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Experimental tests of QCD scaling laws at large momentum transfer in exclusive light-meson photoproduction

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We evaluated CLAS Collaboration measurements for the 90° light pseudoscalar and vector meson photoproduction off the nucleon using a tagged photon beam spanning the energy interval $s = 3 - 11$ GeV^2. The results are compared with the Quark Counting Rule predictions. The role of the Sudakov form-factor is considered.

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Binary reactions in QCD with large momentum transfer involve quark and gluon exchanges between colliding particles. The quark counting rule (QCR) of Brodsky and Farrar [1] and Matveev, Muradyan, and Tavkhelidze [2] has a simple recipe to predict the energy dependence of the differential cross sections of two-body reactions at large meson scattering or production angles when t/s is finite and is kept constant. The fixed scattering angle behavior for exclusive processes is expected to be

$$d\sigma/dt(s) \propto s^{-(n-2)}, \tag{1}$$

where n is the minimum number of fundamental constituents (quarks) and s, t, and u are Mandelstam variables.

After the Brodsky-Lepage [3], the hard elastic scattering in QCD and the corrections to the leading behaviour were intensively discussed. For the hadron-proton interaction, the QCR works well, where the hadron is a pion, kaon, proton, or antiproton.

If the photon is assumed to be one elementary field, then the prediction for a meson photoproduction is

$$d\sigma/dt(s) \propto s^{-7}. \tag{2}$$

As has been observed, first of all at SLAC, the reaction $\gamma p \to \pi^+ n$ ($s = 8.4 - 15$ GeV^2) shows agreement with the QCR that predict the cross section should vary as s^{-7} [4]. However, the

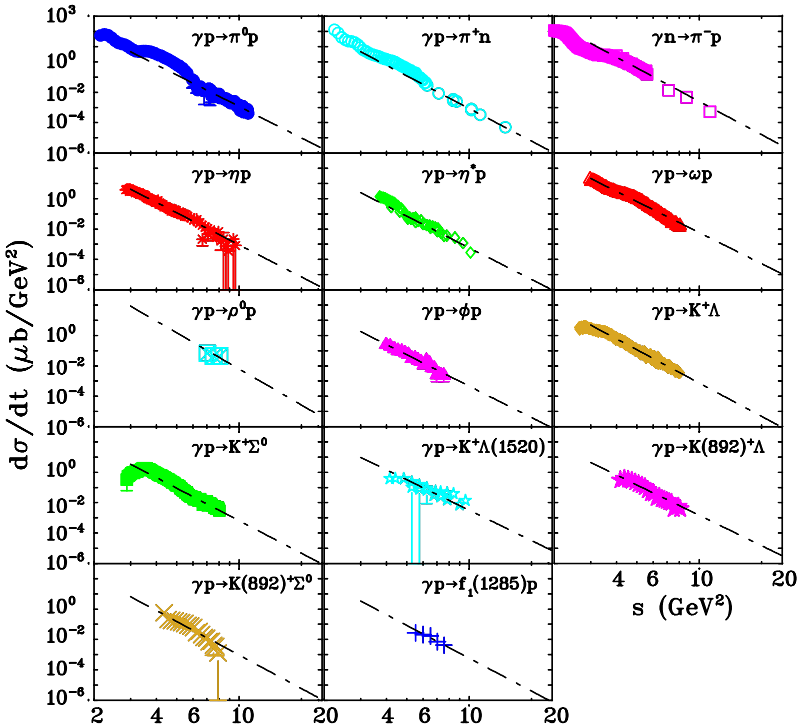

Figure 1: Differential cross section of $\gamma N \to MB$, dσ/dt, at large meson production angle $\theta = 90^\circ$ in c.m. as a function of invariant energy squared, s (here M is a meson and B is a baryon) [8]. The list of CLAS data is given in Ref. [8]. The black dash-dotted line is a result of the best-fits.

QCR account for the minimum numbers of elementary hard processes needed to provide a large momentum transfer to the hadron. At high energies, this rule is modified by the so-called Sudakov form factor (the probability not to emit any additional gluons) [5]. Thus for a very large s, we expect that the cross section of the large angle hadron-hadron scattering should fall down with s faster than the QCR prediction [6].

On the other hand, it was shown in Ref. [7] that due to the point-like nature of the photon, the Sudakov form factor is absent in the case of large angle meson photoproduction. Thus, photoproduction allows one to check the QCR directly in its original form.

