

# Wide-angle photoproduction of the $\eta'$ -meson and its gluon content

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We investigate wide-angle photoproduction of the  $\eta'$ -meson within the handbag approach to twist-3 accuracy. It turns out that, due to the gluon content of the  $\eta'$ , this process is dominated by twist 2 in contrast with pion and  $\eta$  photoproduction. Using the presently available information on the twist-2 and twist-3 distribution amplitudes and on the  $\eta - \eta'$  mixing, we provide prediction for the  $\eta'$  cross section and helicity correlations. It is argued that  $\eta'$  photoproduction is well suited to improve our knowledge of the two-gluon distribution amplitude.

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## I. INTRODUCTION

The  $\eta'$ -meson is a complicated object. It is mainly a flavor-singlet state with a small admixture of a flavor-octet component. This fact leads to the familiar  $\eta - \eta'$  mixing. A further complication of the description of the  $\eta'$ -meson is that, at the twist-2 level, there are two Fock components contributing to the flavor-singlet state, the quark-antiquark one and the two-gluon one. The associated distribution amplitudes,  $\Phi_{q1}(\tau, \mu_F)$  and  $\Phi_g(\tau, \mu_F)$ , mix under evolution. Here,  $\tau$  is a momentum fraction and  $\mu_F$  denotes the factorization scale. Moreover, it is expected that the twist-3 contribution, which includes two- and three-body ( $q\bar{q}g$ ) Fock components, also plays an important role since this is the case for pion and eta photoproduction [1] as well as deeply virtual electroproduction [2–4].

An accurate determination of the two-gluon distribution amplitude is of utmost importance since the corresponding Fock component of the  $\eta'$ , and to a lesser extent of the  $\eta$ , plays a role in many hard processes involving these mesons. Thus, the  $g^*g^*\eta'(\eta)$  vertex substantially contributes to decay processes such as  $\Upsilon(1S) \rightarrow \eta'X$  [5]. It also contributes to the inclusive [6] and exclusive central [7] production of the  $\eta'$  in high-energy proton-proton collisions at the LHC. The  $B \rightarrow \eta'$  form factor, appearing in  $B$ -meson decays into channels involving the  $\eta'$ , is affected by the  $gg$  Fock component of the  $\eta'$ -meson too [8]. More information

on the role of that Fock component can be found in the review by Bass and Moskal [9].

Information on the two-gluon distribution amplitude can be extracted from the  $\eta'(\eta)$ -photon transition form factor in a leading-twist analysis to next-to-leading order (NLO) of QCD [10,11]. However, the present data on these form factors [12–14] allow only to determine the first Gegenbauer coefficients,  $a_2^i$  and  $a_2^g$ , of the quark and gluon distribution amplitudes ( $i = 1, 8$ )<sup>1,2</sup>

$$\begin{aligned}\Phi_{qi}(\tau, \mu_F) &= 6\tau(1-\tau) \left[ 1 + \sum_{n=2,4,\dots} a_n^i(\mu_F) C_n^{3/2}(2\tau-1) \right], \\ \Phi_g(\tau, \mu_F) &= 30\tau^2(1-\tau)^2 \sum_{n=2,4,\dots} a_n^g(\mu_F) C_{n-1}^{5/2}(2\tau-1).\end{aligned}\quad (1)$$

The Gegenbauer coefficients depend on the factorization scale,  $\mu_F$ , and the flavor-singlet coefficients mix with the gluon ones under evolution [17].

The Gegenbauer coefficients  $a_2$  obtained in [11] and evolved to the scale  $\mu_0 = 2$  GeV, take the following values:

$$\begin{aligned}a_2^8(\mu_0) &= -0.039 \pm 0.016, \\ a_2^1(\mu_0) &= -0.057 \pm 0.012, \quad a_2^g(\mu_0) = 0.38 \pm 0.10.\end{aligned}\quad (2)$$

<sup>1</sup>Particle independence of the distribution amplitudes is assumed as in [10,11]. Since in hard processes only small spatial quark-antiquark (gluon-gluon) separations are relevant it seems plausible to embed the particle dependence solely in the decay constants, see also [15].

<sup>2</sup>In order to facilitate comparison with other work we have changed the definition of the gluon distribution amplitude [16] compared to our previous work [10,11].

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The contribution  $\propto a_2^g$  is small for the  $\gamma\eta'$  form factor since it is suppressed by the strong coupling,  $\alpha_s$ . The coefficients (2) are to be regarded as effective ones; they may be contaminated by contributions from higher order coefficients. Data on the  $\gamma^*\eta'(\eta)$  form factor would, in principle, allow for an extraction of the first few real Gegenbauer coefficients since, for this form factor, the order  $n$  coefficients are suppressed by  $\omega^n$  where  $\omega$  is the difference of the two photon virtualities divided by their sum. However, the present data [18] on that form factor are not accurate enough for such an analysis [16]. Nevertheless, the values quoted in (2) are consistent with these data.

Another source of information on the gluon distribution amplitude is provided by the inclusive  $\Upsilon(1S) \rightarrow \eta'X$  decays. Ali and Parkhomenko [5] used the data on these decays in combination with positivity constraints for the  $\eta'g^*g$  vertex functions and found for the singlet Gegenbauer coefficients the values

$$a_2^1(\mu_0) = -0.04 \pm 0.02, \quad a_2^g(\mu_0) = 0.12 \pm 0.05. \quad (3)$$

The flavor-octet contribution was ignored in this analysis.

