LEPTON SCATTERING AND QUARK-HADRON DUALITY STUDIES AT JLAB

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At high enough energies asymptotic freedom guarantuees the deep inelastic scattering cross sections to be calculated as nearly free electron-quark scattering. However, confinement guarantees that the experimentally observed final states particles are hadrons. Low-energy quark-hadron duality suggests that hadronic cross sections, when averaged over an appropriate energy range, nevertheless coincide with the naive leading-twist quark-gluon calculations. Deep inelastic inclusive scattering shows that scaling at modest Q^2 and ν already arises from very few resonance channels. This is reflected by the striking agreement ($< 10\%$) between data in the nucleon resonance region and the deep inelastic ($W^2 > 4$ GeV^2) region for $Q^2 > 0.5$ (GeV/c)^2, known as Bloom-Gilman duality. Electron-hadron scattering allows for further investigation of quark-hadron duality by virtue of its ability to select resonances, by tagging with either spin or flavor.

1 Introduction

In QCD, the quark and gluon degrees of freedom are confined, and therefore the transition from quark-gluon to hadron degrees of freedom should in principle just be a matter of convenience. This is referred to as quark-hadron duality. At high energies, where the interactions between quarks and gluons become weak and quarks can be considered asymptotically free, an efficient description of nuclear and particle physics is possible in terms of quarks. At low energies, where the effects of confinement make QCD highly nonperturbative, it is more convenient to work in terms of the physical mesons and baryons. Quark-hadron duality is therefore an expression of the relationship between confinement and asymptotic freedom, and is intimately related to the nature of the transition from non-perturbative to perturbative QCD.

A global kind of quark-hadron duality is well established: low-energy resonance production can be shown to be related to the high-energy behavior of hadron-hadron scattering [1]; the familiar ratio of $e^+e^- \to$ hadrons over $e^+e^- \to$ muons uses duality to relate the hadron production to the sum of the squared charges of the quarks [2]; rigorous calculations exist in the infinite number of colors limit in leptonic heavy-quark decays [3].

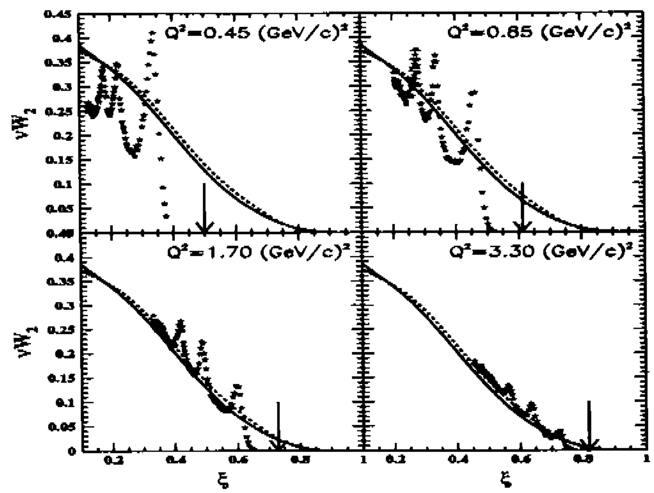

Figure 1. Sample hydrogen νW_2 structure function spectra obtained at $Q^2 = 0.45, 0.85, 1.70$, and 3.30 (GeV/c)^2 and plotted as a function of the Nachtmann scaling variable ξ ($= 2x/(1+\sqrt{1+4M^2x^2/Q^2})$). Arrows indicate elastic kinematics. The solid (dashed) line represents the NMC fit of deep inelastic structure function data at $Q^2 = 10$ (GeV/c)^2 ($Q^2 = 5$ (GeV/c)^2).

