Onset of Asymptotic Scaling in Deuteron Photodisintegration

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We investigate the transition from the nucleon-meson to the quark-gluon description of the strong interaction using the photon energy dependence of the $d(\gamma, p)n$ differential cross section for photon energies above 0.5 GeV and center-of-mass proton angles between 30° and 150°. A possible signature for this transition is the onset of cross-section s^{-11} scaling with the total energy squared, s, at some proton transverse momentum P_T. The results show that the scaling has been reached for proton transverse momentum above about 1.1 GeV/c. This may indicate that the quark-gluon regime is reached above this momentum.

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The interplay between the nucleonic and partonic pictures of the strong interaction represents one of the major issues in contemporary nuclear physics. Although standard nuclear models are successful in describing the interactions between hadrons at large distances, and quantum chromodynamics (QCD) accounts well for the quark interactions at short distances, the physics connecting the two regimes remains unclear. In fact, the classical nucleonic description must break down once the probing distances become comparable to those separating the quarks. The challenge is to study this transition region by looking for the onset of some experimentally accessible phenomena naturally predicted by perturbative QCD. The simplest is the constituent counting rule (CCR) for high-energy exclusive reactions [1,2], in which $d\sigma/dt \propto s^{-n+2}$, with n the total number of pointlike particles and gauge fields in the initial plus final states. Here s and t are the invariant Mandelstam variables for the total energy squared and the four-momentum transfer squared, respectively.

Deuteron photodisintegration is especially suited for this study, because a relatively large amount of momentum is transferred to the nucleons for a relatively low incident photon energy [3,4]. This reaction received renewed interest after an apparent onset of the expected asymptotic s^{-11} scaling of the cross section was observed at Stanford Linear Accelerator Center (SLAC) [5,6] at center-of-mass proton scattering angle $\vartheta_p^{\mathrm{c.m.}} = 90°$ and at about $E_\gamma = 1$ GeV photon energy. (For this reaction $n = 13$, as there is one photon and $6 + 6 = 12$ quarks.) Following this initial result, additional measurements were performed at SLAC [7] and more recently at Thomas Jefferson National Accelerator Facility (TJNAF) [8–12] using different experimental techniques. These data cover only a few proton angles. They show that a transition to QCD scaling seems to exist, but its boundaries are not well defined. Scaling seems to be confirmed for center-of-mass proton angles $\vartheta_p^{\mathrm{c.m.}} = 69°$ and 89° [8] already at $E_\gamma = 1$ GeV photon energies, while at the forward angles $\vartheta_p^{\mathrm{c.m.}} = 52°$ and 36°, the cross section falls off more slowly than s^{-11} until about 3 and 4 GeV beam energies, respectively [9].

The recent, extensive cross-section data obtained at the TJNAF by Cebaf Large Acceptance Spectrometer (CLAS) experiment E93-017 between 0.5 and 3.0 GeV with nearly complete proton angular coverage offer the unique opportunity for a detailed study of the energy dependence of the $d(\gamma, p)n$ differential cross section at fixed angles. A detailed description of the measurement and results has been reported in a separate paper [12]. Here we only point out that these data are consistent with previous measurements, and systematically cover the whole photon energy regime of interest.

In this Letter, we present the results of a detailed study of the behavior of $d\sigma/dt$ at fixed proton angle, $\vartheta_p^{\mathrm{c.m.}}$, made to check the CCR s^{-11} prediction as a function of the center-of-mass proton transverse momentum

$$P_T = \sqrt{\frac{1}{2} E_\gamma M_d \sin^2(\vartheta_p^{\mathrm{c.m.}})}, \qquad (1)$$

TABLE I. Photon energies and center-of-mass proton angles of the $\gamma d \to pn$ experiments whose data are used in the present work.