Wide-angle photoproduction of the  $\eta'$  offers a new possibility to learn about the two-gluon distribution amplitude. The advantage of this process over the transition form factors is that the gluon distribution amplitude contributes to leading order now [19]. The analysis of this process is the subject of the present article. For comparison we occasionally refer to  $\eta$  photoproduction. Our study is timely since the GlueX experiment at the Jefferson Lab will measure this process.

The plan of the paper is as follows: In Sec. II we recapitulate the handbag approach to wide-angle photoproduction of pseudoscalar mesons and  $\eta - \eta'$  mixing. In the next section we present the twist-2 and twist-3 subprocess amplitudes for the flavor-octet and -singlet contributions. They are basically taken from our preceding papers [1, 19–21]. In Sec. IV we discuss properties and predictions for the cross section and helicity correlations for  $\eta'$ , as well as  $\eta$ , photoproduction. The paper ends with our summary.

## II. HANDBAG FACTORIZATION

The theoretical framework for wide-angle photoproduction of  $\eta'$ -mesons is the generalization of the treatment of pion production<sup>3</sup> [1]. Thus, for Mandelstam variables,  $s$ ,  $-t$  and  $-u$ , much larger than  $\Lambda^2$  where  $\Lambda$  is a typical hadronic scale of order 1 GeV, one can apply handbag factorization in a symmetrical center-of-mass frame in which skewness, defined by

<sup>3</sup>The photoproduction of the  $\eta$ -meson has also been investigated in [1]. However, the contribution from the  $gg$  Fock component has been ignored in that work which, for the  $\eta$ -meson, is a reasonable simplification.

$$\xi = \frac{(p - p')^+}{(p + p')^+}, \quad (4)$$

is zero [20,22]. The momenta of the ingoing and outgoing protons are denoted by  $p$  and  $p'$ , respectively. With the help of a few plausible assumptions one can show that the Mandelstam variables of the partonic subprocess,  $\hat{s}$ ,  $\hat{t}$  and  $\hat{u}$ , coincide with the ones for the full process up to corrections of order  $\Lambda^2/s$ :

$$\hat{t} \simeq t, \quad \hat{s} \simeq s, \quad \hat{u} \simeq u. \quad (5)$$

The active partons, i.e., those which participate in the subprocess, are approximately on shell, move collinear with their parent hadron and carry a momentum fraction close to unity. As in deeply virtual exclusive scattering the physical situation is that of a hard parton-level subprocess,  $\gamma q_a \rightarrow \eta' q_a$ , and a soft emission and reabsorption of quarks from the proton. Up to corrections of order  $\Lambda/\sqrt{-t}$  the (light-cone) helicity amplitudes of wide-angle photoproduction of the  $\eta'$  are given by a product of subprocess amplitudes,  $\mathcal{H}$ , and form factors which represent  $1/x$ -moments of zero-skewness generalized parton distributions (GPDs):

$$\begin{aligned} \mathcal{M}_{0+,\mu+}^{(i)} &= \frac{e_0}{2} \sum_{\lambda} \left[ \mathcal{H}_{0\lambda,\mu\lambda}^i(R_V^i(t) + 2\lambda R_A^i(t)) \right. \\ &\quad \left. - 2\lambda \frac{\sqrt{-t}}{2m} \mathcal{H}_{0-\lambda,\mu\lambda}^i \bar{S}_T^i(t) \right], \\ \mathcal{M}_{0-,\mu+}^{(i)} &= \frac{e_0}{2} \sum_{\lambda} \left[ \frac{\sqrt{-t}}{2m} \mathcal{H}_{0\lambda,\mu\lambda}^i R_T^i(t) \right. \\ &\quad \left. - 2\lambda \frac{t}{2m^2} \mathcal{H}_{0-\lambda,\mu\lambda}^i S_S^i(t) \right] + e_0 \mathcal{H}_{0-,\mu+}^i S_T^i(t), \quad (6) \end{aligned}$$

where  $i$  is either the flavor singlet or octet amplitude and  $\mu$  denotes the helicity of the photon,  $\lambda$  that one of the active quark and  $e_0$  the positron charge. According to [15] the helicity amplitudes for  $\eta'$  and  $\eta$  production are given by

$$\begin{aligned} \mathcal{M}^{\eta'} &= \sin \theta_8 \mathcal{M}^{(8)} + \cos \theta_1 \mathcal{M}^{(1)}, \\ \mathcal{M}^{\eta} &= \cos \theta_8 \mathcal{M}^{(8)} - \sin \theta_1 \mathcal{M}^{(1)}. \quad (7) \end{aligned}$$

For the mixing angles the phenomenological values [15]

$$\theta_8 = -(21.2 \pm 1.4)^\circ, \quad \theta_1 = -(9.2 \pm 1.4)^\circ, \quad (8)$$

are adopted. These values are in reasonable agreement with the results from a recent lattice QCD study [23] and from the broken hidden symmetry model [24]. Somewhat larger differences to the values given in (8) have been found by Escribano and Frere [25] in a phenomenological study of the decays of pseudoscalar and vector mesons. Since their

results lead to strong violations of the Okubo-Zweig-Iizuka rule we do not use their mixing parameters.

