Quark-Hadron Duality: The Resonance-Scaling Transition (very preliminary version)

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I. INTRODUCTION AND THEORETICAL OVERVIEW

Understanding the structure and interaction of hadrons in terms of the quark and gluon degrees of freedom of QCD is the greatest unsolved problem of the Standard Model of nuclear and particle physics. While at present we cannot describe the physics of hadrons directly from QCD, we know that in principle it should just be a matter of convenience in choosing to describe a process in terms of quark-gluon or hadronic degrees of freedom. This fact is referred to as *quark-hadron duality*, and means that one can use either set of complete basis states to describe physical phenomena. At high energies, where the interactions between quarks and gluons become weak and quarks can be considered asymptotically free, an efficient description of phenomena would be afforded in terms of quarks; at low energies, where the effects of confinement make strongly-coupled QCD highly non-perturbative, it would be more efficient to work in terms of collective degrees of freedom, the physical mesons and baryons.

The duality between quark and hadron descriptions reflects the relationship between confinement and asymptotic freedom, and is intimately related to the nature of the transition from non-perturbative to perturbative QCD. A better understanding of this transition was the main reason for building CEBAF at Jefferson Lab.

Although the duality between quark and hadron descriptions is formally exact in principle, how this reveals itself specifically in different physical processes and under different kinematical conditions is the key to understanding the consequences of QCD for hadronic structure. The phenomenon of duality is in fact quite general in nature and can be studied in a variety of processes, such as $e^+e^- \to$ hadrons, or semi-leptonic decays of heavy quarks [1]. For the latter one does not even need to invoke an averaging process — the results in terms of quark and hadronic variables are identical in the limit of infinitely heavy quarks [2]. One of the more intriguing examples, initially observed some 30 years ago, is in inclusive inelastic electron–nucleon scattering.

In studying deep-inelastic scattering in the resonance region and the onset of scaling behavior, Bloom and Gilman [3] 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. Furthermore, the equivalence of the averaged resonance and scaling structure functions appears to hold for each resonance, over restricted regions in W, so that the resonance—scaling duality also exists locally. More recently, high precision data on the F_2 structure function from Jefferson Lab [4] have confirmed the earlier observations, demonstrating that duality works remarkably well for each of the low-lying resonances, including the elastic, to rather low values of Q^2 (~ 0.5 GeV^2).

Bloom-Gilman duality can be thought of as a 'truncated' version of duality, in the sense that one can describe the physical process with a limited set of quark states, as in perturbative QCD calculations, or in terms of a few resonances which average to the quark result. Understanding duality therefore gives insight into the relationship between inclusive (deep-inelastic scattering) and exclusive (resonance production) processes. At present, however, we do not adequately understand the specific origin of Bloom-Gilman duality in QCD.

Bloom-Gilman duality can be formulated in the language of an operator product expansion (OPE) of QCD moments of structure functions, in which contributions are organized according to powers of $1/Q^2$ [5]. The leading terms are associated with free quark scattering, and are responsible for the scaling of the structure function. The $1/Q^2$ terms involve interactions between quarks and gluons and hence reflect elements of confinement dynamics. The weak Q^2 dependence of the low moments of F_2 can be interpreted within the OPE as indicating that the non-leading, $1/Q^2$-suppressed, interaction terms do not play a major role even at low Q^2 (≈ 1 GeV^2).

On the other hand, while the OPE formalism allows us to organize hadronic observables in terms of an asymptotic expansion, it does not tell us *a priori* why certain matrix elements are small or cancel. This can only be addressed via numerical solutions of QCD, or from experiment. Since the details of quark–hadron duality are process dependent, there is no reason to expect the accuracy to which it holds and the kinematic regime where it applies to be similar for different observables. In fact, there could be qualitative differences between the workings of duality in spin-dependent structure functions and spin-averaged ones, or for different hadrons — protons compared with neutrons, for instance. At present there are data on the F_2 structure function of the proton and deuteron [4], but essentially no information at all exists on the spin-dependent g_1 and g_2 structure functions (which correspond to differences of cross sections), nor on the longitudinal to transverse structure function ratio, R. It is vital for our understanding of duality and its practical exploitation that the spin and flavor dependence of duality be established empirically.

Since it is a perturbative expansion, the OPE must at some stage, when Q^2 becomes too small, break down and cease to be a meaningful framework. On the other hand, Bloom-Gilman duality has been observed [4] for Q^2 down to ≈ 0.5 GeV^2, where the validity of the OPE already becomes questionable. It is of crucial importance, therefore, to understand the limitations of the use of the asymptotic expansion and assess its validity at low energy for various processes. Duality can thus be utilized to put strong constraints on low-energy models of QCD.

After establishing the validity of Bloom-Gilman duality, one can apply it to explore a wide range of phenomena beyond the resonance region. An important consequence of duality is that the strict distinction between the resonance and deep-inelastic regions is quite artificial — both regions are intimately related, and properly averaged resonance data can help us understand the deep-inelastic region. For example, at $Q^2 = 1$ GeV^2 around 70% of the total cross section comes from the resonance region, $W < W_{\rm res} = 2$ GeV. However, because of duality, the resonances and the deep-inelastic continuum conspire to produce only about a 10% correction to the lowest moment of the scaling F_2 structure function at the same Q^2 [6]. Resonances are therefore an integral part of the deep-inelastic scaling structure functions.

It is standard procedure in global analyses [7,8] of deep-inelastic scattering to omit from the data base the entire resonance region below $W = 2$ GeV. The vast quantity of data which this excludes would not only significantly improve the statistics, but also decrease uncertainties which arise from extrapolations into the regions excluded by the W cuts. This is of practical relevance especially for the large-x region, where deep-inelastic data are scarce. This is especially pertinent for structure functions at large x, where for finite Q^2 one is always limited by the kinematics to $x < x_{\rm res} = Q^2/(W_{\rm res}^2 - M_N^2 + Q^2)$. Extending to very large x at a finite Q^2 one always encounters the resonance region. A revolutionary application of duality, if one understands the workings of the resonance—deep-inelastic interplay, would be to allow access to the region of very high x, which has not been possible in any other experiment.

The region of $x \approx 1$ is an important testing ground for mechanisms of spin-flavor symmetry breaking in valence quark distributions of the nucleon [9]. In addition, with nuclear targets it would permit measurement of the nuclear medium modification of the nucleon structure function (nuclear EMC effect) [10] at large x, where the deviation from unity of the ratio of nuclear to nucleon structure functions is largest, and sensitivity to different nuclear structure models greatest.

Another largely unexplored domain with potentially broad applications is the production of mesons (M) in semi-inclusive electron scattering, $eN \to e'MX$. At high energy the scattering and production mechanisms factorize: the cross section at leading order in QCD becomes a simple product of the structure function, which gives the probability to find a quark in the nucleon, and a quark $\rightarrow$ meson fragmentation function, or the probability that the quark hadronizes into the meson M. The usefulness of semi-inclusive production lies in its ability to identify individual quark species in the nucleon by tagging specific mesons in the final state, so that both the flavor and spin of quarks and antiquarks can be uniquely determined.

