Experiment E97-010 Update: Measurement of Hydrogen and Deuterium Inclusive Resonance Cross Sections at Intermediate Q^2 for Parton-Hadron Duality Studies

Abstract

We propose to extend precision Hall C measurements of inclusive nucleon resonance electroproduction cross sections from hydrogen and deuterium targets throughout the resonance region ($1 < W^2 < 4$ GeV^2), such that the entire data set spans the four-momentum transfer range $0.05 < Q^2 < 7.0$ (GeV/c)^2. The cross sections will be used in conjunction with existing deep inelastic and elastic data for precision experimental tests of parton-hadron (Bloom-Gilman) duality in the nucleon structure functions. Substantial progress in understanding QCD and the concept of duality allows for measurement of the QCD moments of $F_2(x, Q^2)$ from resonance data in the moderate Q^2 region. The experimental F_2 moments may be used to extract the matrix elements of higher-twist operators.

We request three days of beam time to measure inclusive nucleon resonance electroproduction cross sections spanning the entire resonance region and covering the higher Q^2 segment of the Jefferson Lab kinematic range ($4.0 < Q^2 < 7.0$). The lower Q^2 range either has been measured already [1], or will be measured by approved experiment E00-002. This proposed experiment utilizes the existing equipment in Hall C with 5.0 GeV or higher electron beam energy. Electrons scattered from 15 cm liquid hydrogen and deuterium targets will be detected in both the High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS) in simultaneous single arm mode.

MOTIVATION

Three decades ago Bloom and Gilman observed the behavior of elastic scattering and of the electroproduction of nucleon resonances to be closely related to the behavior of deep inelastic electron-nucleon scattering [2, 3]. Precisely, the prominent resonances in inclusive electron-proton scattering do not disappear with increasing four-momentum transfer squared (Q^2) relative to the background under them, but instead fall at roughly the same rate. Also, the smooth scaling limit seen at high Q^2 and large missing mass squared (W^2) for the structure function $\nu W_2(\omega')$ ($= F_2$) is an average of the resonance enhancements at the same ω', but lower Q^2 and W^2. Here, ω' is an "improved" scaling variable and is equal to $1+ W^2 / Q^2 = (2M\nu + M^2)/Q^2$. These observations are termed

Bloom-Gilman duality, or parton-hadron duality. Bloom and Gilman quantified the latter observation with the following finite energy sum rule:

$$\frac{2M}{Q^2}\int_0^{\nu_m} \nu W_2(\nu, Q^2) d\nu = \int_1^{(2M\nu_m+m^2)/Q^2} \nu W_2(\omega') d\omega'. \tag{1}$$

Here, ν is the energy transfer. This observed duality relationship between resonance electroproduction and scaling behavior as observed in deep inelastic scattering suggests a common origin for both phenomena.

Recent Jefferson Lab data has verified that this dual relationship between resonance electroproduction and deep inelastic scattering holds within 10% down to Q^2 values as low as 1 (GeV/c)^2, and that the resonances oscillate around a smooth scaling curve down to even $Q^2 \approx 0.5$ (GeV/c)^2 [4]. Furthermore, duality was also found to hold locally, i.e. around the individual prominent resonance enhancement regions, to within 10%.

Inclusive deep inelastic scattering on nucleons is a firmly-established tool for the investigation of the quark-parton model. At large enough values of invariant mass squared W^2 ($= M^2 + Q^2(1/x$ - 1), with M the proton mass and x the Bjorken scaling variable) and Q^2, QCD provides a rigorous description of the physics that generates the Q^2 behavior of the nucleon structure function $F_2 = \nu W_2$. The well-known logarithmic scaling violations in the F_2 structure function of the nucleon, predicted by asymptotic freedom, played a crucial role in establishing QCD as the accepted theory of strong interactions [5, 6]. Such behavior becomes especially transparent in comparing high Q^2 (≥ 10 (GeV/c)^2) Cornwall-Norton or Nachtmann moments [7] of F_2 structure functions with the logarithmic formulae of asymptotic freedom [8, 9].

The description of hadrons and their excitations in terms of elementary quark and gluon constituents is one of the fundamental challenges in physics today. Quantum chromodynamics (QCD) is the theory of strong interactions that describes particles in terms of these elementary quantities. A QCD-based explanation of duality and why the resonance structure functions average to the F_2 scaling curve was offered by De Rujula, Georgi, and Politzer in 1977 [10, 11]. While original studies were somewhat qualitative, enormous progress has been made in understanding QCD in the past two decades and recent work has focused once again on Bloom-Gilman duality (for example, see [12, 13, 14, 15, 16]).