The form factors  $R_V$ ,  $R_A$  and  $R_T$  are related to the helicity non-flip GPDs,  $H$ ,  $\tilde{H}$  and  $E$ , at zero skewness, respectively. These form factors go together with quark helicity nonflip in the subprocess, i.e., with the twist-2 subprocess amplitude  $\mathcal{H}_{0\lambda,\mu\lambda}$ . The second set of form factors,  $S_T$ ,  $\tilde{S}_T$  and  $S_S$ , are related to the helicity-flip or transversity GPDs  $H_T$ ,  $\tilde{E}_T$  and  $\tilde{H}_T$ , at zero skewness, respectively. These form factors are multiplied in (6) by the quark helicity-flip subprocess amplitude  $\mathcal{H}_{0-\lambda,\mu\lambda}$  which is of twist-3 nature.<sup>4</sup>

As discussed in [1] the flavor-octet and singlet form factors  $F_j^{(i)}(t) = R_j^{(i)}(t), S_j^{(i)}(t)$  read ( $e_a$  is the charge of a flavor- $a$  quark in units of the positron charge)

$$F_j^{(8)} = \frac{1}{\sqrt{2}} F_j^{(1)} = \frac{1}{\sqrt{6}} [e_u F_j^u + e_d F_j^d] \quad (9)$$

for a proton target where the flavor form factors are

$$F_j^a(t) = \int_0^1 \frac{dx}{x} K_j^a(x, \xi = 0, t). \quad (10)$$

For charge-conjugation even mesons only valence quarks contribute.<sup>5</sup> For a neutron target the form factors, expressed in terms of proton GPDs,  $K_j^a$ , read [1]

$$F_{jn}^{(8)} = \frac{1}{\sqrt{2}} F_{jn}^{(1)} = \frac{1}{\sqrt{6}} [e_u F_j^d + e_d F_j^u]. \quad (11)$$

For the numerical estimates of  $\eta'$  photoproduction we take the same form factors as in [1]. The  $R$ -type form factors are rather well known since they are evaluated from the zero-skewness GPDs determined in an analysis of the electromagnetic nucleon form factors [26]. The transversity GPDs,  $H_T$  and  $\tilde{E}_T$ , are extracted from data on deeply virtual pion electroproduction at low  $-t$  [2]. Their large  $-t$  behavior is adjusted to the CLAS data on wide-angle  $\pi^0$  photoproduction [27]. The form factor  $S_S$  is assumed<sup>6</sup> to be  $\tilde{S}_T/2$ . The  $S$ -type form factors demand improvements. However, these form factors are not implausible as a comparison with preliminary GlueX data [28] on  $\eta$  photoproduction reveals (at  $s = 16.36 \text{ GeV}^2$ ), see Sec. IV.

<sup>4</sup>Twist-3 effects can also be generated by twist-3 GPDs. However, these are expected to be small and therefore neglected here as in [1].

<sup>5</sup>In the handbag approach for wide-angle photo- and electroproduction of pseudoscalar mesons, the contributions from sea quarks are generally strongly suppressed. The sea-quark form factors drop typically as  $F_j^{\text{sea}}(t) \sim 1/(-t)^4$  [1,21].

<sup>6</sup>The form factor  $S_S$  is associated to the GPD  $\tilde{H}_T$  for which no information is available. As an estimate of its significance we take  $S_S \simeq \tilde{S}_T/2$  which, due to  $\tilde{E}_T = 2\tilde{H}_T + E_T$ , corresponds to the neglect of the GPD  $E_T$  [1].

### III. THE SUBPROCESS AMPLITUDES

Typical leading-order Feynman graphs for the subprocess  $\gamma q_a \rightarrow \eta' q_a$  are shown in Fig. 1. We stress that in the soft meson and nucleon matrix elements defining the distribution amplitudes and GPDs, we are using light-cone gauge. The twist-2 subprocess amplitudes read<sup>7</sup> [19,20]

$$\begin{aligned} \mathcal{H}_{0\lambda,\mu\lambda}^{(8),\text{tw}2} &= \sqrt{2}\pi\alpha_s(\mu_R) f_8 \frac{C_F}{N_C} \frac{\sqrt{-\hat{t}}}{\hat{s}\hat{u}} \\ &\quad \times \langle 1/\tau \rangle_{q8} [(1 + 2\lambda\mu)\hat{s} - (1 - 2\lambda\mu)\hat{u}], \\ \mathcal{H}_{0\lambda,\mu\lambda}^{(1),\text{tw}2} &= \sqrt{2}\pi\alpha_s(\mu_R) f_1 \frac{C_F}{N_C} \frac{\sqrt{-\hat{t}}}{\hat{s}\hat{u}} [\langle 1/\tau \rangle_{q1} - \langle 1/\tau^2 \rangle_g] \\ &\quad \times [(1 + 2\lambda\mu)\hat{s} - (1 - 2\lambda\mu)\hat{u}], \end{aligned} \quad (12)$$

where

$$\begin{aligned} \langle 1/\tau \rangle_{qi} &= \int_0^1 \frac{d\tau}{\tau} \Phi_{qi}(\tau, \mu_F) \simeq 3[1 + a_2^i(\mu_F)], \\ \langle 1/\tau^2 \rangle_g &= \int_0^1 \frac{d\tau}{\tau^2} \Phi_g(\tau, \mu_F) \simeq -25a_2^g(\mu_F) \end{aligned} \quad (13)$$

for the truncated Gegenbauer expansions of the distribution amplitudes defined in (1). As usual  $C_F = (N_C^2 - 1)/(2N_C)$  is a color factor,  $N_C$  denotes the number of colors and  $\mu_R$  is the renormalization scale.