To what extent factorization applies at lower energy is an open question, and the signatures of duality in the resonance region of semi-inclusive scattering are still subject to investigation. It is imperative therefore that answers to both of these questions be found experimentally. 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 decomposition of quark distributions.

CEBAF at 12 GeV would allow for a unique opportunity to shed light on all the issues connected with Bloom-Gilman duality. Several examples are discussed in greater detail in the following.

II. RECENT RESULTS

Substantial progress has been made both theoretically in understanding QCD in the past twenty years and experimentally in determining the scaling behavior of the F_2 structure function. Combining the latter with new precision resonance data from Jefferson Lab [4], it has been possible to revisit quark-hadron duality with a more quantitative approach, addressing the recent theoretical interest in the topic (see, for example, [6,11–16]).

Sample $\nu W_2 = F_2$ spectra extracted from the measured differential cross sections from hydrogen are plotted in Fig. xxx as a function of the Nachtmann scaling variable $\xi = 2x/(1 + (1 + 4M^2x^2/Q^2)^{1/2})$. It has been shown that ξ is the correct variable to use in studying QCD scaling violations in the nucleon [17,5]. The statistical errors are smaller than the data symbols; there is an additional systematic uncertainty of 3%. The solid curve, shown solely above $\xi = 0.3$, is a parameterization of deep inelastic proton structure function data at $Q^2 = 5$ GeV^2 [18]. Notice that the resonance spectra at different Q^2 appear at different ξ on the deep inelastic scaling curve, but that this curve generally resembles an average of the data at the disparate kinematics. This echoes the original Bloom and Gilman observation of duality.

If one assumes duality, i.e. that the resonances oscillate around some smooth curve, then it is also possible to obtain that curve from averaging the resonance region data. Such a curve has been determined and it was surprisingly found that the resonances oscillate around it to better than 10%, even down to Q^2 values as low as 0.5 (GeV/c)^2 [4]. Fig. xxx reflects this, as the resonances still seem to oscillate around each other down to very low values of (Q^2, ξ). Below $Q^2 \approx 0.5$ (GeV/c)^2, sufficient resonance scans are not available yet to quantify this. In summation, the resonances oscillate around a scaling curve in agreement with deep inelastic scattering at higher (Q^2, ξ), but seem to similarly average together or oscillate around a smooth scaling curve even at the lower (Q^2, ξ).

When viewed over the entire range in ξ, the duality-averaged curve yields a clearly valence-like shape. It was found that the duality-averaged curve is in qualitative agreement with neutrino / anti-neutrino xF_3 data, indicating a unique valence-like sensitivity [4].

FIGURES

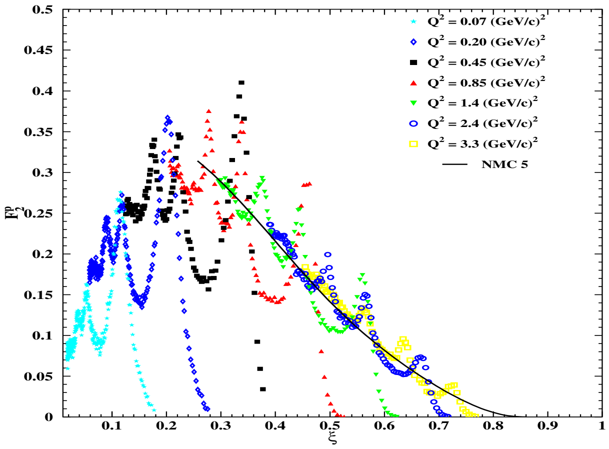

FIG. 1. Recent data from Jefferson Lab obtained at the various Q^2 values indicated, and plotted as a function of the Nachtmann scaling variable ξ. The NMC global fit to deep inelastic scattering data at $Q^2 = 5$ (GeV/c)^2 is shown to average to the resonance data, a manifestation of Bloom-Gilman duality.

In Fig. xxx we display a sample of the world's low Q^2 structure function F_2 data, along with the GRV parameterization from deep inelastic scattering data [19], as a function of the Bjorken scaling variable x. At values of $Q^2 \geq 1$ (GeV/c)^2, the GRV parameterizations are an excellent average of the resonance data, a manifestation of the original Bloom and Gilman observation. Thus, the Q^2-evolution seems rather well understood for $Q^2 \geq 1$ (GeV/c)^2, and the nucleon resonances, when averaged, are indistinguishable from the $W^2 > 4$ deep inelastic region. The dashed curve in the bottom two panels ($Q^2 = 0.5, 0.2$ (GeV/c)^2) is a copy of the GRV parameterization at $Q^2 = 1.0$ (GeV/c)^2. It seems that for this region $Q^2 <$ 1 (GeV/c)^2, the resonances approach the scaling region of $Q^2 \geq 1$ (GeV/c)^2, i.e. there is only a very shallow Q^2 dependence in this large x regime. Furthermore, as shown in Fig. xxx, the nucleon resonances seem to average to the scaling region at low Q^2, in that they visibly still seem to oscillate around each other. In fact, the Q^2-dependence of the various resonance regions seems almost entirely given by their being forced to oscillate around a smooth duality-averaged curve.

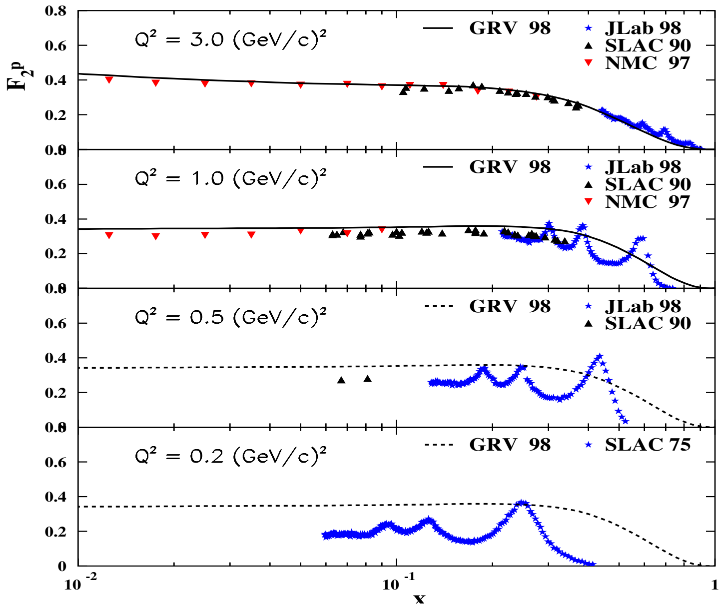

FIG. 2. Sample global data sets at low Q^2 plotted in comparison to the GRV parameterization of deep inelastic scattering data.

