# Analysis of recent CLAS data on $f_1(1285)$ photoproduction

Xiao-Yun Wang[1,*] and Jun He[2,3,†]

[1]*Department of Physics, Lanzhou University of Technology, Lanzhou 730050, China*
[2]*Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing, Jiangsu 210097, China*
[3]*Theoretical Physics Division, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

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Based on the experimental data released recently by the CLAS Collaboration, the $f_1(1285)$ photoproduction off a proton target is investigated in an effective Lagrangian approach. In our model, $s$-channel, $u$-channel, and $t$-channel Born terms are included to calculate the differential cross sections, which are compared with the recent CLAS experiment. An interpolating Reggeized treatment is applied to the $t$ channel, and it is found that the $t$-channel contribution is dominant in the $f_1(1285)$ photoproduction and the $u$-channel contribution is responsible for the enhancement at backward angles. The present calculation does not take into account any explicit $s$-channel nucleon-resonance contribution; nevertheless, our model provides a good description of the main features of the data. It suggests small couplings of the $f_1(1285)$ and the nucleon resonances in this energy region.

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## I. INTRODUCTION

Thanks to high-quality photoproduction data obtained at facilities with electromagnetic probes, great progress has been achieved in the study of the hadron spectroscopy, especially of the nucleon resonance, during the last few decades. Meson photoproduction off a baryon provides one of the most direct routes to extract information regarding the hadronic structure. At present, the nature of nucleon resonances below 2 GeV has been widely investigated in both experiment and theory. However, studies of the properties of nucleon resonances above 2 GeV are somewhat scarce, and there exist many problems to explain their internal structure [1–4].

The $f_1(1285)$ photoproduction attracts special attention due to its large threshold of production energy, which provides an opportunity to study the properties of nucleon resonance above 2 GeV. Furthermore, the nature of the $f_1(1285)$ is also an interesting topic in the hadronic spectroscope and has been studied for many years. In the Review of Particle Physics (PDG) the $f_1(1285)$ is an axial-vector state with quantum number $I^G(J^{PC}) = 0^+(1^{++})$ [5]. In Refs. [6,7], the $f_1(1285)$ was suggested to be a dynamically generated state produced from the $K\bar{K}^*$ interaction. In addition, the $f_1(1285)$ appears as a bound state in the dynamical picture within the frame of chiral unitary approach in Refs. [8,9]. Recently, a calculation in the one-boson-exchange model suggested that the $f_1(1285)$ is the strange partner of the $X(3872)$ in the hadronic molecular state picture [10]. Thus, investigation of the $f_1(1285)$ photoproduction may provide useful information for better understanding the nature of the $f_1(1285)$. Besides its decay pattern extracted in its decay process, we may obtain the information about the decay of a nucleon resonance to the $f_1(1285)$ and a nucleon and its radiative decay to vector meson.

In the past, due to lack of experimental data, studies of the $f_1(1285)$ photoproduction off a proton are scarce, except for some theoretical predictions where only the $t$ channel is considered [11,12], before the recently released CLAS data [13]. Though these theoretical models provide a basic frame for the $f_1(1285)$ photoproduction and are important to push forward the experimental studies, they fail to fit the new CLAS data [13]. In the new data released by the CLAS Collaboration, the differential cross sections were measured from threshold up to a center-of-mass energy of 2.8 GeV in a wide range of production angle. The cross section falls off in the forward-most angle bins, which is not typical in meson photoproduction [13], which suggests a $t$-channel contribution with an interpolating Reggeized treatment [14]. Moreover, new CLAS data also provide results at backward angles where an enhancement can be found, which indicates the possible $u$-channel contribution [1,2]. In the experimental paper [13], a helicity system fit to the $\eta\pi^+\pi^-$ Dalitz distribution was done, and it found that an $s$-channel nucleon resonance with spin parity $J^P = 3/2^+$ instead of the $t$ channel is dominant in the $f_1(1285)$ photoproduction mechanism, but there does not exist such a candidate in the PDG.

The CLAS data provide an opportunity to understand the reaction mechanism of the $f_1(1285)$ photoproduction. It is interesting to make a more explicit analysis of the new CLAS data. In this work, we will analyze the $f_1(1285)$

*xywang@lut.cn
†jun.he.1979@icloud.com

 

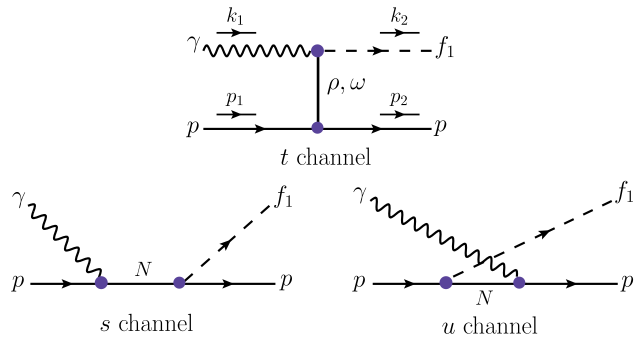


FIG. 1. Feynman diagrams for the $f_1(1285)$ photoproduction.

photoproduction based on the CLAS data in an effective Lagrangian approach. Besides the $t$ channel, which has been considered in the predictions of Ref. [11], the $u$ channel and $s$ channel will also be included in our calculations. The reaction mechanism of the $f_1(1285)$ photoproduction considered in the current work is illustrated in Fig. 1.

