Recent studies of the $Q^2$ dependence of $ep$ scattering in the large $x$ region and in the $Q^2$ range: $1 \leq Q^2 \leq 30$ GeV$^2$, confirm the validity of the phenomenon of quark-hadron duality - the similarity of the deep inelastic (parton) and resonance (hadron) spectra - for values of the invariant mass, $W^2 \geq 2.4$ GeV$^2$. At lower values of $W^2$, duality is found to be significantly violated by an amount that cannot be parametrized in terms of the first few terms of a series of power corrections. We present a dynamical model that explains the $Q^2$ dependence of the data: at low $W^2$, non-partonic components given by color neutral clusters do dominate the cross section and the $Q^2$ dependence is governed by their mass spectrum, predicted within the preconfiment property of QCD; at large $W^2$ the structure function is determined by a convolution of the cluster mass spectrum with the parton distributions.

1 Introduction

Deep inelastic scattering (DIS) experiments provide a wealth of information on the structure of hadrons, from a detailed understanding of their partonic structure, to precision measurements of $\alpha_S$. In order to reveal the partonic structure of hadrons, the four-momentum transfer squared, $Q^2$, must be large, namely well above 1 GeV$^2$. As $Q^2$ is lowered partonic components become less likely to be observed, and a transition to a regime eventually dominated by non-partonic degrees of freedom, and therefore outside the range of applicability of pQCD, is expected to occur. The onset of this regime has been observed in a large number of experiments on $ep$ scattering in the low Bjorken $x$ and large invariant mass, $W^2$, region, where it is a well accepted fact that non-partonic components should replace the partonic structure at low $Q^2$. The data indeed support a sharp transition between the partonic and non-partonic regimes at $Q^2 \approx 1$ GeV$^2$, for $10^{-5} \leq x \leq 10^{-3}$. At large $x$ the proton structure function is clearly dominated by non-partonic components – the nucleon resonances – up to relatively large $Q^2$ ($Q^2 \leq 20$ GeV$^2$). An
equivalence was singled out, however, between the average of the resonance spectrum, written in terms of Mellin moments, and the DIS structure function measured at larger $Q^2$. The moments in the two regimes were found to differ by perturbative corrections and relatively small power corrections. It was conjectured that a form of duality resulted from the cancellation of higher order terms in the twist expansion 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 since considered the most natural one. From a slightly different perspective, a series of recent papers has been devoted to local quark-hadron duality and its violations in semi-leptonic decays, and $\tau$ decays (for a review see Def.). In particular, it was shown in Def. that local duality violations can be traced to the asymptotic nature of the operator product expansion (OPE), namely, to the behavior of operators of both higher dimension and higher twist. This has lead the way to specific models based on instantons, and on large $N_c$ QCD in $(1 + 1)$ dimensions. Approaches consistent with Def. could shed some light on duality in DIS, where quark-hadron duality has been explored so far within the context of quark models Def, thus avoiding the basic questions related to the dynamical nature of QCD. In this contribution, we discuss a possible avenue: Our starting point is similar to Def. 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 Def. conducted in Def. In the following sections we summarize the results found in Def., we introduce our model, and we present some initial results.

## 2 Perturbative QCD Analysis of Parton-Hadron Duality

In Def. the $Q^2$ dependence in the resonance region was extracted by first considering the average of the resonances over $\xi = 2x/(1 + \sqrt{1 + 4M^2x^2/Q^2})$, which properly takes into account Target Mass Corrections (TMC). The averaging procedure, described in detail in Def., yields a smooth curve in $\xi$ which fits the resonance data with a $\chi^2/d.o.f.$ between 0.8 and 1.1. It represents an alternative analysis to the ones using moments. The fit was performed in bins of $W^2$, centered at: $W^2_R = 1.6, 2.3, 2.8, 3.4$ GeV$^2$, respectively. Our subsequent study was aimed at establishing whether it is possible to define a breakpoint where pQCD no longer applies and a transition occurs, similar to what observed in the low $x$ regime Def. The analysis involved a number of steps similar to recent extractions of power corrections from inclusive data Def, Def, Def, Def, namely the form

$$F_2^{exp}(x, Q^2) = F_2^{pQCD+TMC}(x, Q^2) + \frac{H(x, Q^2)}{Q^2} + O(1/Q^4),$$