The commonly-accepted, QCD-based explanation of duality [5] relates the moments of the structure functions at high Q^2, where the deep inelastic regime provides the dominant contribution, to the low Q^2 regime, where the resonance region provides the dominant contribution. The Q^2-dependence of the moments relating the two regions, then, reflects both perturbative evolution (single quark scattering) and Q^{-2}-type higher twist effects (interactions between the struck quark and the other quarks in the nucleon). The above results, i.e. that duality seems to be holding and the resonances average to the perturbative scaling curve, indicate that higher twist contributions to the F_2 moments are small or cancelling on average, even in the low Q^2 regime where they should be maximized due to the Q^{-2} behavior. Higher twists are viewed in this light as deviations from duality. The Q^2 dependence of the (Cornwall-Norton) moments of the structure function is given by

$$M_n(Q^2) = \int x^{n-2} F(x, Q^2) dx. \tag{1}$$

It is clear from this equation that, for higher order moments (higher values of n), the large x resonance region becomes increasingly important. Also, as stated previously, higher twist effects are expected to be maximized at lower values of Q^2. Jefferson Lab is uniquely suited to study this large x, low to moderate Q^2, regime.

The available resonance data from Jefferson Lab have been used in conjunction with the world's data for the F_2 ($= \nu W_2$) structure function and for elastic electron-proton scattering to construct the Cornwall-Norton moments at low Q^2. The total uncertainty in the constructed moments is estimated to be less than 5%. The values for the second, fourth, sixth, and eighth Cornwall-Norton moments of the proton are shown in in Fig. xxx. The solid curve represents the elastic contribution to the moment.

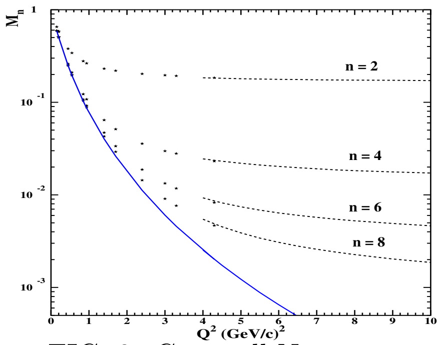

FIG. 3. Cornwall-Norton moments extracted from the world's electron-proton scattering data, for n = 2, 4, 6, and 8. The solid curves indicate the elastic contribution. At low Q^2 ($\leq$ 4.3 (GeV/c)^2), the moments (stars) are directly constructed from the world's electron-proton F_2 database. At larger 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 [20].

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. At higher Q^2, the moments are nearly constant, indicating that the moderate Q^2 regime where the resonances are dominant is nearly equivalent to the higher Q^2 regime - again a manifestation of the early onset of parton-hadron duality.

Although the dynamical origin of local duality is still not understood, it seems intricately intertwined with the behavior between the $Q^2 \rightarrow 0$ point, where only elastic scattering contributes to the moments, and $Q^2 > 5$ (GeV/c)^2, where deep inelastic scattering already dominates the lower moments. In the region $0.2 < Q^2 < 5$ (GeV/c)^2 the nucleon resonances contribute to a substantial part of the moments, and, in their average, seem indistinguishable from deep inelastic scattering at $Q^2 > 1$ (GeV/c)^2, consistent with the findings of Bloom and Gilman and as quantitatively shown in Ref. [4] for the second moment. In the very low Q^2 transition region, $Q^2 < 1$ (GeV/c)^2, the contribution of the coherent elastic peak to the second moment dies out, whereas the nucleon resonances already show the onset of their duality behavior, in that they tend to oscillate, already at $Q^2 \approx 0.2$ (GeV/c)^2, around a smooth curve [4]. Furthermore, the nucleon resonances shuffle their strength around such that, at $Q^2 \approx 1$ (GeV/c)^2, they have reached the same behavior as a function of x as one would expect from deep inelastic data.

Thus, the world's data on F_2, down to $Q^2 \simeq 1$ (GeV/c)^2, are reasonably well described by models obtained by fits to deep inelastic scattering. This **includes** the nucleon resonance data, which average to a similar scaling curve, due to local duality. Local duality seems to prescribe the transition from the elastic contribution only, at $Q^2 = 0$, through the excitations of the nucleon resonances, into the logarithmic scaling region.

III. DUALITY IN UNPOLARIZED STRUCTURE FUNCTIONS

IV. EVOLUTION AT LARGE X_{BJ}

Parton Distribution Functions (PDFs) are determined experimentally from the cross sections for a number of hard processes by using a procedure defined as *global fitting* [19,7,8]. A fully quantitative description of the proton structure in terms of PDFs relies however, on our ability to unravel in detail the Q^2 dependence of the data. In particular it is important to obtain more quantitative information on the boundary or "transition" regions of x and Q^2 where perturbative QCD (pQCD) evolution regulated by DGLAP [21] equations can no longer be considered to be the main mechanism responsible for the Q^2 dependence of the data, and non-perturbative contributions become important. Here the short-distance scattering involving single, non-interacting partons is expected to give way to processes in which two (or more) quarks or gluons participate simultaneously in the scattering. pQCD predicts that these processes contribute inverse power corrections to the Q^2 dependence of the structure functions described formally as Higher Twists (HT), namely the higher order terms in the "twist" expansion (twist=dimension-spin). In pQCD analyses performed so far HT terms have been extracted from DIS data by applying a cut in the kinematics at $W^2 \geq 10\,\mathrm{GeV}^2$ [23,24] (W^2 being th invariant mass of the final hadronic state).

In [20,22] it was shown however that only a relatively small HT contribution, consistent with the one obtained in [23,24] is necessary in order to describe the entire set of DIS data, including the low W^2 region which is dominated by nucleon resonances. These results are also consistent with the definition of Local Duality [4]. Based on the results of [20,22], we wish to reopen the question of the limits of applicability of pQCD in the low W^2 domain with the aim of understanding the origin of the *residual* inverse-powerlike Q^2 dependence of the data.

In this analysis a relevant role is played by the choice of invariant used as a scale for pQCD evolution, since one is probing a kinematic regime where infrared singularities are expected to be largest - thus spoiling the standard NLO perturbative expansion [25]. Indeed the recent Jefferson Lab data show "scaling" in W^2, *i.e.* the invariance with W^2 of the smooth curves interpolating the resonant data plotted as a function of ξ (Bloom-Gilman duality) [4]. From a recent analysis performed using standard NLO pQCD evolution but at fixed W^2 bins, we are able to interpret this behavior as the cancellation of the NLO perturbative contribution with the HT contribution to the structure function. By assuming that the perturbative contribution is known from evaluating the proton initial PDFs as given in [19,7,8] at the W^2 of the data, we can determine the size of the HT coefficient. Results are displayed in Fig. xxx where we plot the coefficient of the $1/Q^2$ correction, $C_{HT}(\xi, Q^2)$ vs. ξ. One can see that while at $\xi \lesssim 0.6$, the extracted HT coefficient is consistent with the deep inelastic analysis of [23], at larger ξ its value becomes less clearly determined and at values of $\xi \gtrsim 0.8$ it is completely undefined. A possible interpretation of the discrepancies at large ξ is that here the perturbative series becomes unreliable and that evolution using the variable W^2 as a scale should instead be performed.