An analysis of the resonance region at smaller W^2 and Q^2 in terms of QCD, as first presented in Refs. [10, 11], re-interpreted Bloom and Gilman's duality, and the integrals of the average scaling curves from equation 1 were equated to the $n = 2$ moment of the F_2 structure function. The Q^2 dependence of these moments can be described by ordering the contributing matrix elements according to their twist (= dimension - spin) in powers of $1/Q^2$. It was concluded that the fall of the resonances along a smooth scaling curve (i.e. Bloom-Gilman duality) with increasing Q^2 was due to the fact that there exist only small changes in these lower moments of the F_2 structure function due to higher twist effects. These higher twist effects can be regarded as interactions between the quark struck in the electron-nucleon 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 and high Q^2 are approximately the same. Notwithstanding, the dynamical origin of local duality, and thus the reason why the higher-twist contributions, undoubtedly required to construct the coherent nucleon resonances, tend to largely cancel on average, *even* at momentum transfers below 5 $(\mathrm{GeV/c})^2$, is still not understood [9, 13].

There exists a large body of precision deep inelastic lepton-nucleon scattering data. Combined with precision resonance data, it will be possible to rigorously study the observations and predictions of duality. Duality will be tested for the neutron by subtraction of the kinematically-matched proton data, using smearing and deuteron wave function modelling. It will also be interesting to test parton-hadron duality on the deuteron itself as a hadron.

An alternative approach to interpretation of the proposed data is to assume equation 1 to be valid as predicted from QCD. It is then possible to study the interplay between resonances and higher twists, i.e. 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

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

The moments $M_n(Q^2)$ of F_2 may be expressed following the operator product expansion and can be expanded in powers of Q^{-2} and depend on the nucleon matrix elements of higher-twist operators composed of quark and gluon fields. Ji [13] defines a kinematic region where higher-twist corrections become important, but stay perturbative, and thus only the first few terms in the twist expansion are of practical importance. The scattering in this region is described by few parton processes. In the region $Q^2 < 10$ ($\mathrm{GeV/c^2}$), the resonance contributions to the moments are significant. Here also the higher-twist corrections are perturbative, so the moments are not very different from those at larger Q^2. In this region, then, the resonances must follow the deep inelastic curve apart from perturbative higher-twist corrections. Or, conversely, the behavior of the resonances is constrained by the higher twist expansion. Since deuterium is a spin-1 nuclear target, another class of twist-four operators is theoretically possible. The kinematic region of the proposed data may be described in terms either of resonance production or the scattering of a few partons: parton-hadron duality.

It is clear from equation 2 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 primary goal of this proposed moment and duality study is, then, with the new resonance region data, to measure the moments accurately using improved large x data and to extract the matrix elements of higher-twist operators. Figure 2 from the original proposal (attached, reference [13]) depicts the ratio of the F_2 moments from the resonance region, including the elastic contribution, to that of the total as a function of Q^2. Conversely, it will be possible to employ higher-twist contributions, either from theoretical calculations or extracted from deep inelastic data, to determine nucleon resonance properties. The new data will also allow the contributions to the total moments from individual resonances to be calculated.

The lower Q^2 data from Jefferson Lab [1] have already been utilized to perform such studies. The Cornwall-Norton and Nachtmann moments from the world's data for the F_2 ($= \nu W_2$) structure function, for the Q^2 range up to 10 (GeV/c)^2 have been constructed. The Cornwall-Norton moments are defined above, and the Nachtmann moments are given by

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

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

$$\nu W_2(x, Q^2) = \delta(1-x) \frac{\left(G_E^2(Q^2) + \frac{Q^2}{4M^2} G_M^2(Q^2)\right)}{\left(1 + \frac{Q^2}{4M^2}\right)}. \quad (4)$$

G_E (G_M) is the proton electric (magnetic) form factor. For the proton form factors, we use a fit to the world's data by Bosted [18].