The octet and singlet decay constants are taken from [15] ( $f_\pi = 132 \text{ MeV}$ )<sup>8</sup>:

$$f_8 = (1.26 \pm 0.06)f_\pi, \quad f_1 = (1.17 \pm 0.04)f_\pi. \quad (14)$$

In contrast to the mixing angles and  $f_8$ , the singlet decay constant is factorization scale dependent but this is an NLO effect [30] which we ignore for consistency as has been done in [15]. In a recent lattice QCD study [23] the scale dependence of  $f_1$  has indeed been observed and its value at the scale 1 GeV agrees very well with the one quoted in (14). Thus, one may assume that the latter value holds at  $\mu_F \simeq 1 \text{ GeV}$ . We would like to add that also  $f_8$  determined in [23] is in good agreement with the above given value.

As shown in [1,21] the twist-3 contribution plays an important role in the photoproduction of pseudoscalar mesons. The flavor-octet case, with the distribution amplitude  $\Phi_{38}$ , is discussed in detail in [1]. The flavor-singlet component, to which a distribution amplitude  $\Phi_{31}$  contributes, has a similar structure. The absence of two- and three-gluon twist-3 contributions can be understood as follows:

<sup>7</sup>We remark that in deeply virtual electroproduction of the  $\eta'$ -meson the gluon-gluon contribution to the subprocess amplitudes is suppressed by  $\hat{t}/Q^2$  in the generalized Bjorken regime, see [10].

<sup>8</sup>The mixing angles and the decay constants can solely be expressed in terms of particle masses. These expressions lead to values for these parameters in very good agreement to those given in (8) and (14), see [29].

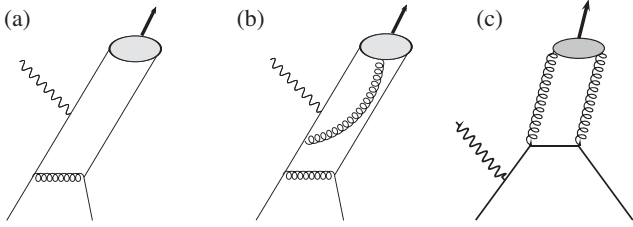


FIG. 1. Typical Feynman graphs for wide-angle photoproduction of the  $\eta'$  ( $\eta$ ) meson: (a) twist-2 and twist-3 for  $\gamma q \rightarrow (q\bar{q})q$ , (b) twist-3 for  $\gamma q \rightarrow (q\bar{q}q)q$ , (c) twist-2 for  $\gamma q \rightarrow (gg)q$ .

Consider an  $\eta'$ -meson moving rapidly along the 3-axis. A light-cone wave function of its  $n$ -parton Fock component with orbital angular momentum projection onto the 3-direction,  $l_3$ , has the dimension  $[\text{mass}]^{(n+|l_3|-1)}$  [31]. In a hard exclusive process this dimension has to be balanced by corresponding inverse powers of the hard scale,  $\sqrt{s}$  in our case. The associated distribution amplitude, i.e., the light-cone wave function integrated upon the parton transverse momenta, is of twist  $n + |l_3|$  nature. Now, consider an  $\eta'$  Fock component consisting of two massless gluons. Its total helicity, i.e., its total spin projection on the 3-direction,  $s_3$ , is either zero or  $\pm 2$ . Hence, for a spin-0 hadron either  $|l_3| = 0$  or 2 is required. The  $l_3 = 0$  case leads to the twist-2 distribution amplitude given in (1), which contributes to the subprocess amplitude  $\mathcal{H}^{(1),\text{tw}2}$  quoted in (12). The  $|l_3| = 2$  one is of twist-4 nature and is neglected here in this work. For a three-gluon state one has either  $s_3 = \pm 1$  or 3, demanding  $|l_3| = 1$  or 3, respectively. The associated distribution amplitudes are of twist-4 or higher nature. Hence, there is neither a two-gluon nor a three-gluon twist-3 distribution amplitude for the  $\eta'$ -meson. These observations are in accordance with the glueball spectrum [32,33].

The three-body flavor-singlet distribution amplitude,  $\Phi_{31}$ , is completely unknown as yet. The situation for the flavor-octet distribution amplitude is somewhat better. Flavor symmetry tells us that  $\Phi_{38}$  should be close to  $\Phi_{3\pi}$  which is supported by a QCD sum rule study [34]. Thus, the best one can do at present is to assume

$$\Phi_{38}(\tau_a, \tau_b, \tau_g) = \Phi_{31}(\tau_a, \tau_b, \tau_g) \simeq \Phi_{3\pi}(\tau_a, \tau_b, \tau_g). \quad (15)$$

We stress that the assumption on  $\Phi_{31}$  is a pure guess. The twist-3 pion distribution amplitude is taken from [1] where a truncated Jacobi-polynomial expansion [35] has been employed. Therefore, we have

$$\begin{aligned} \Phi_{38}(\tau_a, \tau_b, \tau_g, \mu_F) &= \Phi_{31}(\tau_a, \tau_b, \tau_g, \mu_F) \\ &= 360\tau_a\tau_b\tau_g^2 \left[ 1 + \omega_{1,0}(\mu_F)\frac{1}{2}(7\tau_g - 3) \right. \\ &\quad + \omega_{2,0}(\mu_F)(2 - 4\tau_a\tau_b - 8\tau_g + 8\tau_g^2) \\ &\quad \left. + \omega_{1,1}(\mu_F)(3\tau_a\tau_b - 2\tau_g + 3\tau_g^2) \right]. \quad (16) \end{aligned}$$