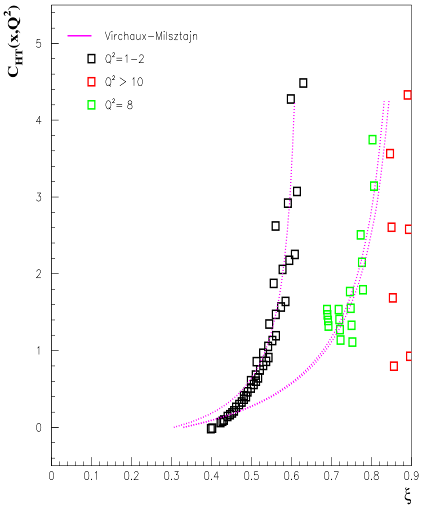

FIG. 4. Higher Twist extraction based on the observation of W^2-scaling

Further detailed analyses would be possible with an 11 GeV beam at JLab providing data at larger x and Q^2. Another interesting outcome would be that with a better constraint on the Q^2 dependence in this kinematic region, one could derive parameterizations for the PDFs at large x directly from the data without necessarily resorting to theoretical inputs (*e.g.* $F_2 \approx (1-x)^a$ with $a \approx 3$).

V. DUALITY IN SPIN-STRUCTURE FUNCTIONS

A long series of inclusive DIS experiments dating back to the late seventies [26–35], have exhaustively studied the spin structure functions. The proposed 11 GeV JLab beam energy opens up more opportunities for additional studies of the spin structure in the region of the resonances, in particular, in connection with the question of polarized local duality. The question of whether the polarized structure functions will exhibit local duality remains unresolved to date. The main results of existing data may be summarized as follows:

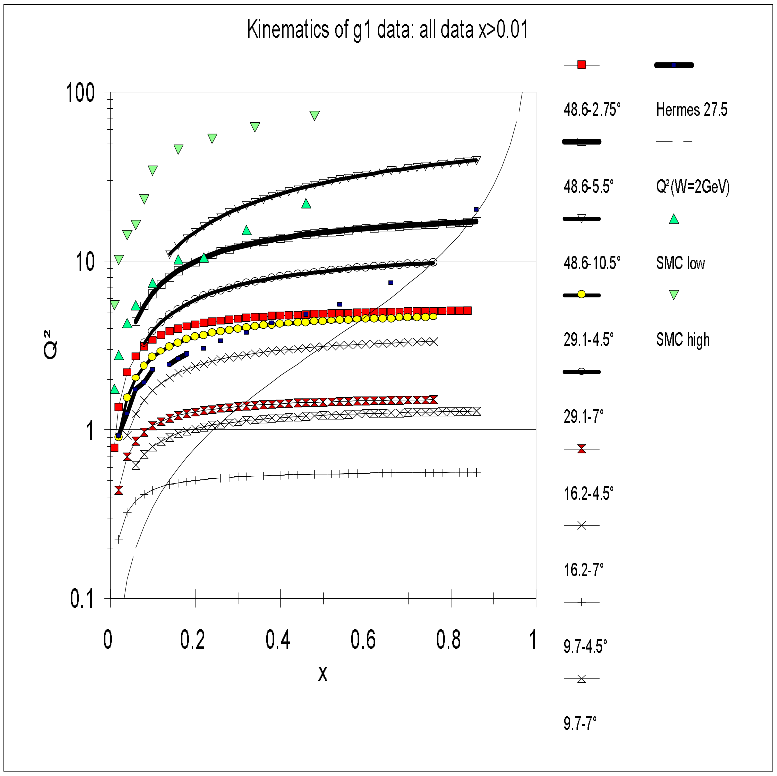

FIG. 5. Kinematic coverage of $g_1(x > 0.01)$. Symbols are indicative, and not actual data.

• Data exist in a very broad kinematic region, $0.003 \leq x \leq 0.9$ and 1 GeV$^2 \leq Q^2 \leq$30 GeV^2 (and for even greater Q^2 at intermediate $x < 0.4$). Figs. xxx and xxx illustrate the coverage for the SLAC [30,32,33,35], CERN (SMC [36]) and DESY (HERMES [37]) experiments for g_1 and g_2, respectively. For the SLAC and DESY experiments, lines of constant beam energy and central scattering angle are shown; however, the range of Q^2 at every value of x extends significantly about this central value. For the CERN experiment upper and lower limits are shown instead. The SLAC g_1 data are available for both protons and deuterons at all the kinematics shown in the figures, and for neutrons at some values (48.8 GeV; the 22 GeV data are not shown) [1]. The g_2 data is limited to protons and deuterons. The curve of constant invariant mass $W = 2$ GeV, which corresponds to the region of W above which the nucleon resonances cannot be resolved, is displayed as well.

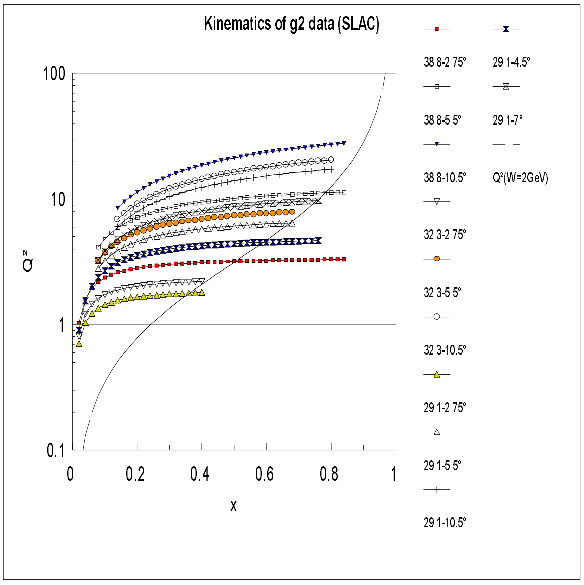

FIG. 6. Kinematic coverage of g_2. Symbols are indicative, and not actual data.

From Fig. xxx it can also be seen that the region below invariant mass W= 2 GeV, corresponding to the nucleon resonances, is still poorly covered above $Q^2 = 1$ (GeV/c)^2. Data below this value of the four-momentum transfer are limited to the neutron (Hall A E94-010 [38]). Fig. xxx shows the additional coverage expected from planned JLab experiments (Hall B eg1 and eg2000 [39,40], and Hall C 96-002 [41]. The curve of constant invariant mass $W = 1.232$ GeV, which corresponds to the $\Delta(1232)$ resonances is also shown.

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[1] Not shown either are the earlier $A_1 + \eta A_2$ SLAC-Yale data [26,27].