In Ref. [11], the $t$-channel $\rho$ and $\omega$ meson exchanges were considered with the Reggeized trajectory, which failed to reproduce the rapid falloff at forward angles in the CLAS data. In this work, we will adopt an interpolating Reggeized trajectory instead of the traditional Reggeized treatment to reproduce the behavior of the experimental data at forward angles [14]. Usually, the contribution from the $s$ channel with nucleon pole is expected to be very small and the $u$-channel contribution will produce an enhancement at backward angles [1,2]. We hope to reproduce the differential cross section of the new CLAS data only with the $t$- and $u$-channel contributions. Hence, in the present work, we do not include the contributions from the nucleon resonances in the $s$ channel, which was suggested in Ref. [13]. A calculation with the major background mechanisms may be enough to capture the main features of the data. Of course, such assumptions need explicit calculation to confirm them, which will be done in this work.

This paper is organized as follows. After the introduction, we present the formalism including Lagrangians and amplitudes of the $f_1(1285)$ photoproduction in Sec. II. The numerical results of differential cross section follow in Sec. III and are compared with the CLAS data. Finally, the paper ends with a brief summary.

## II. FORMALISM

### A. Lagrangians and amplitudes

The $f_1(1285)$ photoproduction off a proton target occurs through the mechanism in Fig. 1, which includes $t$-channel $\rho$ and $\omega$ exchanges, and $s$ and $u$ channels with intermediate nucleons. To gauge the contributions from these mechanisms, the relevant Lagrangians are needed, which will be given in the following.

For the $t$-channel vector-meson ($V = \rho$ or $\omega$) exchange, one needs the following Lagrangians [11,12,15–17]:

$$\mathcal{L}_{VNN} = -g_{VNN}\bar{N}\left[\gamma_\mu V^\mu - \frac{\kappa_V}{2m_N}\sigma_{\mu\nu}\partial^\nu V^\mu\right]N, \tag{1}$$

$$\mathcal{L}_{Vf_1\gamma} = g_{Vf_1\gamma}\epsilon_{\mu\nu\alpha\beta}\partial^\mu A^\alpha \partial^2 V^\nu f_1^\beta, \tag{2}$$

where $N$, $V$, $f_1$, and $A$ are the nucleon, vector meson, $f_1(1285)$ meson, and photon fields, respectively. The coupling constant $g_{\rho f_1\gamma}$ is determined from the decay width

$$\Gamma_{f_1\to\rho\gamma} = g^2_{\rho f_1\gamma}\frac{m_\rho^2(m_{f_1}^2+m_\rho^2)(m_{f_1}^2-m_\rho^2)^3}{96\pi m_{f_1}^5}. \tag{3}$$

In the new CLAS experiment, the radiative decay of the $f_1(1285)$ to $\rho$ meson was extracted from the $f_1(1285)$ decay process, a decay width $\Gamma_{f_1\to\rho\gamma} \simeq 453 \pm 177$ keV was obtained, which is much smaller than the PDG value of $1331 \pm 320$ keV [13]. In the current work, the CLAS value will be adopted in the calculation for consistency, and one gets $g_{\rho f_1\gamma} \simeq 0.56\ \mathrm{GeV}^{-2}$. The value of $g_{\omega f_1\gamma}$ can be obtained via quark model and SU(2) symmetry [11], i.e.

$$g_{\omega f_1\gamma} = \frac{1}{3}g_{\rho f_1\gamma}.$$

In the literature [11,12,17], the correspondent coupling constants $g_{VNN}$ and $\kappa_V$ have been calculated. In Table I, we list the values of the coupling constants associated with $\rho$ and $\omega$ mesons which will be adopted in the calculation.

According to the above Lagrangians, the scattering amplitude of the $f_1(1285)$ photoproduction via vector meson exchange can be written as

$$i\mathcal{M}_t = ig_{VNN}g_{Vf_1\gamma}F_t(q_V)\epsilon^{\nu*}_{f_1}(k_2)\bar{u}(p_2)q_V^2\epsilon_{\mu\nu\alpha\beta}\frac{\mathcal{P}^{\alpha\xi}}{t-m_V^2} \times\left(\gamma_\xi - i\frac{\kappa_V}{2m_N}\gamma_\xi \not{q}_V\right)k_1^\beta u(p_1)\epsilon^\mu(k_1), \tag{4}$$

with propagator of the vector meson as $\mathcal{P}^{\alpha\xi} = i(g^{\alpha\xi}+q_V^\alpha q_V^\xi/m_V^2)$. For the $t$-channel vector-meson exchange, the general form factors $F_{Vf_1\gamma} = [(\Lambda_t^2-m_V^2)/(\Lambda_t^2-q_V^2)]^2$ and $F_{VNN} = (\Lambda_t^2-m_V^2)/(\Lambda_t^2-q_V^2)$ are taken into account and in this work the cutoffs are taken as the same ones for the simplification as done in Ref. [11]. Here,

TABLE I. The values of coupling constants related to the vector mesons [11,12,17].

| $V$ | $g_{VNN}$ | $\kappa_V$ | $g_{Vf_1\gamma}$ |
|---|---|---|---|
| $\rho$ | 2.4 | 6.1 | 0.56 |
| $\omega$ | 9 | 0 | 0.18 |

$q_V$ and $m_V$ are the four-momentum and mass of the exchanged meson, respectively.