2 Bloom-Gilman Duality

One of the more intriguing examples, initially observed three decades ago, is in inclusive electron-nucleon scattering. In studying inelastic electron scattering in the resonance region and the onset of scaling behavior, Bloom and Gilman [4] found that the inclusive F_2 structure function at low W generally follows a global scaling curve which describes high W data, to which the resonance structure function averages. Recently, high precision data on the F_2 structure function from Hall C at Jefferson Lab [5] have quantified these earlier observations, and demonstrated that duality works to better than 10% for both the total nucleon resonance region and each of the separate low-lying nucleon resonance regions, for $Q^2 \geq 0.5$ (GeV/c)^2. This is illustrated in Fig. 1, where the nucleon resonance data for various Q^2 are compared to a parameterizations of deep inelastic scattering data at constant $Q^2 = 5$ and 10 (GeV/c)^2 [6]. Such behavior shows that the distinction between the nucleon resonance region and the deep inelastic region is spurious; if properly averaged, the nucleon resonance regions closely mimic the deep inelastic region.

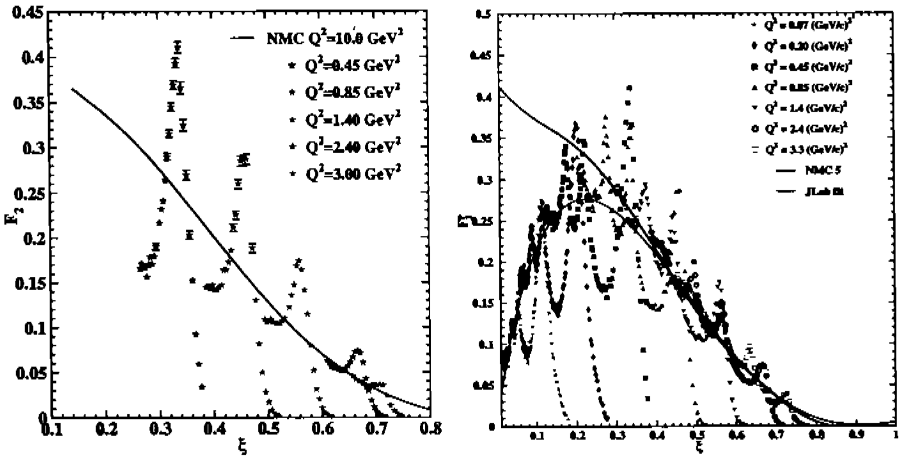

Figure 2. (left) Sample hydrogen νW_2 structure function spectra obtained at various Q^2, for the $N-\Delta$ transition region, defined as $1.2 < W^2 < 1.9$ GeV^2, only, and plotted as a function of the Nachtmann scaling variable ξ. The solid line represents the NMC fit of deep inelastic structure function data at $Q^2 = 10$ (GeV/c)^2. (right) Sample hydrogen νW_2 structure function spectra obtained at various Q^2 and plotted as a function of the Nachtmann scaling variable ξ. The data at $Q^2 = 0.07$ and 0.20 (GeV/c)^2 are from older SLAC experiments. The solid line represents the NMC fit of deep inelastic structure function data at $Q^2 = 5$ (GeV/c)^2. The light solid line represents a fit of the various nucleon resonance spectra.

To emphasize that this, at least for the F_2 structure function, also works in a localized region, we show in Fig. 2 (left) the region of $1.2 < W^2 <1.9$ (GeV/c)^2, the "N-Δ" region, for various values of Q^2, in comparison to the NMC parameterization at $Q^2 = 10$ (GeV/c)^2. Recently, Close and Isgur [7] argued that in the quark model one expects duality in the F_2 structure function to work at low Q^2 (≈ 0.5 (GeV/c)^2), and to start at $Q^2 \approx 0$ for magnetic contributions only. It is also argued that for neutron targets, in contrast, duality only works if one integrates over the full nucleon resonance region, up to $W^2 \approx 3.3$ (GeV/c)^2.

Experiments investigating such behavior have started. In Hall A a $^3\vec{\mathrm{He}}$(e,e$'$) experiment is being analyzed [8], whereas in Hall B the results of a $^1\vec{\mathrm{H}}$(e,e$'$) experiment are under investigation [9]. Results are anticipated for Q^2 up to 1-2 (GeV/c)^2. Initial results of the Hall A experiment [10] indicate impressive agreement between g_1 data in the nucleon resonance region and deep inelastic region at $Q^2 \approx 1$ (GeV/c)^2 (for the nucleon resonance region), with the exception of the region of the $N - \Delta$ transition that, at this Q^2, still renders negative values as opposed to the positive values of the deep inelastic region. A dedicated experiment to investigate this issue up to $Q^2 = 5$ $(\text{GeV/c})^2$ has recently been approved [11]. In addition, duality results on the longitudinal structure function F_L are forthcoming from a Hall C experiment [12]. There are predictions [13] and some scant experimental evidence [14] that F_L exhibits duality.