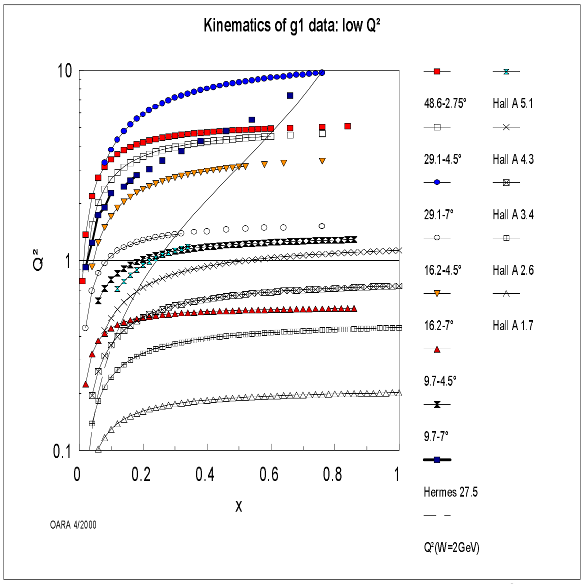

FIG. 7. Kinematic coverage of $g_1(Q^2 < 10\ \mathrm{GeV}^2, x > .01)$. Symbols are indicative, not actual dat.

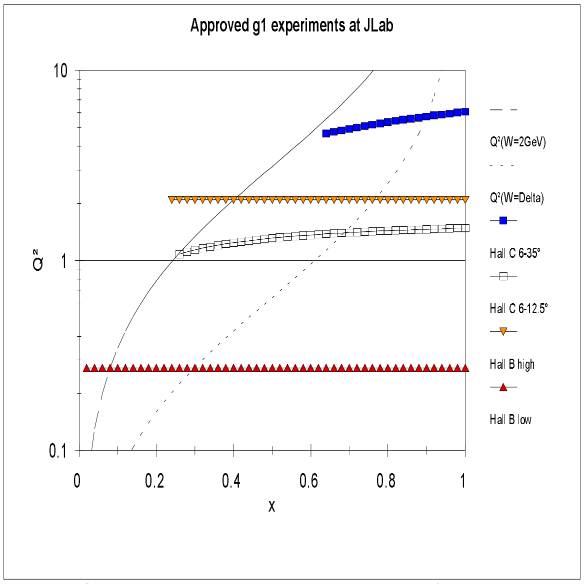

FIG. 8. Kinematic coverage of g_1 by planned JLab experiments. Symbols are indicative, not actual data.

• The quark contribution to the nucleon spin can be extracted from the integrals $\int g_1^{p,d,n} dx$ computed from the data for the region measured in each experiment, and extrapolated to

$x = 0$ with perturbative QCD NLO fits (the contribution of the extrapolation to $x = 1$ is generally small or negligible). The quark component of the nucleon spin in the $\overline{MS}$ scheme is $\Sigma q = 0.15 \pm 0.03 \pm 0.08$ with the E154 fit [42], and $\Sigma q = 0.18$ with the SMC [43] fit. These values are well below the naive quark model prediction of 0.6.

• The deuteron and proton integrals indicate that the Bjorken sum rule [44] (with first order QCD corrections for finite Q^2)

$$\int (g_1^p - g_1^n) dx = \frac{1}{6} \Big| \frac{g_A}{g_V} \Big|_{n \to pe^- \bar{\nu}} \Big(1 - \frac{\alpha_s(Q^2)}{\pi} \Big) \tag{2}$$

where g_A and g_V are the nucleon axial-vector and vector coupling constants, is satisfied to about 10% [42,43]:

Theory $\int (g_1^p - g_1^n) dx = 0.181 \pm 0.003$, Experiment $\int (g_1^p - g_1^n) dx = 0.172 \pm 0.018$,

both evaluated at Q^2=5 GeV^2.

• The data on g_2 comes almost entirely from SLAC [30] (some low precision A_2 data from CERN exist, too). The high precision data of SLAC E155x are still preliminary, and cannot be included in this document. However, the combined world data on g_2 will likely have statistical power to rule out some models for this structure function, and give us a glimpse into the size of the twist-3 contributions to DIS, which can be extracted using the OPE sum rules of eq. (11) .

Current and future work on the DIS spin structure functions is now being devoted to the study of semi-inclusive asymmetries and the measurement of the gluon contribution to the nucleon helicity [45,46].

The region of $W < 2$ GeV, that corresponds to the higher values of x has been much less studied in the past. There are only two measurements of $g_1^{p,d}$ above $Q^2 = 1$ Gev^2 [47,30], which are shown in Fig. xxx. g_1^n and g_2^n data for $Q^2 \leq 1$ GeV^2 are only now becoming available [38]. In the near future, JLab experiments in Hall B (EG1 and EG200) and Hall C (E96-002) will explore this region in far more detail, as shown in Fig. xxx.

Hall C experiment 96-002 will specifically concentrate on a high precision and high resolution measurement of the spin asymmetries A_1 and A_2 for both protons and deuterons, at two values of $Q^2 \sim 1.2$ and ~ 5.7 GeV^2. A sample of the expected results for the intermediate Q^2 data is shown in Fig. xxx.

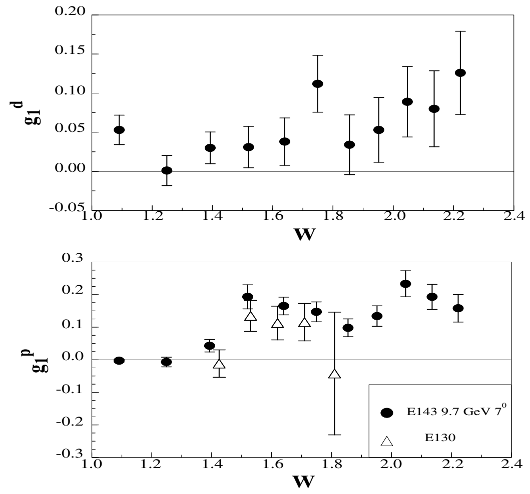

FIG. 9. g_1 in the resonances from SLACs' E143 and E130 at $Q^2 \sim 1.1$ GeV^2. There are E143 data at $Q^2 \sim 0.5$ GeV^2 too.

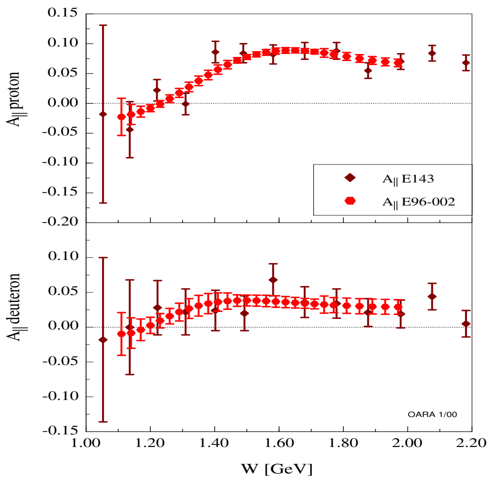

FIG. 10. Expected errors for JLab E96-002 at $Q^2 \sim 1.2$ GeV^2 and actual E143 errors at similar Q^2 (see Fig. xxx).