The variable  $\tau_g$  refers to the fraction of the meson momentum the gluon carries. The expansion coefficients are [1]

$$\omega_{1,0}(\mu_0) = -2.55, \quad \omega_{1,1}(\mu_0) = 0. \quad (17)$$

As in [1,21] we consider the coefficient  $\omega_{2,0}$  as a free parameter fitted to available data, in the present case to the preliminary GlueX data [28] on  $\eta$  photoproduction.<sup>9</sup> The expansion coefficients  $\omega_{2,0}$  and  $\omega_{1,1}$  mix under evolution. The three-body twist-3 distribution amplitudes are to be multiplied by the normalizations  $f_{3i}$  ( $i = 8, 1$ ), defined such that the corresponding distribution amplitudes integrated upon the momentum fractions are unity. For the normalizations we take similarly to [1]

$$f_{38}(\mu_0) = 0.86f_{3\pi}(\mu_0), \quad f_{31}(\mu_0) = 0.86f_{3\pi}(\mu_0), \quad (18)$$

with

$$f_{3\pi}(\mu_0) = 0.004 \pm 0.001 \text{ GeV}^2. \quad (19)$$

The normalizations  $f_{38}$  and  $f_{3\pi}$  are supported by QCD sum rule studies [34,35]. The value of  $f_{31}$  is a supposition which is, to some extent, justified by the fair agreement of our predictions with the preliminary GlueX data [28] on wide-angle photoproduction of the  $\eta$ -meson.

There are also two two-body twist-3 distribution amplitudes,  $\Phi_{\rho i}$  and  $\Phi_{\sigma i}$ . They are not needed explicitly here, since, due to the equation of motion [1], the complete twist-3 subprocess amplitude can solely be expressed by the three-body distribution amplitude.<sup>10</sup> It reads

$$\begin{aligned} \mathcal{H}_{0-\lambda,\mu\lambda}^{(i),\text{tw}3} &= 2\sqrt{2}\pi(2\lambda - \mu)\alpha_s(\mu_R)\frac{C_F}{N_C}f_{3i}(\mu_F)\frac{\sqrt{-\hat{u}\hat{s}}}{\hat{s}^2\hat{u}^2}\int_0^1 d\tau \\ &\quad \times \int_0^{\bar{\tau}} \frac{d\tau_g}{\tau_g}\Phi_{3i}(\tau, \bar{\tau} - \tau_g, \tau_g, \mu_F) \\ &\quad \times \left[ \left( \frac{1}{\bar{\tau}^2} - \frac{1}{\bar{\tau}(\bar{\tau} - \tau_g)} \right) (\hat{s}^2 + \hat{u}^2) \right. \\ &\quad \left. - \left( 1 - \frac{1}{2}\frac{N_C}{C_F} \right) \left( \frac{1}{\tau} + \frac{1}{\bar{\tau} - \tau_g} \right) \frac{\hat{t}(\hat{s} + \hat{u})}{\tau_g} \right]. \quad (20) \end{aligned}$$

The subprocess amplitudes,  $\mathcal{H}^{(i),\text{tw}2}$  (12) and  $\mathcal{H}^{(i),\text{tw}3}$ , satisfy current conservation and are gauge invariant in QCD.

<sup>9</sup>For comparison we repeat the value of this coefficient for the pion:  $\omega_{20} = 8.0$  if evolution of distribution amplitudes is taken into account and 10.3 for the fixed-scale calculation.

<sup>10</sup>This result implies that the Wandzura-Wilczek approximation is zero in hard wide-angle photoproduction of pseudoscalar mesons.

#### IV. PREDICTIONS ON AND PROPERTIES OF $\eta'$ PHOTOPRODUCTION

Before we present numerical results on  $\eta'$  photoproduction an important issue, the energy dependence of the cross section, is to be discussed. According to leading-twist dimensional counting the cross sections for photoproduction of pseudoscalar mesons should scale as  $s^{-7}$  at fixed  $\cos\theta$  where  $\theta$  is the scattering angle in the center-of-mass system. Further energy dependence comes from the running of  $\alpha_s$ , the evolution of the decay constants and the distribution amplitudes as well as from the twist-3 contribution which is suppressed by  $1/\sqrt{s}$  at the amplitude level compared to the twist-2 one, cf. (12) and (20). The soft form factors also contribute to the extra energy dependence except they, including possible prefactors of  $\sqrt{-t}$  and  $t$  appearing in (6), fall  $\propto 1/t^2$ . For the present parametrization [1,21] the form factors fall slightly faster and the  $d$ -quark form factors even faster than the  $u$ -quark ones. In the range of  $s$  between, say, 10 and 20  $\text{GeV}^2$  our cross sections for  $\eta'$  and  $\eta$  photoproduction effectively fall