Exp.	E_γ (GeV)	$\vartheta_p^{\rm c.m.}$ (deg)
[15]	0.5–0.78	40–160
[12]	0.5–3.0	10–160
[5]	0.8, 1.1, 1.3, 1.6	90
[6]	0.8, 1.0, 1.2	52, 66, 78, 90, 113, 126, 142
	1.4, 1.6, 1.8	90, 113, 142
[8]	0.8, 1.5, 2.4, 3.2, 4.0	36, 52, 69, 89
[7]	1.5, 1.9, 2.3, 2.7	37, 53, 89
[11]	1.6, 1.9, 2.4	30, 36, 52, 70, 90, 110, 127, 142
[9]	5.0, 5.5	37, 53, 70

in which M_d is the deuteron mass. P_T is the correct kinematical variable for determining the onset of scaling [13,14].

Differential cross sections $d\sigma/dt$ obtained above 0.5 GeV for fixed $\vartheta_p^{\rm c.m.}$ from all existing high-energy $\gamma d \to pn$ experiments [5–9,11,12,15] have been grouped in 10° wide bins and then fit to a power law s^{-11} (one free parameter). Table I gives the photon energies and the proton angles where the differential cross sections have been measured by the experiments. Data were considered without any renormalization to each other and with their statistical and systematic errors added in quadrature. In order to determine whether, and at which proton transverse momentum threshold, $P_T^{\rm th}$, data start to follow the power law s^{-11}, fits were performed for partial samples of the data over about 1.2 GeV wide windows in E_γ. These energy windows correspond to P_T intervals of 200–400 MeV$/c$, depending on the photon energy and the proton angle. (For fixed $\vartheta_p^{\rm c.m.}$, P_T, E_γ, and s are directly related, and each variable can be used interchangeably.) The window in E_γ was then shifted by 100 MeV, and another fit was made. The process was repeated up to the highest E_γ window.

Figure 1 shows the reduced χ_ν^2 values of the fits versus the related transverse proton momentum P_T corresponding to the lower E_γ value of each interval for $\vartheta_p^{\rm c.m.}$ between 30° and 150°. We limited the study to these angles because the data at more forward and backward angles lack the statistics for fits over a significant P_T interval. These results are not changed significantly by the size of the E_γ window, which if too large makes the fit insensitive to deviations from s^{-11} at low s, and if too small makes it not reliable.

Apart from 45°, where the χ_ν^2 is approximately constant around unity over the full P_T range, at all other angles, the χ_ν^2 decreases from values ≥ 10 at low P_T towards unity at some $P_T^{\rm th}$, and then remains approximately flat up to the highest P_T. Clearly, $P_T^{\rm th}$ is the value above which the cross sections have a reliable s^{-11} dependence.

The 10° wide angular bins, the 100 MeV wide shifts among the E_γ windows over which the fits are done, and

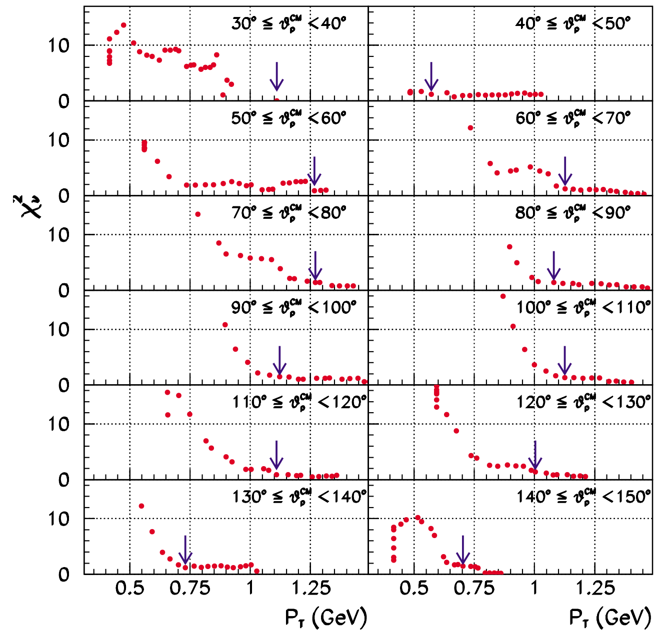

FIG. 1 (color). Values of the reduced χ_ν^2 of the fits of the differential cross sections $d\sigma/dt$ in ≈ 1.2 GeV E_γ intervals with a power law s^{-11} versus the related minimum proton transverse momentum P_T for proton angles between 30° and 150°. The vertical arrows indicate the transverse momentum thresholds for scaling.

