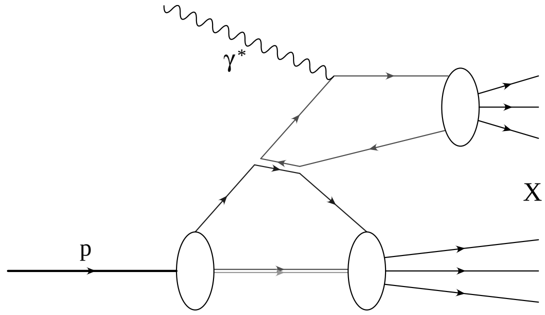

Fig. 2. Conversion of a hadron into a parton through a cluster stage in large-N_c approximation.

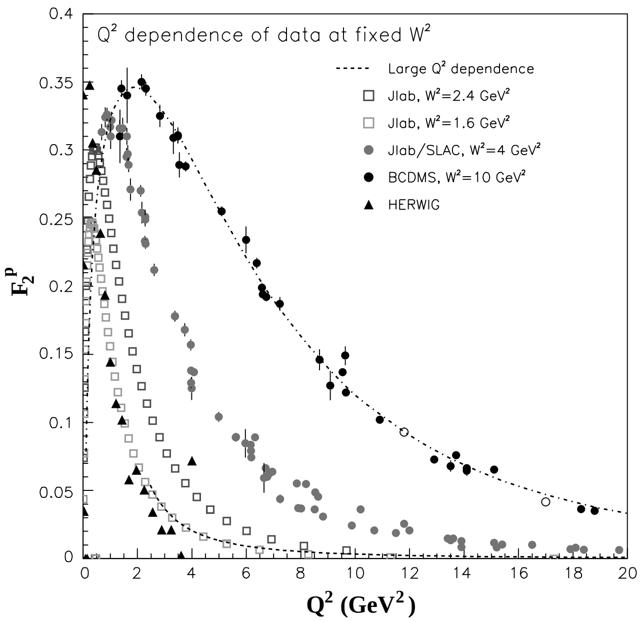

Fig. 3. Q^2-dependence of DIS data at fixed W^2, plotted along with evaluations of eq. (3) at $W^2 = 1.6$ GeV^2 using HERWIG [15], (triangles), and the large-Q^2 limit (dashed curve).

As a preliminary study, we considered both the low- and the very large-W^2 limits of eq. (3). At low W^2, $F_2 \to P(Q^2)$, namely it is described by the behavior of the cluster distribution function. At large W^2, $P \approx \delta(\mu^2 - Q_0^2)$, *i.e.* it determines the value of the initial Q_0^2. In fig. 3 we present our result for F_2 at a fixed low value of W^2, $W^2 = 1.6$ GeV^2, (triangles and dashed line) along with a pQCD based parametrization of large W^2, $W^2 = 10$ GeV^2. The trend of data between these two values is also shown. The cluster distribution was obtained directly from the QCD-MC HERWIG [15]. We find this initial agreement with data quite encouraging, considering that no modeling has gone yet into eq. (3). A modification due to the rescattering term shown by the second lower blob in fig. 2 allows us to bring the complete analytical calculation closer to the data at the peak value. Results are presented in [16]. At large Q^2 we show the limiting, Sudakov-type, behavior of the distribution.

4 Conclusions and outlook

We address the problem of parton-hadron duality in DIS within a QCD framework. We imagine a semi-hard phase of the scattering process occurring at large Bjorken x, according to which the soft parton, before undergoing pQCD evolution, is emitted from a color-neutral cluster with mass distribution peaked around $Q_0^2 \approx 1$ GeV^2. These color-neutral clusters are identified with the objects appearing in hadron formation in the preconfinement phase of QCD [14]. Our preliminary evaluations using the cluster distribution from the QCD Monte Carlo HERWIG [15] agree in a rather astonishing way with the data at low W^2. More modeling for the specific case of DIS, is needed and it is being addressed in [16]. This scenario purports to explain global duality and its violations recently uncovered in [4]. The origin of resonances as oscillations in the cross-section, or strong violations of local duality, is not addressed explicitely in this work. However, a connection with refs. [2,3], where local duality violations are shown to be related to the power corrections implicit in the pQCD series, can in principle be established. Finally, our model can be applied to other hard processes, including semi-inclusive reactions, and processes with hadrons in the initial state, a goal that we are looking forward to fulfilling.

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