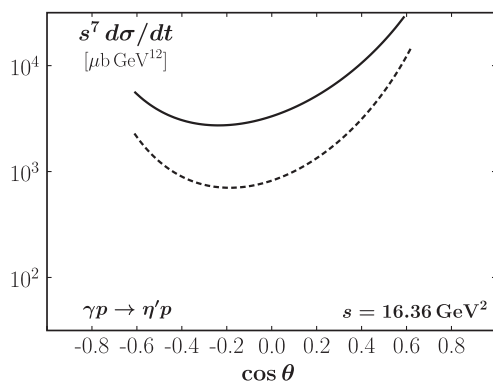
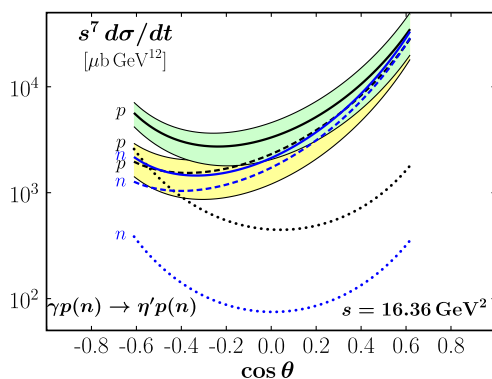


FIG. 2. The  $\eta'$  cross section, scaled by  $s^7$ , at  $s = 16.36 \text{ GeV}^2$  with (dashed line) and without evolution (solid line). The twist-3 expansion coefficient  $\omega_{2,0}$  is 6.0.



about as  $s^{-9}$ . This is perhaps too strong. We stress that  $\eta'$  photoproduction has not been measured yet in the wide-angle region at high energies and for  $\eta$  photoproduction we only have at disposal the preliminary GlueX data [28] at a single energy  $s = 16.36 \text{ GeV}^2$ . Only for pion photoproduction there are data for several values of large  $s$  available from an old SLAC experiment [36] which, for  $\pi^+$  production, are in agreement with the dimensional counting result of a  $s^{-7}$  drop. One may however wonder why the QCD logarithms from the evolution and from the running of  $\alpha_s$  are not perceptible. For  $\pi^0$  production the situation is unclear since the SLAC data are not compatible with the recent CLAS measurement [27].

In this situation we follow the remedy advocated for in [21] and evaluate the cross sections at the fixed scale  $\mu_R = \mu_F = 1 \text{ GeV}$ . In this case the effective energy dependence of the cross sections is milder, about  $s^{-8}$ . This can be seen from Fig. 2 where we display the  $\eta'$  cross section evaluated with the fixed and with the running scale at  $s = 16.36 \text{ GeV}^2$ . This value of  $s$  is chosen in order to facilitate the comparison with the GlueX data on  $\eta$  photoproduction [28] as soon as they are published. For the evaluation of the cross sections we use the mixing angles (8), the twist-2 parameters (2) and (14) as well as the twist-3 ones, (17) and (18). As in our previous work [1,21] for the running scale we take  $\mu_F = \mu_R = \hat{t}\hat{u}/\hat{s}$  and evaluate  $\alpha_s(\mu_R)$  from the one-loop approximation with  $\Lambda_{\text{QCD}} = 0.22 \text{ GeV}$  and  $n_f = 4$  flavors. The anomalous dimensions required for the evolution of the various distribution amplitudes have been derived in [17,34,35] and are systematized in [11,21]. We see that without evolution the cross section is substantially larger than with evolution. All results shown in the following are evaluated at the fixed scale. As soon as sufficient data on these cross sections will become available the issue of the scale dependence is to be taken up again.

In Fig. 3 we display the  $\eta'$  cross sections for a proton and a neutron target at  $s = 16.36 \text{ GeV}^2$ . For comparison we also show the analogous  $\eta$  cross section. The expansion

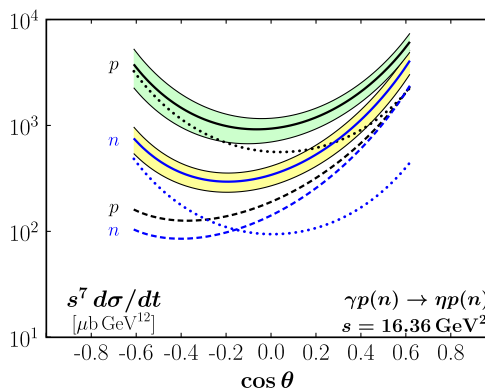


FIG. 3.  $\eta'$  (left) and  $\eta$  (right) cross sections, scaled by  $s^7$ , at  $s = 16.36 \text{ GeV}^2$  and  $\omega_{2,0} = 6.0$ . Solid (dashed, dotted) lines are for the full (twist 2, twist 3) cross sections for a proton (labeled p) and neutron (labeled n) target. The parameters are (2), (17) and (21). The shaded bands represent the parametric errors of the full cross sections.