the slow variation in χ_ν^2 do not allow the extraction of a precise $P_T^{\rm th}$ for this transition. Nevertheless, one can evaluate an approximate value of $P_T^{\rm th}$ by using a statistical criterion. Specifically, for each angle a $\chi_\nu^2(90\%)$ ($\approx$ 1.4–1.6, depending on the number of data points) has been fixed, corresponding to a 90% confidence level for the fit; the transverse momentum threshold for scaling, $P_T^{\rm th}$, has been chosen where χ_ν^2 of the fit becomes less or equal to the value $\chi_\nu^2(90\%)$. The values of $P_T^{\rm th}$ are shown by the vertical arrows in Fig. 1. They range between 1.00 and 1.27 GeV$/c$ (average value 1.13 GeV$/c$) at 35° and in the angular bins between 50° and 130°, and are about 0.6–0.7 GeV$/c$, at 45°, 135°, and 145°. The uncertainties on P_T values, estimated by changing the confidence level of the fits by $\pm 5\%$, are up to 80 MeV$/c$. However, this would seem to be an underestimate of the uncertainty given a visual inspection of Fig. 1. In particular, the uncertainty on P_T is larger for the extreme angles (35°, 45°, 135°, and 145°), where the derivative of $\sin(\vartheta_p^{\rm c.m.})$ over the 10° width of the angular bin is larger. [From Eq. (1), it results that P_T is proportional to $\vartheta_p^{\rm c.m.}$.] Overall, we believe that a reasonable uncertainty is larger than 100 MeV$/c$.

Then, to further check the consistency of data to the CCR prediction, we have fit all cross-section data at fixed proton angle between 55° and 125° and $P_T \geq 1.1$ GeV$/c$ to s^{-11}. We limited the fit to these angles, because at $\vartheta_p^{\rm c.m.} = 35°$, 45°, 135°, and 145° there are not enough data above $P_T = 1.1$ GeV$/c$ to make a reliable fit. These