Although the quality of of the existing g_1 data at $x \geq 0.6$ needs improvement, it can be safely concluded that the information that can be obtained from further inclusive DIS studies of g_1 is marginal. From the constant invariant mass $W = 2$ GeV curve shown in Fig. xxx, it can be seen that the $x \geq 0.7$ range for DIS lies above $Q^2 \simeq 10$ GeV^2. This large momentum transfer represents a serious counting rate limitation for experiments with 11 GeV beam energy, given the maximum luminosity of ~ 100 Hz/nb achievable with solid polarized targets, the only ones available for protons and deuterons. In order to extend the DIS range in x with significantly greater precision than that of the current data (which is about 25% at $x = 0.75$) substantial improvements will be needed in the solid angle of any spectrometer that would be used in such extensions. The situation for the neutron structure functions is different for two reasons: there are no data on g_1^n above $x \simeq 0.62$, and the luminosity of polarized ^{3}He targets in the JLab beam can be up to three times greater than that of the solid targets. The connection between the ^{3}He and neutron spin structure functions is reasonably well established in DIS, but more work is needed to extend it into the resonances.

On the other hand, the JLab electron beam available at the present time is fine for low momentum transfer studies such as the Gerasimov-Drell-Hearn sum rules. High beam energy is not needed for this kinematic regime.

The main advantage of having a high energy beam, outside of opening up a wide range of kinematic coverage at large x and the resonance region for duality studies, is the ability of reaching large values of Q^2 at smaller scattering angles than at low energy, with the attendant larger Mott cross section. On the other hand, the final electron momenta also tend to be large at small angles, requiring new spectrometers. Hall C's planned Super HMS meets this requirement, although its proposed solid angle ≤ 0.003 sterradian may not be adequate at some kinematics. Alternatively, large Q^2 can be reached with large scattering angles, for which the final electron momentum may be smaller than 7.5 GeV/c, which is the current upper limit at JLab (corresponding to Hall C's HMS which has double the solid angle of that planned for the SHMS). A proposed Hall A large solid angle spectrometer Medium Acceptance Device (~ 30 msr) may be an option, provided it could accept momenta up to about 6 GeV/c, and have the necessary resolution.

Figure xxx depicts the kinematic range of possible 11 GeV Hall B CLAS measurements of the spin asymmetry $A_1^{p,n}$ assuming duality to hold. Note the dramatic increase in x range afforded by utilizing duality-averaging. All 11 GeV points are measured at the same $Q^2 = 9 \pm 1$ (GeV/c)^2. CLAS can take data for Q^2 from 1 to 14 (GeV/c)^2 at the same time. The $Q^2 = 9$ (GeV/c)^2 kinematics were chosen to optimize count rate and x coverage in the high x region of interest. The currently-planned EG1 run period will use $\simeq 5.6$ GeV beam energies on both NH3 and ND3 targets, covering up to about $x = 0.6$ in the deep inelastic and resonance regions. This should permit a test of the duality principle in this x region. The 11 GeV beam energy will provide a good cross check of the lower x region, and allow extension of such measurements up to $x = 0.9$.

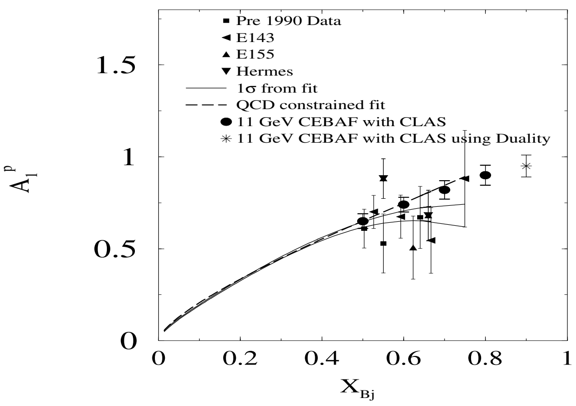

FIG. 11. The spin asymmetry A_1^p as measureable at an 11 GeV CEBAF, with and without duality-averaging to achieve large x_{Bj} scaling region data.

Examples of possible choices for kinematics for Halls A and C type measurements of the spin asymmetries in the region of the resonances up to $Q^2 = 8$ GeV^2 are given in the table below. It should be possible to extend the four-momentum to ~ 10 GeV^2. Notice that because of the larger HMS solid angle compared to the SHMS, the intermediate Q^2 region can probably be explored better with the former device, with beam energy less than 11 GeV, as illustrated by the first and last rows of the table. Notice also the relative widths of invariant mass and final energy bins. Finally, it must be pointed out that a large momentum bite is needed to measure the entire region in one momentum setting.

Possible Kinematics Choices

E	θ	Q^2	E′(Δ1232)	ΔW	ΔE′(Δ1232)	Spectrometer	sigma Mott	dp/p
GeV		GeV²	GeV	MeV	MeV		nb/sr	+/-
11	12.5°	4.2	8.34	30	31	SHMS (?)*	301	7.2%
	16°	6	7.33	30	27	HMS		7.2%
	20°	8	6.25	30	24	HMS		7.2%
	"	"	6.25	60	45	HMS		7.2%
9	16°	4.2	6.32	30	28	HMS	170	9.0%

*Solid angle < 3 msr

Assumptions and input parameters

NH3 Polarization	80%
Beam polarization	80%
Dilution factor	~0.22
Luminosity [Hz/nb]	100
Spectrometer solid angle [msr]	6.4
Invariant mass range W [GeV]	1.1 - 2.0

The expected errors in the experimental asymmetry $A_{\parallel}$ for a possible measurement on a proton target at $Q^2 = 8$ GeV^2 (corresponding to rows 3 and 4 of the table) are shown in Fig. xxx, where $A_{\parallel}$ is plotted as a function of the invariant mass, at fixed arbitrary values 0 and 1/2. Two levels of resolution in W, 30 and 60 MeV, are considered. The error bars represent the statistical uncertainties for 620 hours with 30 MeV bins and 310 h with 60 MeV bins. The latter is the absolute minimum resolution required to resolve the individual resonances. No allowance is being made for experimental overhead, nor for the measurement of $A_{\perp}$, required to separate A_1 and A_2 (about 10% additional time).

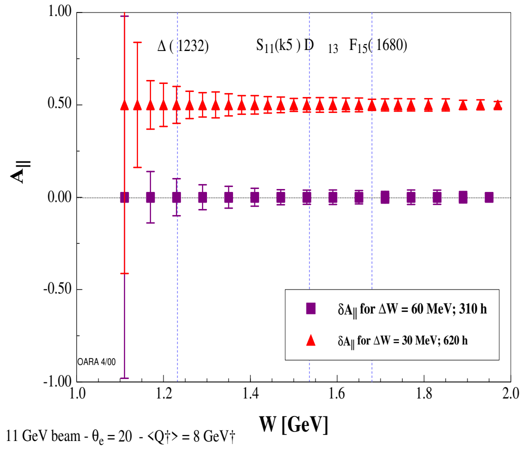

FIG. 12. Expected errors for possible measurements at $Q^2 = 8$ GeV^2 with an 11 GeV beam.