was adopted, where $F_2^{pQCD+TMC}(x, Q^2)$ is the twist-2 contribution, including the kinematical TMC; the other terms in the formula are the dynamical power corrections, formally arising from higher order terms in the twist expansion. Both $F_2^{pQCD+TMC}$ and $H$ were extracted from the data at large $x$. The shape of the initial NS PDFs was found to be well constrained at variance with the singlet and gluon distributions at low $Q^2$, whose shape is strongly correlated with the value of $\alpha_S$. NNLO corrections were not included. These would introduce further theoretical uncertainties. In fact, the question of whether they can “mimick” the contributions of higher twists, including the uncertainties due to the well known scale/scheme dependence of calculations, within the current precision of data is still a subject of intense investigations Def. Large $x$ resummation was performed directly in $x$ space by replacing the $Q^2$ scale with a $z$-dependent one, $W^2 = Q^2(1-z)/z$. It was found that over the range $0.45 \leq x \leq 0.85$, large $x$ resummation, and TMC improve the agreement with the data. We parametrized the remaining discrepancies through the Higher Twist (HT) coefficient $H(x, Q^2) = F_2^{pQCD+TMC}(x, Q^2)C_{HT}(x)$. In Fig. 1a we show $C_{HT}$, 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 $W^2$. The figure also shows the range of extractions previous to the current one Def. While the large $W^2$ data track a curve that is consistent with the $1/W^2$...
behavior expected from most models, the low \( W^2 \) data yield a much smaller value for \( C_{HT} \) and they show a bend-over of the slope vs. \( x \). 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 common wisdom developed since the pioneering analysis of \( \| \) or, in the language of \( \| \), we observe a violation of global duality. Similar results, expressed through a \( Q^2 \) dependent HT coefficient, were also obtained in \( \| \).

3 Large \( N_c \) Model for Initial Parton Evolution

We propose a simple dynamical model for the structure function in the low \( W^2 \) (\( W^2 \leq 4 \ \text{GeV}^2 \)) and low \( Q^2 \) (\( Q^2 < 10 \ \text{GeV}^2 \)) regime, where non-partonic configurations are expected to be dominant. The DIS cross section for \( ep \) scattering is proportional to the structure functions \( F_{1(2)}^p(x, Q^2) \) which in turn, measure combinations of the parton longitudinal momentum distributions, \( q_i(x, Q^2), i = u, d, s, \ldots, \) at the scale \( Q^2 \). 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 \( Q^2_o \) where pQCD is believed to be still applicable. \( Q^2_o \) serves as a boundary between the perturbative and non-perturbative domains, although its value is somewhat arbitrary (in current parametrizations \( Q^2_o \approx 0.4 - 10 \ \text{GeV}^2 \)). We refer to this situation as the “fixed initial scale” description, and we write explicitly the dependence of \( q_i(x, Q^2, Q^2_o) \) on \( Q^2_o \). A simple kinematical argument shows that \( Q^2_o \) is related to the invariant mass squared of the proton remnant after a parton is emitted, by: \( M_X^2 \approx Q^2_o/x \). At large \( x \) \( M_X^2 \approx Q^2_o \) (at low \( x \) this simple kinematical observation, and the factorization properties of the diffractive part of \( F_2 \), support the idea that the parton is emitted from a large mass object, identified with a soft pomeron \( \| \)). We, therefore, explore the possibility that partons are not emitted directly from the nucleon, but that, 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: \( \mu_{peak}^2 \approx Q^2_o \). As a result, the nucleon structure function is related to the quark distribution by a smearing of the initial \( Q^2_o \), namely

\[
F_2(x, Q^2) = x \sum \int_{\mu_i^2 > \Lambda^2}^W \frac{d\mu^2}{\mu^2} P(\mu^2)q_i(x, Q^2, \mu^2),
\]

where \( P(\mu^2) \) (\( P_{peak}(\mu^2) \approx P(Q^2_o) \)) is the clusters’ mass distribution, and the sum is extended to valence quarks only since we are describing the large \( x \) region. Eq.(2) 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.

Our model is derived within the framework of the large \( N_c \) approximation, in analogy to the cluster hadronization schemes implemented in the HERWIG Monte Carlo simulation \( \| \). In this scheme, hadronization proceeds as prescribed by the pQCD property of preconfinement of color \( \| \); 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 \( \| \), 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 colour: 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 transition hadrons \( \rightarrow \) quarks \( \rightarrow \) 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 the function \( P \) in Eq.(2) \( \| \).

As a preliminary study, we considered both the low and the very large \( W^2 \) limits of Eq.(2). At low \( W^2 \), \( F_2(W^2, Q^2) \approx P(Q^2) \), namely it is described by the behavior of the cluster distribution
Figure 1: (a) Higher Twist coefficient from Eq.(2); (b) $Q^2$ dependence at fixed $W^2 = 1.6$ GeV$^2$.

function. At very large $W^2$, $P_{\text{peak}}$ determines the value of the initial $Q_0^2$. In Fig.1(b) we present our result for $F_2$ at $W^2 = 1.6$ GeV$^2$, where the cluster distribution was obtained from HERWIG\cite{15} (triangles), whereas the red curve is an analytic calculation of the Sudakov-type behavior valid at large $Q^2$.

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