The Hall C experiments additionally showed that the nucleon resonance region data *at all* Q^2 oscillate around a single smooth curve, as shown in Fig. 2 (right). This curve coincides with the deep inelastic scaling curve at $Q^2 > 0.5$ $(\text{GeV/c})^2$, consistent with Bloom-Gilman duality, and resembles neutrino/anti-neutrino xF_3 data or a valence-like sensitivity only [15] below $Q^2 \approx 0.5$ $(\text{GeV/c})^2$. This is perhaps not too surprising in the quark model where the nucleon resonances act as valence quark transitions, while at low Q^2 not many sea quarks can be "seen" yet. However, it is surprising that all the strongly-interacting nucleon resonances shuffle their strength around to closely follow a single scaling curve. Do we see duality down to the lowest values of Q^2?

A simple quantum-mechanical model assuming two confined, relativistic, valence scalar quarks, with one of the quarks infinitely heavy, is able to reproduce all qualitative features of Bloom-Gilman duality [16] described above. Such modeling is instrumental to understand the physical mechanism that causes the large cancellations, on average, of the higher-twist processes responsible for the nucleon resonance transitions, in inclusive electron-proton scattering. Previous work on understanding Bloom-Gilman duality was done in terms of the operator-product expansion [17]. This is the subject of the next Section.

3 Moments of the F_2 Structure Function at Low Q^2

An analysis of the resonance region at smaller W^2 and Q^2 in terms of QCD was first presented by DeRujula, Georgi, and Politzer [17]. The integrals of the structure function, performed by Bloom and Gilman [4] over the energy transfer ν, were translated into integrals over the variable x (or Nachtmann $\xi = 2x/(1+\sqrt{1+4M^2x^2/Q^2})$, in order to account for finite target mass effects). Bloom-Gilman duality was translated into a correspondence between the n =2 moment of the F_2 structure function in the low Q^2 region, characterized by resonances, and in the high Q^2 scaling region, respectively. The fall of the resonances along a smooth scaling curve with increasing Q^2 was to be attributed [17] to the fact that there exist only small changes in the low n moments of the F_2 structure function due to power corrections in addition to the predicted perturbative ones. The appearence of power corrections is interpreted as a signal of deviations of the inclusive cross section from perturbative predictions, which one can envisage as due to the increasing importance of interactions between the quark struck in the electron-nucleon hard scattering process and the other quarks in the nucleon. Such effects are inversely proportional to Q^2, and can therefore be large at small Q^2. If they are not, averages of the F_2 structure function over a sufficient range in x at moderate Q^2 are approximately the same as at high Q^2. Recently, similar arguments were presented for the case of polarized lepton-nucleon scattering [18].

We constructed the experimental moments of the structure function, F_2, for the Q^2 range up to 5 $(\mathrm{GeV/c})^2$ [19]. The Cornwall-Norton moments are defined as

$$M_n(Q^2) = \int_0^{x_{thr}} dx x^{n-2} F_2(x, Q^2), \tag{1}$$

and the Nachtmann moments as

$$M_n(Q^2) = \int_0^{x_{thr}} dx \frac{\xi^{n+1}}{x^3} \left[\frac{3 + 3(n+1)r + n(n+2)r^2}{(n+2)(n+3)}\right] \nu W_2(x, Q^2). \tag{2}$$

Here, $r = (1 + 4M^2x^2/Q^2)^{1/2}$, and x_{thr} is Bjorken x for pion threshold. We add to these integrals the elastic contribution, at $x = 1$.