The measurement of the deuteron asymmetries would require about 1.5 times longer for comparable errors. Of course, the measurements at lower Q^2 would involve significantly shorter run times. One would expect that $g_1^{p,d}$ could be measured in the resonances for two or three values of Q^2 from $\sim$ 4 GeV^2 to $\sim$ 8 GeV^2 in about six to eight weeks of beam time at 100% efficiency. A set of measurements would be needed in order to be able to either evolve or interpolate the structure functions to constant Q^2 for computing the duality integrals and averages.

It would be a straightforward matter to extend all the measurements discussed into the DIS region, at constant beam energy and scattering angle, just by changing the momentum setting of the spectrometer. The counting rate for such measurements would improve since the corresponding Q^2 is lower.

The question of the required resolution of the data comes up for two reasons:

- The spin structure functions in the region of the resonances probably have a lot of structure, just like their unpolarized counterparts. In order to observe that structure and to make meaningful comparisons with models, the measured spectra should have at least three bins per resonance region. Otherwise, unexpected effects, such as a substantial change in the asymmetry in the Roper region which barely shows up in the cross sections, could easily be missed with broad bins. The width of each bin should be no larger than $\Gamma_R/2$, where Γ_R is the width of a Lorentzian shaped peak. For example, for the $\Delta(1232)$ $\Gamma_R/2 \sim 60$MeV. Also, care must be taken to plan experiments with the appropriate momentum bins, since there is often a magnification effect in going from bins in final energy E' to bins in invariant mass W

$$\Delta E' = \frac{W}{M + 2E\sin^2(\theta/2)}\Delta W \tag{3}$$

As the final energy increases with beam energy and with smaller W (E' gets close to E in the resonances), good momentum resolution $\delta p/p$ of the spectrometer becomes important, too, especially for polarized targets that need to have the beam rastered over large areas. Large raster radii ($\sim$1 cm) introduce very large shifts in the reconstructed momentum of the scattered particles.

- On the other hand, the authors of Ref. [5] give a criterion for the range of $\xi \pm \Gamma$ over which local duality can be observed, as $\Gamma \gg M_0^2/Q^2$. As Q^2 increases, this region of local duality narrows. At $Q^2 = 10$ GeV^2, $\Gamma \gg 0.016$, assuming that $M_0 \sim 400$ MeV, from estimates of higher twist contributions [5]. Translated to invariant mass resolution at the $\Delta(1232)$ this implies $\Delta W \gg 90$ MeV ($\Delta E' = 60$ MeV). However, Γ is very sensitive to M_0: if M_0 was actually 250 MeV instead of 400, ΔW would narrow down to $\gg$35 MeV, and $\Delta E'$ to 23 MeV. At this kinematics a bin equivalent to the full width of the $\Delta(1232)$ would clearly satisfy this criterion. This conclusion is not incompatible with the need to have high precision data in narrow bins: it is always possible to combine bins for integration purposes, but it may be impossible to go the other way.

VI. DUALITY IN SEMI-INCLUSIVE PROCESSES

While the phenomenon of duality in inclusive scattering is well established, duality in the related case of semi-inclusive meson electroproduction has not been experimentally tested.

Here we will concentrate on the semi-inclusive reaction typified by $\gamma + p \to \pi + X$, where the photon may be real or virtual. Typically, one can substitute a pion anywhere in the remainder of this Section for a kaon, with a loss in rate of order 10.

First we will concentrate on reactions where the pion exits with large transverse momentum. The interesting kinematic region for the purpose at hand is one where the pion is directly produced at short range and exits the reaction in kinematic isolation from other exiting particles [49].

Direct pion production is calculable within perturbative QCD by dint of the pion's high transverse momentum. An interesting feature, reminiscent of deep inelastic scattering, is that the momentum fraction x of the struck quark can be expressed in terms of experimentally measurable quantities, in this case using

$$x = \frac{-t}{s + u - 2m_N^2 - q^2 - m_\pi^2}, \tag{4}$$

where s, t, and u are Mandelstam variables and q is the momentum of the photon.

The cross section for hard pion photoproduction can be written as a kinematic factor times a scaling function [50], where the latter is a function that in general depends on several variables but in the limit of large t and large m_X depends only on the variable x (up to logarithmic corrections). A goal here is to see what happens at smaller recoiling mass m_X, particularly in the resonance region. The scaling curve will become bumpy at low m_X, and we may ask, Will the resonances averaged over their own width reproduce the scaling curve already (by that time) established? Will the resonance peak to background ratio remain constant for a given resonance as $|t|$ increases?

One needs, of course, to have a scaling region where m_X is large and direct pion production is dominant. One problem when the energy or transverse momentum is not high is a background coming from soft processes, which can be estimated using vector meson dominance (VMD) ideas. One can reduce the VMD background by having the photon off shell. For a 12 GeV incoming beam, preliminary estimates based on earlier work [51] indicate that, with photons spacelike by 1 GeV^2, there is a significant scaling region with m_X

between 2 and 3 GeV and with direct pion production dominating both fragmentation or VMD processes. There is also a resonance region with m_X between 1 and 2 GeV. Thus, a 12 GeV beam at CEBAF would undeniably allow this category of semi-inclusive duality experiment to be performed.

Related to the above case is semi-inclusive deep inelastic scattering in parallel kinematics. Here a parton exits the fundamental reaction, and then at some distance fragments into a jet of hadrons, one of which is the observed pion. This is in contrast to the process described above, where, at very high transverse momentum, short-range direct production dominates. Here again duality would manifest itself with an observed scaling in the meson plus resonance final state. Fig. xxx shows a diagrammatic picture of meson electroproduction. The struck quark carries momentum xp, where x is the fraction of the light-cone momentum of the target nucleon carried away by the struck quark. The outgoing meson is detected (as is the outgoing electron), and we define z in terms of target, photon, and meson four vectors: $z = (p \cdot m)/(p \cdot \gamma^*)$. In the target rest (lab) frame, this becomes $z = E_m/\nu$, the fraction of the virtual photon energy taken away by the meson. In the elastic limit, $z = 1$, and the meson carries away all of the photon's energy. We define $p_\perp$ to be the transverse momentum of the meson in the virtual photon-nucleon system.

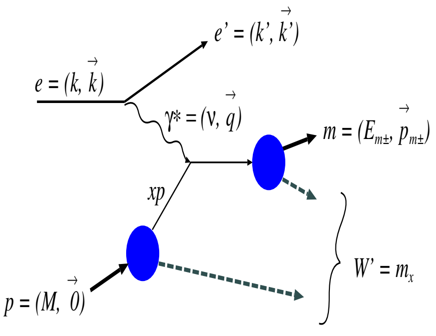

FIG. 13. A diagram of meson electroproduction. In the proposed experiment, we detect the outgoing electron e and the outgoing meson $m^{\pm}$ (a negatively- or positively-charged pion or kaon).