In our recent paper [8], we examined how QCR is applicable to the lightest meson photoproduction off the nucleon up to $s = 11$ GeV^2, where modern data are available mostly produced by the CLAS Collaboration at Jefferson Laboratory. The minimum value of s in all these data exceeds 3 GeV^2. The CLAS high statistical cross sections at 90° in c.m. meson production angle are shown in Fig. 1. All these CLAS measurements are consistent with s^{-7} as was shown on Fig. 2 and scaling expected from the QCR. Oscillations observed at low energies (Fig. 1) indicate that the QCR requires higher energies and higher $|t|$ and $|u|$ before it can provide a valid description. Obviously, the extended energy range would be more definitive; our results do appear to be consistent with this limit. The JLab12, EIC, and EicC programs are capable of providing the data needed to improve our results.

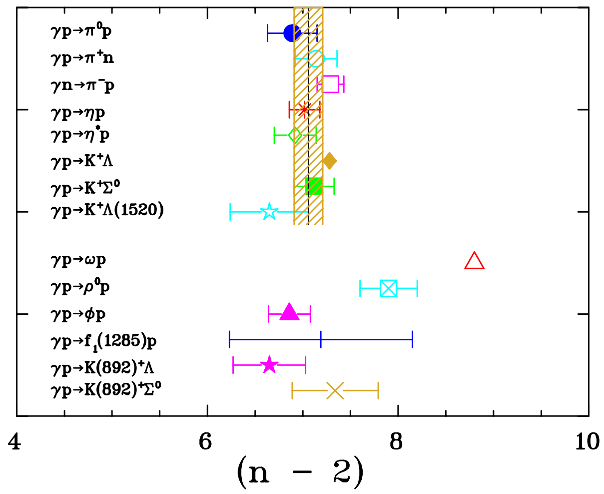

Figure 2: Power factor $(n-2)$ for light meson photoproduction off the nucleon came from the CLAS Collaboration [8]. Black solid vertical line shows average value for pseudoscalar-mesons $<(n-2)>=$ 7.06 ± 0.15. Yellow band presents its uncertainty. In the case of the ω, the result corresponds to the higher energy range, $s = 5 - 8.1$ GeV^2.

Recall that there are three options of how one can consider a photon when it interacts to nucleon: (i) No constituents: $(n_\gamma = 0)$ or $d\sigma/dt(s) \propto s^{-6}$, (ii) Photon is a point-like particle which participate the strong interaction: $(n_\gamma = 1)$ or $d\sigma/dt(s) \propto s^{-7}$, (iii) There is a $q\bar{q}$ configuration which actually participates in the strong interaction: $(n_\gamma = 2)$ or $d\sigma/dt(s) \propto s^{-8}$.

The explanation of the s^{-7} instead of s^{-8} or s^{-6} is: (i) In terms of Brodsky-Farrar [1]: "In photoproduction amplitude, the balance between the quarks momenta was provided by the highly virtual quark with propagator $1/\hat{q} \propto 1/\sqrt{s}$ instead of the gluon for which the propagator is $\propto 1/s$." (ii) It terms of Matveev *et al.* [2]: "In photoproduction, the incoming $q\bar{q}$ pair is produced (in the case of a large momentum transferred) very close to the interaction point and not in advance (at a large distance) as in the vector-meson dominance model. That is in the incoming state, we deal with a "point-like" $q\bar{q}$ pair and only in the final state we have two quarks separated by a large ($\sim 0.5 - 1$ fm) distances. The small factor corresponding to the probability to have two quarks very close to each other is needed now for the final state only (and not for the initial state). This leads to the root square of the usual $1/s^2$ factor."

Thanks to the point-like nature of the photon in high energy large angle scattering, there is no Sudakov form factor in these processes and the 90° cross section $d\sigma/dt \propto s^{-7}$ for the pseudoscalar-meson production [8]. The average value of $< (n-2) >$ for pseudoscalar-meson reactions is 7.06 ± 0.15. Obviously, the vector meson case requires more measurements.

Due to a vector nature of ω, ρ, and ϕ mesons in order to form the spin part of the corresponding wave function, we have to violate the s-channel helicity conservation (SCHC). Therefore, we have to expect an additional suppression of 90° high energy photoproduction [3]. Thus we can say that the observed energy dependence of vector meson cross section at a larger s is consistent with the QCR.

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