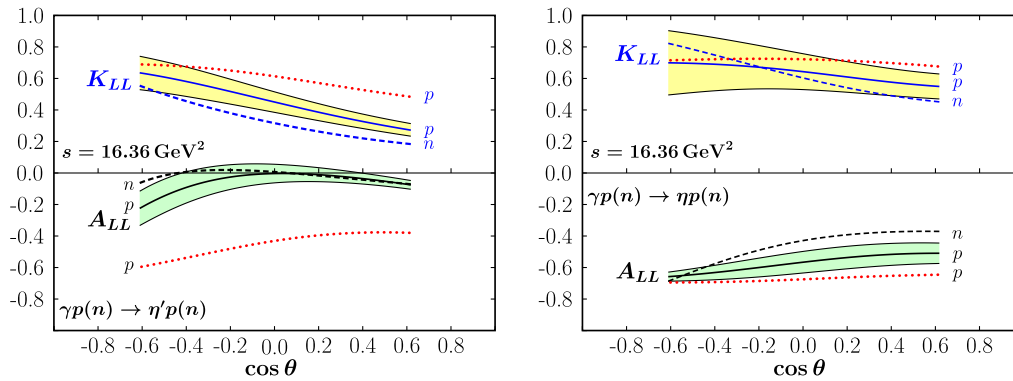


FIG. 4. The helicity correlations  $A_{LL}$  and  $K_{LL}$  for  $\eta'$  (left) and  $\eta$  (right) photoproduction off protons (solid lines) and off neutrons (dashed lines) at  $s = 16.36 \text{ GeV}^2$ . Solid lines: using the parameters (2), (17) and (21); dotted lines: using the twist-2 singlet coefficients (3) and  $\omega_{20}(\mu_0) = 7.3$ . The shaded bands represent the parametric errors of  $A_{LL}$  and  $K_{LL}$  for  $\eta$  and  $\eta'$  photoproduction off protons.

coefficient  $\omega_{2,0}$  of the twist-3 distribution amplitudes  $\Phi_{38} = \Phi_{31}$ , fitted to the available  $\gamma p \rightarrow \eta p$  cross section data<sup>11</sup> [28], is

$$\omega_{2,0}(\mu_0) = 6.0. \quad (21)$$

We also show in Fig. 3 the pure twist-2 and twist-3 contributions separately. As is evident from this plot twist 2 predominates  $\eta'$  photoproduction for  $\cos \theta \geq 0$  both for proton and neutron target. In the backward region the twist-2/twist-3 interference is substantial and, for a proton target, twist 3 is large for  $\cos \theta \lesssim -0.4$ . On the other hand, twist 3 predominates  $\eta$  photoproduction off protons except in the very forward region where the twist-2 contribution is of about the same size as the twist-3 one. For a neutron target the forward hemisphere is dominated by twist 2, the backward one by twist 3. The twist-2/twist-3 interference is strong in both regions. In Fig. 3 we also display error bands. They represent the parametric errors of the cross sections evaluated from all errors mentioned in the text as well as from those of the soft form factors [1,26]. For  $\eta'$  production the most important error is that of the twist-2 parameter  $a_2^g$  [see Eq. (2)] except for  $\cos \theta \lesssim -0.4$  where also the error of  $f_{3\pi}$  [see Eqs. (18) and (19)] matters. The latter error influences strongly the error bands for  $\eta$  production for all relevant scattering angles.

Interesting spin-dependent observables are the correlations between the helicities of the photon and that of either the incoming or the outgoing nucleon,  $A_{LL}$  and  $K_{LL}$ , respectively. As we showed in [1], for twist 2, one has

$$A_{LL}^{\text{tw}2} = K_{LL}^{\text{tw}2} \quad (22)$$

whereas for twist 3

<sup>11</sup>The GlueX collaboration did not give us the permission to show their data.

$$A_{LL}^{\text{tw}3} = -K_{LL}^{\text{tw}3} \quad (23)$$

holds. In Fig. 4 we display these correlations for  $\eta$  and  $\eta'$  photoproduction.<sup>12</sup> The pattern of curves is very different for the two cases. For  $\eta$  photoproduction approximate mirror symmetry is to be seen, implying strong twist-3 contributions in accordance with the behavior of the corresponding cross section, see Fig. 3. For  $\eta'$  photoproduction, on the other hand, the correlation  $A_{LL}$  is much smaller in absolute value than  $K_{LL}$ . This indicates a larger significance of twist 2. We emphasize that the twist-2/twist-3 interference is more important for the helicity correlations than for the cross sections.

The results for cross sections and helicity correlations at  $s = 16.36 \text{ GeV}^2$  are characteristic for the energy range  $10 \text{ GeV}^2 \lesssim s \lesssim 20 \text{ GeV}^2$  in the wide-angle region defined by  $-t$  and  $-u$  larger than about  $2.5 \text{ GeV}^2$  and  $|\cos \theta| \lesssim 0.6$ . The relative order of twist-2 and twist-3 contributions remains about the same in the wide-angle region although for increasing  $s$  twist 2 becomes more important. Asymptotically the twist-2 contribution dominates.

It remains to examine the influence of the unknown flavor-singlet twist-3 distribution amplitude for which we made the assumptions (15) and (18). In order to check that we drastically enlarge the flavor-singlet twist-3 contribution by multiplying it by 1.3. Doing so we observe that, for  $\cos \theta \simeq 0.6$  the  $\eta'$  cross section off protons (neutrons) changes by about  $\pm 10(7)\%$ . The effect on the cross section increases with decreasing  $\cos \theta$ . It amounts to about  $\pm 20(12)\%$  at  $\cos \theta \simeq 0$  and to about  $\pm 50(30)\%$  at  $\cos \theta \simeq -0.6$ .

The above discussion in combination with Figs. 3 and 4 makes it clear that photoproduction of the  $\eta'$ -meson in the

<sup>12</sup>The  $\mathcal{M}_{0\lambda',\mu\lambda}$  are light-cone helicity amplitudes. For comparison with experimental data on spin-dependent observables the use of the ordinary helicity basis is more convenient. The transform of the light-cone helicity amplitudes to the ordinary helicity ones is discussed for photoproduction of pseudoscalar mesons in [1].