We show the values for the second, fourth, sixth, and eigth Cornwall-Norton (top) and Nachtmann (bottom) moments of the proton, extracted from the world's data, including deep inelastic, nucleon resonance, and elastic data, as described above, in Fig. 3. The elastic contribution dominates the moments at the lowest Q^2. Note that the Cornwall-Norton moments will become unity, i.e. the proton charge squared, at $Q^2 = 0$, whereas the Nachtmann moments will vanish at $Q^2 = 0$.

We find that the moments of F_2 show a smooth transition from the deep inelastic limit down to $Q^2 \approx 0$ $(\mathrm{GeV/c})^2$, and that the nucleon resonances tend to oscillate around one smooth curve, supporting the findings [20,21] that higher-twist effects are small if one looks at the low-Q^2 behavior of F_2 for $Q^2 \simeq 1$ $(\mathrm{GeV/c})^2$. The dynamical process of local duality dictates minimal Q^2 dependence of F_2 at small Q^2; in terms of pQCD this can be explained if the higher-twist effects are reduced *on average* in the nucleon resonance region. Nonetheless, higher-twist effects must be responsible for the nucleon resonances themselves.

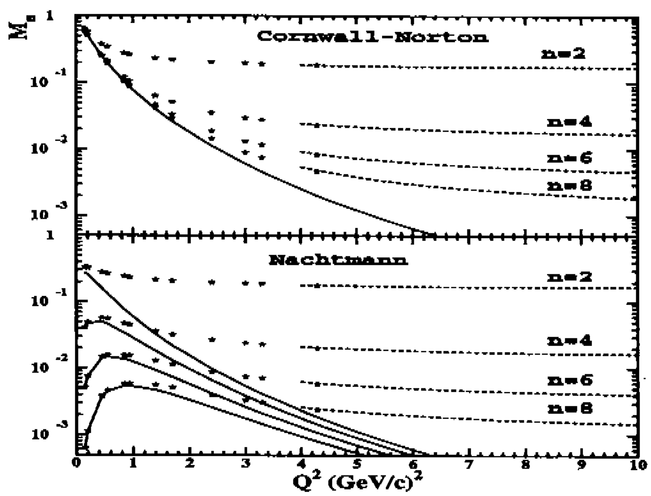

Figure 3. Cornwall-Norton moments (top) and Nachtmann moments (bottom) extracted from the world's electron-proton scattering data, for $n = 2$, 4, 6, and 8. The solid lines indicate the elastic contribution. At low Q^2 (≤ 4.3 (GeV/c)^2) the moments (stars) are directly constructed from the world's electron-proton F_2 database. At larger Q^2, the moments have been extracted from appropriate fits to the world's data on inclusive scattering to both the nucleon resonance and deep inelastic regions (dashed lines).

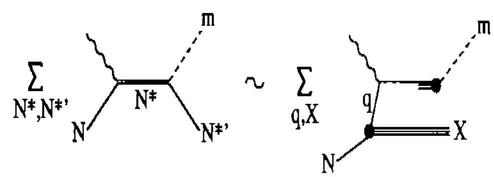

Figure 4. Duality between descriptions of semi-inclusive meson production in terms of quark (right) and nucleon resonance (left) degrees of freedom.

4 Fragmentation Duality

A largely unexplored domain with potentially broad applications is the production of mesons (M) in semi-inclusive electron scattering, $eN \to e'MX$ [22]. At high energy the scattering and production mechanisms factorize, with the cross section at leading order in QCD given by a simple product of the structure function, $\sim \sum_q e_q^2\, q(x)$, and a quark $\to$ meson fragmentation function, $D_{q\to M}$, for a given elasticity $z = E_M/\nu$, as in Fig. 4.