To obtain the inelastic contributions we integrate the available resonance region and deep inelastic data. For $Q^2 < 0.6$ (GeV/c)^2, we have constrained our search to elastic and nucleon resonance data, including data from SLAC [19]. For $0.6 < Q^2 < 4$ (GeV/c)^2 we have used nucleon resonance data in combination with deep inelastic data, whereas for $Q^2 > 4$ (GeV/c)^2 we have constructed the moments utilizing both deep inelastic and nucleon resonance models, similar as in Ref. [20]. With the approval of this proposed experiment, we can extend the use of real data and not models for this type of analysis out to $Q^2 > 4$ (GeV/c)^2. For the smallest values of Q^2 (< 0.6 (GeV/c)^2), we assume a constant value of F_2 below x for $W^2 = 4.0$ GeV^2, as no data exists. This may not be a bad approximation for $Q^2 < 0.6$ (GeV/c)^2, especially since the nucleon resonance region data extend down to $x \leq 0.1$, and the integration area below $x = 0.1$ is expected to be small only. To judge the uncertainty in this procedure, we have also integrated the $Q^2 \approx 0.2$ (GeV/c)^2 data starting at $W^2 = 9.0$ GeV^2 (rather than $W^2 = 4.0$ GeV^2). This changes the second moment by less than 3%. Lastly, in some cases, we used a model to construct data at fixed Q^2, rather than allowing for the small range of Q^2 in the data. This effect on the second moments was found to be small, $< 3\%$, and far smaller on the higher moments. Thus, we believe the total uncertainty in the moments we calculate to be less than 5%. 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 Figure 1.

As expected, 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 $Q^2 = 0$, as can readily be seen from equation 3. We believe the latter is due to the fact that, with respect to Bjorken x, the Nachtmann scaling variable ξ correctly takes into account the finite