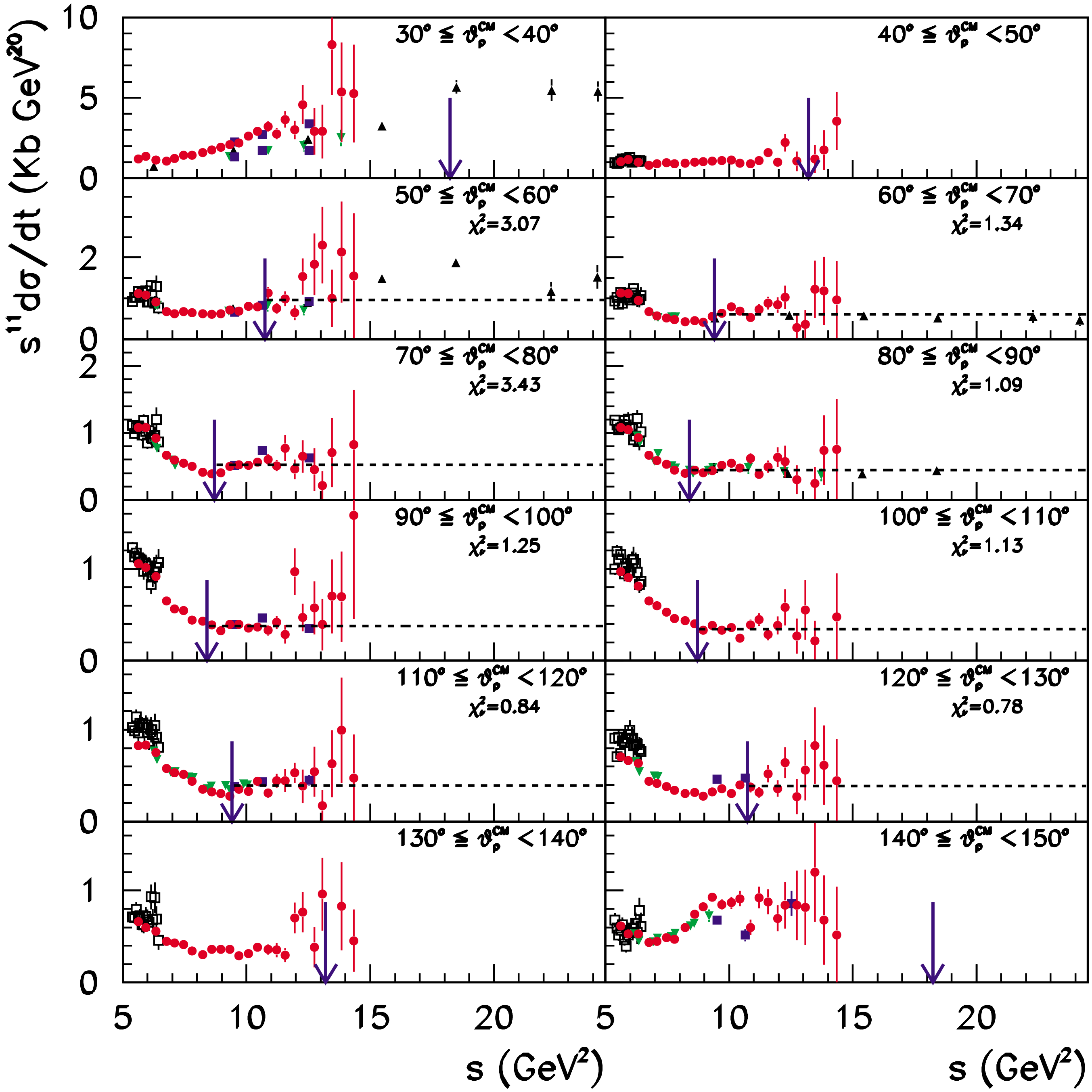

FIG. 2 (color). Deuteron photodisintegration cross section, $s^{11}d\sigma/dt$, as a function of s for the given proton scattering angles. Dashed lines are the fits of the data to s^{-11} for $P_T \geq 1.1$ GeV/c. The vertical arrows indicate the s value corresponding to $P_T = 1.1$ GeV/c. Fits are not shown for $\vartheta_p^{\mathrm{c.m.}} = 35°, 45°, 135°$, and $145°$ where there are not enough data above 1.1 GeV/c. Also shown in each panel is the χ^2_ν value of the fit. Data are from CLAS [12] (solid red circles), Mainz [15] (open black squares), SLAC [5–7] (solid down-pointing green triangles), JLab Hall A [11] (solid blue squares) and Hall C [8,9] (solid up-pointing black triangles).

fits are shown in Fig. 2 together with the data from all the high-energy $\gamma d \rightarrow pn$ experiments [5–9,11,12,15] used in this study. For a sake of clearness, data have been multiplied by s^{11}. The χ^2_ν of the fits are given in the plots. The vertical arrows indicate the s value corresponding to $P_T = 1.1$ GeV/c. It is worth noticing that for $\vartheta_p^{\mathrm{c.m.}} = 35°$ the last three points show a clear flat behavior well consistent with an s^{-11} dependence, as it is proven by the very low value $\chi^2_\nu = 0.03$ of the last P_T bin (1.10–1.30 GeV/c) in the first panel of Fig. 1.

For all but two of the fits, $\chi^2_\nu \leq 1.34$. At 55° and, in particular, at 75°, the worse χ^2_ν could be due to discrepancies in the absolute values of data from various experiments. As an example, the fit for 75° with the data sets [11,12] renormalized to each other gives a $\chi^2_\nu = 2.51$. This shows that the s^{-11} dependence of the cross section is established for $P_T \geq 1.1$ GeV/c. This is a necessary condition for the transition to the QCD scaling. Then, one might argue that the quark-gluon regime is reached for the proton transverse momenta above about 1.1 GeV/c.

In conclusion, the new, nearly complete angular distributions of two-body deuteron photodisintegration—obtained by CLAS at TJNAF for photon energies between 0.5 and 3.0 GeV—have been used, together with all previous data, for a detailed study of the power law s dependence of the differential cross section. The results show that the s^{-11} scaling has been reached for proton transverse momentum above about 1.1 GeV/c. This may indicate that the quark-gluon regime is reached above this momentum.

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