In terms of hadronic variables, the same process can be described through the excitation of nucleon resonances, N^*, where the $\gamma^* N \to N^*$ transition form factor, $F_{\gamma^* N \to N^*}$, depends on the mass of the virtual photon and the excited nucleon, $W = M_{N^*}$, and a function $\mathcal{D}_{N^* \to N^{*'} M}$ describing their subsequent decays into mesons and lower lying resonances, $N^{*'}$, with W' the invariant mass of the final state $N^{*'}$:

$$\sum_{N^*, N^{*'}} F_{\gamma^* N \to N^*}(Q^2, W^2)\ \mathcal{D}_{N^* \to N^{*'} M}(W^2, W'^2)\ \sim \sum_q e_q^2\, q(x)\ D_{q \to M}(z)\ .$$

The hadronic description is rather elaborate, as the production of a fast outgoing meson in the current fragmentation region at high energy requires non-trivial cancellations of the angular distributions from various decay channels [16]. Such a cancellation may not be unlikely if one realizes that duality has also been observed in hadronic τ decays [23].

For a kinematics region that mimics single-quark scattering, in analogy with the inclusive scattering case ($W^2 > 4$ GeV^2 and $Q^2 > 1$ (GeV/c)^2), the question here is whether the remaining part of the process can be described in terms of a struck quark hadronizing into the detected meson. Similar as in the inclusive case where the nucleon resonances average at low energies to a scaling curve, here the nucleon resonances left in the final state after removing a fast meson may average to a fragmentation function. Such a signature of "truncated" or "tagged" duality has never been investigated yet, and could be related to the open question to what extent factorization applies at lower than asymptotic energy. Recently, it has been suggested that one may expect factorization and approximate duality to work at $Q^2 < 3$ (GeV/c)^2 and relatively low W^2 [7]. In addition, hints of a scaling behavior in older Cornell data can be observed [24]. Lastly, we show in Fig. 5 a comparison between $\pi^\pm$ electroproduction data at low energy (beam energy of 5.5 GeV, $W^2 = 5.3$ GeV^2, $W'^2 < 4$ GeV^2) and a next-to-leading order fragmentation function fit to high energy data. Experiment E00-108 has recently been approved at JLab to investigate fragmentation duality and the onset of factorization in more detail [25].

5 Conclusion

If one understands duality it may be used as a tool. It can give guidance to cuts typically used to select "hard scattering" regions. E.g., it shows that the $W^2 > 4$ cut to select deep inelastic events is spurious. One can access the very large x region [26], where, without escape, one encounters the nucleon resonance region. This could provide us with data for parton distribution functions in

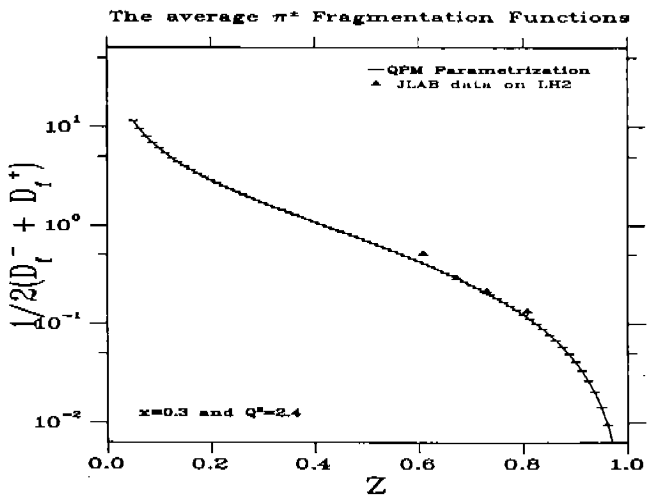

Figure 5. A comparison between $\pi^{\pm}$ electroproduction data at low energy and a next-to-leading order (NLO) fragmentation function fit to high energy data (solid line). The curve corresponds to the average of positive and negative fragmentation functions, which is compared to the average of π^{+} and π^{-} data points. The data shown here were limited to pion momenta above 2.4 GeV/c in order to minimize $\pi^{\pm}N$ interactions in the final state.

the strict valence region, and allow investigations of the Q^2 evolution of large-x parton distribution functions. Initial studies utilizing the fermi broadening in nuclear targets as "averaging tool" are underway [27,28].

Additionally, it is worth stressing that confirmation of factorization and truncated duality would open the way to an enormously rich semi-inclusive program, allowing unprecedented spin and flavor decompositions of quark distributions.

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