Duality in Meson Electroproduction

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Understanding the structure and interaction of hadrons in terms of the quark and gluon degrees of freedom of QCD is one of the great unsolved problems of the Standard Model of nuclear and particle physics. In QCD, the quark and gluon degrees of freedom are confined, and thus, if one accepts QCD as the correct theory of the strong interactions, the transition from quark-gluon to hadron degrees of freedom should, in principle, just amount to a change of basis. In practice, however, understanding how QCD makes the transition from a perturbatively calculable system in terms of quarks and gluons in the region of asymptotic freedom, to an effective description in terms of hadrons in the region of confinement, is still largely a mystery.

In high-energy inclusive electron scattering, the initial and final states are strongly-interacting hadrons, but the (hard) scattering process is perturbatively calculable. Here, a phenomenological quark distribution function, or single-quark probability density, is introduced to parameterize the non-perturbative long-distance dynamics. Similarly, in electron-positron annihilation or high-energy electron scattering with the detection of an additional hadron in the final state, phenomenological current (target) fragmentation functions are introduced to describe the process how a struck (spectator) quark evolves into a hadron. The latter process also appears in an astrophysical context, as part of the transition from a deconfined state of free quarks and gluons in the Big Bang into stable protons, providing the seeds for nuclear synthesis. At present, our understanding of this "hadronization" process is sporadic at best.

Initial investigations of the hadronization process were by electron-positron annihilation and deep inelastic scattering. In the latter case, high energies were used to separate the hadrons originating from the struck quark from those hadrons originating from the spectator quarks, by means of a large interval in rapidity. In Fig. 1 a plot of rapidity versus fragmentation energy fraction (or elasticity) z is shown for $W = 2.5$ GeV [1]. Experience from CERN results [2] suggests that a rapidity gap of $\Delta\eta \approx 2$ is needed to kinematically separate both regions, where the rapidity is defined as $\eta = 0.5$ $\ln(P_h^-/P_h^+)$ [1]. Even at low W, it is possible to reach kinematical separation in the case of charged pions, **provided** one selects large z values.

Given such a rapidity gap, the cross section may, just as in the asymptotic energy limit, under certain conditions still factorize into a structure function,

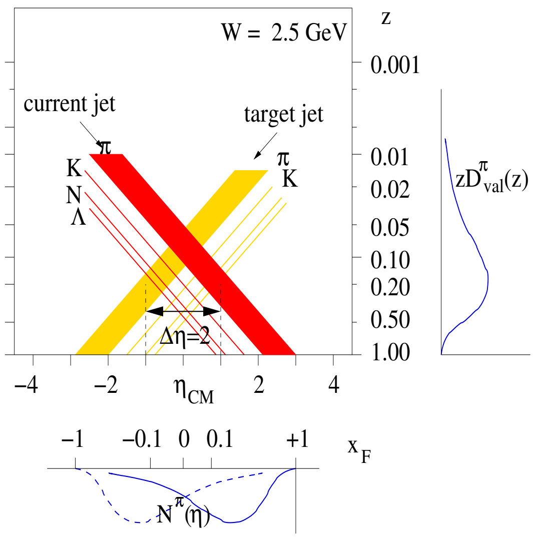

Figure 1: Relation between elasticity z and center-of-mass rapidity in semi-inclusive fragmentation for an invariant mass W of 2.5 GeV.

giving the probability to find a quark in the nucleon, and a quark $\longrightarrow$ meson fragmentation function, or the probability that the quark hadronizes into the detected meson M, as in Fig. 2(right). Such pre-asymptotic factorization conditions may be related to the concept of quark-hadron duality [3].

Quark-hadron duality is an expression of the intrinsic 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 [4]; the familiar ratio of $e^+e^- \longrightarrow$ hadrons over $e^+e^- \longrightarrow$ muons uses duality to relate the hadron production to the sum of the squared charges of the quarks [5]; rigorous calculations exist in the infinite number of colors limit in leptonic heavy-quark decays [6].

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 [7] 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

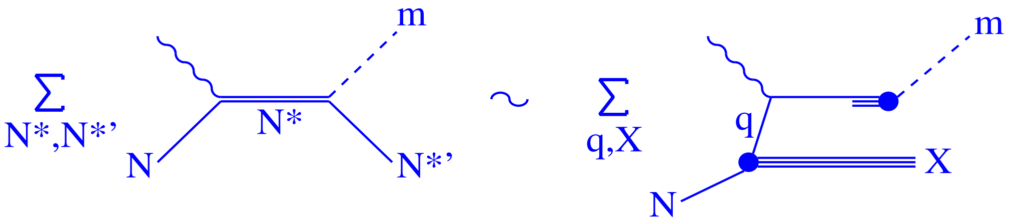

Figure 2: Duality between descriptions of semi-inclusive meson production in terms of quark (right) and nucleon resonance (left) degrees of freedom.

the F_2 structure function from Jefferson Lab [8] 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.