We reconstruct the invariant mass m_x that goes undetected. Here we refer to this quantity as W' to highlight the fact that *it could play a role analogous to W for duality* *in the inclusive case* [50]. If we assume the pion (meson) to be collinear with the virtual photon momentum and neglect terms of $O(\mathrm{m}_\pi^2 x^2/Q^2)$, W'^2 is given by

$$W'^2 = m_p^2 + Q^2\,(1-z)\,(\frac{1}{x} - 1)\,.$$

Assuming one is in a kinematics region that mimics single-quark scattering, in analogy with the inclusive scattering case, the question here is whether the remaining part of the process can be described in terms of a process where the struck quark hadronizes into the detected meson. One would assume such a factorization approach, where the cross section decomposes into a part, $f_i(x, Q^2)$, dependent on the photon-quark interaction, and another part described by the quark fragmentation functions $D^h_{q_i}(z, Q^2)$ (or the probabilities that a quark of flavor q_i hadronizes into a hadron h). This approach is strictly valid at asymptotic energies only, as at low energies there may not be clear separation of target and current fragmentation regions [52,53].

However, similar as in the inclusive case where the nucleon resonances average at low energies to the scaling curve, the nucleon resonances remaining in the final state after having produced a fast meson may average to the fragmentation function. If duality holds for semi-inclusive scattering, the overall scale of scattering in the low-W' region must mirror that at high W'. This may come about *if* the various decay channels from resonances with varying W' interfere such that factorization holds. Where the usual Bloom-Gilman duality involves comparison of a structure function over some range in Bjorken x at low W^2 (and hence low Q^2) with that structure function over the same range in x but at high W^2 (and Q^2, as in Fig. xxx), we may find a similar behavior in terms of the fragmentation functions $D^h_i(z, Q^2)$ in the case of semi-inclusive meson electroproduction, if we find that the cross section factorizes. Given the (x, Q^2)-dependent part, we can look for dual behavior in the (z, Q^2)-dependent part.

Indeed, several recent results indicate that factorization seems to hold at lower than asymptotic energies, **provided** one makes an additional cut in z [54,55]. Furthermore, sparse information from older Cornell data suggests that we are in the right kinematics region to study the onset of the duality phenomenon in meson electroproduction [56,55].

In practice, we will extract the meson yield $\frac{dN^m}{dz}$ over a range of z at several values of x and Q^2. This allows the comparison of $\frac{dN^m}{dz}$ in the resonance region to that in the deep inelastic regime, which we obtain from the quark model or from parameterizations of data. As in the case of Bloom-Gilman duality, we would like to know whether spectra in z at low Q^2 and W'^2 tend to average to the scaling curve obtained at high Q^2 and W'^2, and whether we understand from there on the Q^2 behavior of the resonance region in a perturbative picture.

To exhibit the importance of understanding the onset of factorization for our understanding of the flavor content of the nucleon, we highlight a projected extraction of the flavor asymmetry of the light quark sea from semi-inclusive deep inelastic scattering, assuming duality works for $Q^2 > 1$ (GeV/c)^2 **and** $z > 0.3$. We highlight this case despite the fact that this asymmetry is expected to be small at large x, as it shows the overall quality of the data one could obtain. Fig. xxx shows the quality of the data we might obtain at two *fixed* values of z, as a function of x, to probe the assumption of factorization.

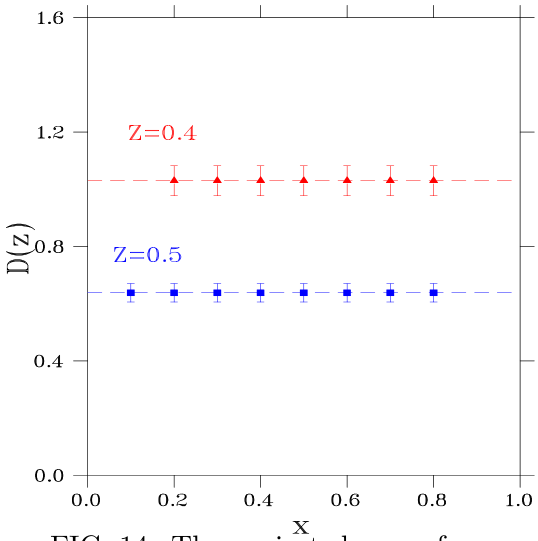

FIG. 14. The projected mean fragmentation function as a function of x for two bins in z. The uncertainties represent statistics only for a two-day measurement total for each bin of z.

Fig. xxx shows the extracted values of $\bar{d}-\bar{u}$ from the Drell-Yan E866 data [57] and the semi-inclusive deep-inelastic HERMES data [54]. In the latter the quantity $\bar{d}-\bar{u}$ is extracted from a ratio of the differences of π^- and π^+ production on proton and deuteron targets. We compare the extracted values with results of the CTEQ [8] and GRV [19] parameterizations, in addition to an instanton-inspired parameterization of [58]. Here we would like to emphasize the quality of the 12-GeV JLab data, obtainable in only a small amount of beam time. These measurements cover a range in x between 0.1 and 0.8, and assume a 4 GeV spectrometer in combination with a 7 GeV spectrometer, with a smallest angle for the 7 GeV spectrometer of about 6° and a minimum angle separation of of order 15°.

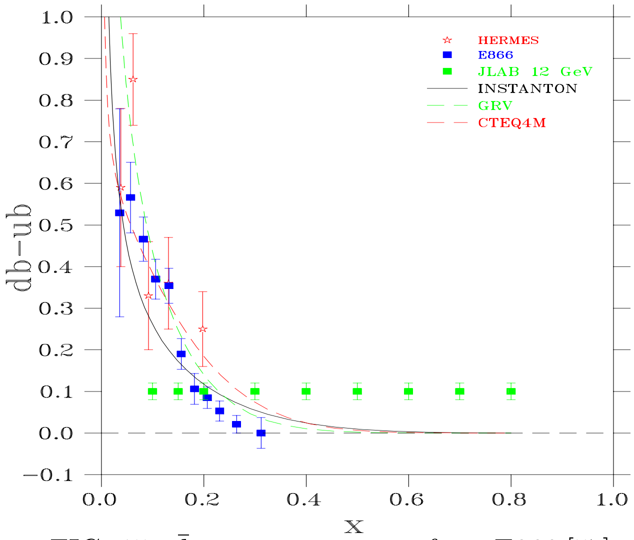

FIG. 15. $\bar{d}-\bar{u}$ measurements from E866 [57] and HERMES [54], in combination with projected uncertainties for a one month 12 GeV JLab run. The dashed curves represent the CTEQ [8] and GRV [19] parameterizations, the solid curve an instanton-inspired model calculation [58].

VII. SUMMARY

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