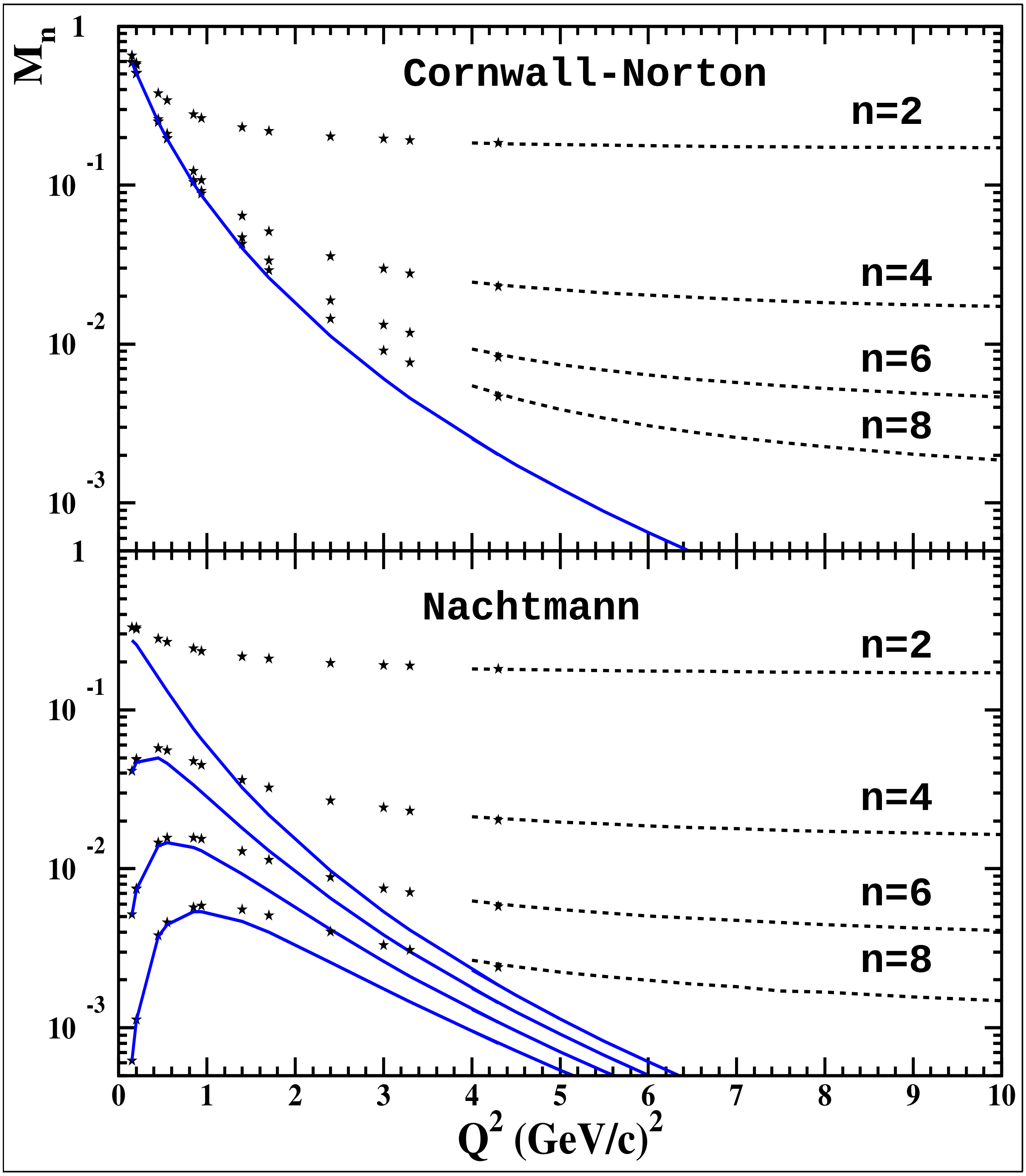

Figure 1: Cornwall-Norton moments (top) and Nachtmann moments (bottom) extracted from the world's electron-proton scattering data, for $n = 2$, 4, 6, and 8. The solid curves indicate the elastic contribution. At low Q^2 (≤ 4.3 (GeV/c)^2) the moments (stars) are directly constructed from the world's electron-proton 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 [20]. With the proposed data, fits will not be necessary out to $Q^2 \approx 7$ (GeV/c)^2.

proton mass scale [7], but does not account for any other significant mass scale (like the quark masses).

In Figure 2 we show the second (Fig. 2a), fourth (2b), sixth (2c) and eigth (2d) Cornwall-Norton moments for $Q^2 < 5$ (GeV/c)^2, separated in the elastic contribution (squares, due to our choice of vertical scale sometimes only visible at the higher Q^2), the contribution of the $N - \Delta$ transition region (triangles, $1.2 < W^2 < 1.9$ GeV^2), of the second resonance region (open circles, $1.9 < W^2 < 2.5$ GeV^2) and of the "deep inelastic" region (stars, $W^2 > 4$ GeV^2). The total moment is given by the solid circles, and the curves connect the various data to guide the eye. The chosen finite W^2 regions will start contributing to the moments at low Q^2, recovering part of the loss of strength due to the fall-off of the elastic contribution, and then also die off, as the resonances move to the larger ξ side of the scaling curve. The contribution of the $W^2 > 4$ GeV^2 region does not die off, as this is not a finite W^2 region, so higher-W^2 resonances and/or higher-W^2 inelastic background start becoming important with increasing Q^2, eventually yielding the logarithmic behavior of the moments prescribed by QCD. As evidenced by the difference between the $W^2 > 4$ (GeV)^2 contribution and the total moment, the contribution of the region of $W^2 < 4$ GeV^2 is non-negligible up to $Q^2 \approx 5$ (GeV/c)^2, even for the second moment. Similar conclusions can be drawn from the various Nachtmann moments.

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 [21]. 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.

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 scaling curve, due to local duality. Down to $Q^2 \simeq 0.1$ (GeV/c)^2, the nucleon resonance data still tend to oscillate around one smooth curve. The contribution of the nucleon resonances to the lower moments of F_2 die out at very small Q^2 as they have moved to smaller Bjorken x. Instead, the moments below $Q^2 \approx 1$ (GeV/c)^2 are governed by the elastic contribution. Thus, an analysis of the moments of F_2 in terms of the Operator-Product Expansion will render higher-twist terms which are predominantly due to the elastic contribution. Local duality seems to prescribe the transition from this elastic contribution to the logarithmic scaling region.

This transition reqion will be probed in greater detail by this proposed experiment, facilitating a greater understanding of parton-hadron duality, and the extraction of higher twist effects using moment-based analyses.