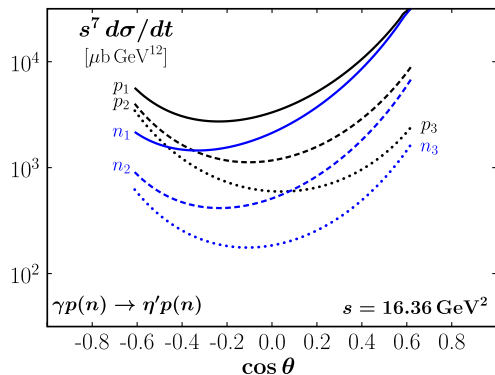


FIG. 5. The cross section for  $\eta'$  photoproduction off protons and off neutrons at  $s = 16.36 \text{ GeV}^2$  for three different scenarios. Solid lines: expansion coefficients according to (2), (17) and (21); dashed lines: using the twist-2 singlet coefficients (3) and  $\omega_{20}(\mu_0) = 7.3$ ; dotted lines: using  $a_2^8(\mu_0) = a_2^1(\mu_0) = a_{2\pi}(\mu_0)$ ,  $a_2^9(\mu_0) = 0$  and  $\omega_{20}(\mu_0) = 7.8$ .

forward hemisphere seems to be suitable for a determination of the twist-2 gluon-gluon distribution amplitude. In order to see whether this result also holds for flavor-singlet distribution amplitudes that are not close to the one given in Eq. (2) we next evaluate the  $\eta'$  and  $\eta$  cross sections for the twist-2 flavor-singlet expansion coefficients (3) but keeping the value  $a_2^8(\mu_0)$  given in (2). All other parameters remain unchanged except of  $\omega_{2,0}$  which is taken to be 7.3 in order to have still fair agreement with the GlueX data [28] on the  $\eta$  cross section. The results on the  $\eta$  cross section for this set of parameters lie within the error band shown in Fig. 3. The predictions on the  $\eta'$  cross section are shown in Fig. 5. We see that for this second scenario the  $\eta'$  cross section is substantially smaller than that one obtained from the flavor-singlet Gegenbauer coefficients given in Eq. (2). Nevertheless we have twist-2 dominance in the forward hemisphere and the helicity correlations differ only mildly from those obtained with the first set of parameters, see Fig. 4. At present we cannot say which of the scenarios is to be favored.

For comparison we also display in Fig. 5 results of a third scenario for which the gluon distribution amplitude is assumed to be zero at the initial scale  $\mu_0$  and  $a_2^8(\mu_0) = a_2^1(\mu_0) = a_{2\pi}(\mu_0)$ . For the second Gegenbauer coefficient of the pion distribution amplitude we take a recent lattice QCD result [37]:  $a_{2\pi}(\mu_0) = 0.1364$ . We now take  $\omega_{2,0} = 7.8$  which, as for the other scenarios, also leads to fair agreement with the GlueX data [28]. For this extreme scenario the  $\eta'$  cross section is even smaller than for the second one. The twist-3 contribution to the  $\eta'$  cross section now also dominates in the forward hemisphere. In accordance with that the helicity correlations are now similar to those of  $\eta$  production.

## V. SUMMARY

We have investigated wide-angle photoproduction of  $\eta'$ -mesons at high energies within the handbag approach in which the process amplitudes factorize into hard perturbatively calculable subprocesses and soft form factors representing  $1/x$  moments of GPDs. The soft form factors for given flavors are taken from our analysis of pion photoproduction [1]. For the evaluation of the subprocess amplitudes the twist-2 and twist-3 distribution amplitudes for flavor-singlet and -octet components of the  $\eta'$ -mesons are needed. Whereas fair knowledge of the flavor-octet distribution amplitudes is available the twist-2 flavor-singlet distribution amplitudes, the quark-antiquark one as well as the gluon-gluon one, are poorly known. The available information mainly comes from a NLO analysis of the  $\eta$ - and  $\eta'$ -photon transition form factor. The twist-3 flavor-singlet distribution amplitude is yet totally unknown. Assuming  $\Phi_{38} = \Phi_{31}$  and  $f_{38} = f_{31}$ , we have found that  $\eta'$  photoproduction is dominated by the twist-2 contribution in the forward hemisphere. Thus, the twist-3 flavor-singlet distribution amplitude plays only a minor role for  $\eta'$  photoproduction in that region. This is to be contrasted with  $\eta$  photoproduction where the twist-3 contributions play the leading role. We have found that, with our assumption on  $\Phi_{31}$  and  $f_{31}$ , reasonable agreement with the preliminary GlueX data [28] on  $\eta$  photoproduction at  $s = 16.36 \text{ GeV}^2$  is obtained. We have shown that the cross sections for  $\eta'$  photoproduction off protons or neutrons are very sensitive to the twist-2 gluon distribution amplitude in particular for  $\cos \theta \geq 0$ . We emphasize that, in contrast to the meson-photon transition form factors, the contribution from the gluon-gluon Fock component is not suppressed by  $\alpha_s$ . It will be interesting to confront our predictions with the forthcoming data from the Jefferson Lab GlueX experiment and to see what we can learn on the twist-2 flavor-singlet distribution amplitudes. The planned measurement of the helicity correlation  $A_{LL}$  for the processes of interest by the Jefferson Lab Frozen Spin experiment will provide additional information on these distribution amplitudes. With sufficient data on wide-angle  $\eta'$  (and  $\eta$ ) photoproduction at disposal the issue of the scale dependence is to be resumed.

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