While duality between inclusive electron-hadron scattering in the resonance and deep inelastic regimes (Bloom-Gilman or quark-baryon duality) is well established, the existence of a similar duality in meson electroproduction $eN \to e'MX$ [9] has not yet been tested. In terms of hadronic variables, the process of Fig. 2(right) can be described through the excitation of nucleon resonances, N^*, and their subsequent decays into mesons and lower lying resonances, $N^{*'}$, as indicated in Fig. 2(left). This 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 [10]. Such a cancellation may not be unlikely if one realizes that duality has also been observed in hadronic τ decays [11].

Heuristically, the duality between the quark and hadron descriptions of semi-inclusive meson production can be written as (see Fig. 2):

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

where $D_{q \to M}$ is the quark $\to$ meson fragmentation function for a given $z = E_M/\nu$, and $F_{\gamma^* N \to N^*}$ is the $\gamma^* N \to N^*$ transition form factor, which depends on the mass of the virtual photon and the excited nucleon, $W = M_{N^*}$. $\mathcal{D}_{N^* \to N^{*'} M}$ is a function representing the decay of the resonance $N^* \to N^{*'} M$, where W' is the invariant mass of the final state $N^{*'}$. If the outgoing meson has small mass, is collinear with the virtual photon, and $Q^2/\nu^2 \ll 1$, then $W'^2 = M^2 + Q^2(\frac{1}{x} - 1)(1 - z)$ [9]. With respect to the inclusive case, the invariant mass of the final state now also depends on $(1 - z)$.

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^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 not yet been investigated.

Recently, it has been suggested [3] that one may expect factorization and approximate duality to work at $Q^2 < 3$ GeV^2 and relatively low W', well within the range of the JLab at 12 GeV kinematics. Hints of a scaling behavior in Cornell data at low W' have been reported [12]. Presumably, one needs, for a given W^2, large enough z to separate the current and target fragmentation regions in addition to either a large enough value of W' to be unambiguously beyond the resonance region, or a duality-prescribed averaging procedure over a range in W'.

The extent to which factorization applies at lower energy is an open question, and the signatures of duality in the resonance region of semi-inclusive scattering need to be investigated. It is imperative that both of these questions be answered experimentally, and the HMS-SHMS setup at 12 GeV beam energy is optimally suited for this. This is illustrated in Fig. 3, where the shaded area shows the kinematics region for deep exclusive reactions, arbitrarily cut off at a maximum $Q^2 \sim 5$ (GeV/c)^2. Here, it is assumed that HMS, with a minimum angle of 10.5°, will detect the scattered electrons, and SHMS, with a minimum angle of 5.5° will detect the electroproduced mesons. For a fixed Q^2, the large kinematic acceptance in ν allows for a large variation in terms of elasticity z. E.g., at $Q^2 = 2.5$ (GeV/c)^2 the HMS-SHMS combination allows for precise measurements to verify the validity of factorization (or duality) for $0.2 < x < 0.7$ and $0.3 < z < 0.8$, within one week of beam time.

It is worth stressing here 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. It possibly would also allow a similar spin and flavor decomposition of the fragmentation process, enabling us to understand the mechanism by which

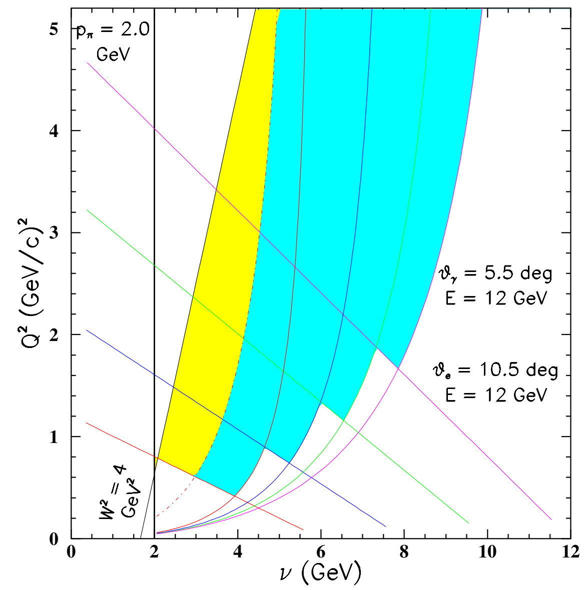

Figure 3: Kinematics plot for meson electroproduction experiments showing energy loss ν versus momentum transfer squared Q^2, assuming the HMS-SHMS magnetic spectrometer combination. Kinematics of interest are in the deep inelastic region, i.e. $W^2 > 4$ GeV^2 and accessible with HMS measuring the scattered electron (angle $> 10.5°$) and SHMS measuring the produced meson (angle $> 5.5°$). Beam energies of 6, 8, 10, and 12 GeV are assumed. The light-shaded area is what can be accessed at a 6 GeV beam energy with the present HMS-SOS magnetic spectrometer combination. The full shaded area is what can be accessed with the HMS-SHMS combination at a 12 GeV beam energy.

the quarks struck in the electron scattering process neutralize their color, to end up as the detected hadrons.

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