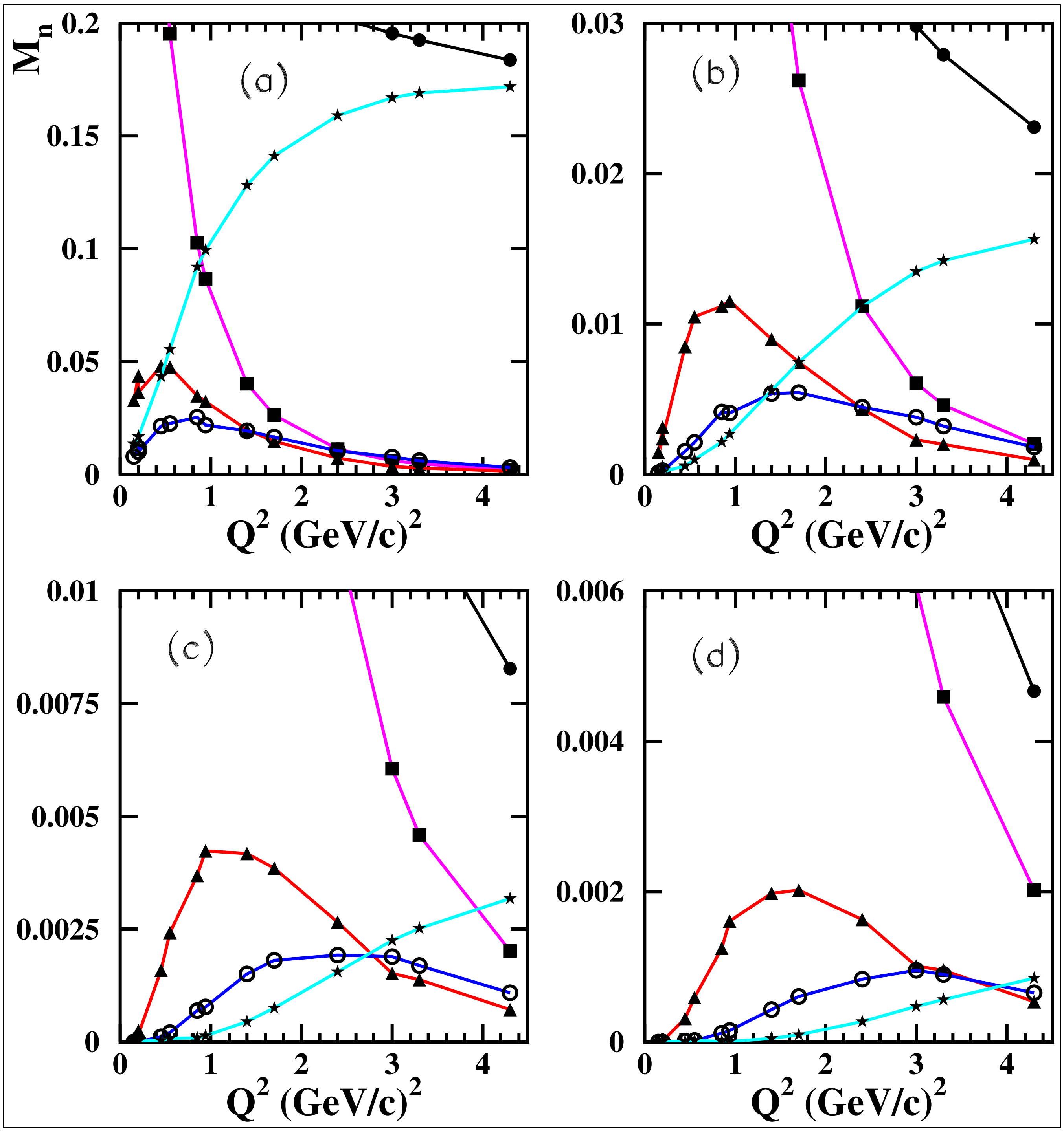

Figure 2: Second (a), fourth (b), sixth (c) and eigth (d) Cornwall-Norton moments. Contributions due to the elastic peak (squares), the regions $1.2 < W^2 < 1.9$ GeV^2 (triangles), $1.9 < W^2 < 2.5$ GeV^2 (open circles), and $W^2 > 4$ GeV^2 (stars) are separately shown, in combination with the total moment (solid circles), as a function of the momentum transfer. Curves connect the various data, and are to guide the eye only.

As a final note, the smooth scaling curve obtained by duality averaging the deuterium resonance region data can be compared to that similarly obtained for hydrogen. Because higher Q^2 resonance data move toward higher ξ or x, this type of comparison can also enable studies of the neutron to proton structure function ratio at large x.

EXPERIMENT AND SUMMARY

Neither the proposed experimental set-up nor the beam time request have changed since the original proposal. We request a total time of 72 hours (3 days) to measure high-precision resonance region cross sections on both LH2 and LD2 targets. The beam time request is summarized in Table 2 of the attached original proposal. This beam time request extends the high precision LH2 and LD2 resonance region database up to momentum transfers of about 7 $(\mathrm{GeV/c})^2$, enabling precision tests of parton-hadron duality or, conversely, the extraction of higher twist effects.

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