To study the contribution from the nucleon exchange, one needs to construct the Lagrangians for the $\gamma NN$ and the $f_1NN$ couplings [12,18],

$$\mathcal{L}_{\gamma NN} = \frac{e\kappa_p}{2m_N}\bar{N}\sigma_{\mu\nu}\partial^\nu A^\mu N + \text{H.c.}, \tag{5}$$

$$\mathcal{L}_{f_1NN} = g_{f_1NN}\bar{N}\left(f_1^\mu - i\frac{\kappa_{f_1}}{2m_N}\gamma^\nu\partial_\nu f_1^\mu\right)\gamma_\mu\gamma^5 N + \text{H.c.} \tag{6}$$

The value of coupling constant $g_{f_1NN}$ is not well determined, and a value of about 2.5 will be taken as discussed in Ref. [19]. $\kappa_p \simeq 1.79$ is the anomalous magnetic moment of the proton. The value of $\kappa_{f_1}$ will be determined by fitting the CLAS experimental data [13]. For the $s$ and $u$ channels with intermediate nucleons, we adopt the general form factor to describe the size of the hadrons [11],

$$F_{s/u}(q_N) = \frac{\Lambda_{s/u}^4}{\Lambda_{s/u}^4 + (q_N^2 - m_N^2)^2}, \tag{7}$$

where $q_N$ and $m_N$ are the four-momentum and mass of the exchanged nucleon, respectively. Since the $s$-channel contribution is usually very small, we take $\Lambda_s = \Lambda_u$. The values of cutoffs $\Lambda_u$ and $\Lambda_t$ will be determined by fitting experimental data.

The scattering amplitudes via the nucleon exchanges read as

$$i\mathcal{M}_s = \frac{e\kappa_p}{2m_N}g_{f_1NN}F_s(q_N)\epsilon_{f_1}^{\nu*}(k_2)\bar{u}(p_2)\left(1 - i\frac{\kappa_{f_1}}{2m_N}\not{k}_2\right)\gamma_\nu\gamma^5 \times \frac{(\not{q}_N + m_N)}{s - m_N^2}\gamma_\mu\not{k}_1 u(p_1)\epsilon^\mu(k_1), \tag{8}$$

$$i\mathcal{M}_u = \frac{e\kappa_p}{2m_N}g_{f_1NN}F_u(q_N)\epsilon_{f_1}^{\nu*}(k_2)\bar{u}(p_2)\gamma_\mu\not{k}_1\left(1 - i\frac{\kappa_{f_1}}{2m_N}\not{k}_2\right) \times \gamma_\nu\gamma^5\frac{(\not{q}_N + m_N)}{u - m_N^2}u(p_1)\epsilon^\mu(k_1), \tag{9}$$

where $s = (k_1 + p_1)^2$, $t = (k_1 - k_2)^2$, and $u = (p_2 - k_1)^2$ are the Mandelstam variables.

### B. Interpolating Reggeized $t$ channel

To analyze hadron photoproduction at high energies, a more economical approach may be furnished by a Reggeized treatment [20]. In Refs. [20,21], standard Reggeized treatment for $t$-channel meson exchange consists of replacing the product of the form factor in Eq. (4) with

$$F_t(q_\rho) \to \mathcal{F}_t(q_\rho) = \left(\frac{s}{s_{\text{scale}}}\right)^{\alpha_\rho(t)-1}\frac{\pi\alpha'_\rho(t - m_\rho^2)}{\Gamma[\alpha_\rho(t)]\sin[\pi\alpha_\rho(t)]}, \tag{10}$$

$$F_t(q_\omega) \to \mathcal{F}_t(q_\omega) = \left(\frac{s}{s_{\text{scale}}}\right)^{\alpha_\omega(t)-1}\frac{\pi\alpha'_\omega(t - m_\omega^2)}{\Gamma[\alpha_\omega(t)]\sin[\pi\alpha_\omega(t)]}. \tag{11}$$

The scale factor $s_{\text{scale}}$ is fixed at 1 GeV. In addition, the Regge trajectories $\alpha_\rho(t)$ and $\alpha_\omega(t)$ read as [11,22]

$$\alpha_\rho(t) = 0.55 + 0.8t, \qquad \alpha_\omega(t) = 0.44 + 0.9t. \tag{12}$$

In practical applications, the onset of the "Regge regime" is often very much under debate. In this work, we adopt the interpolating Reggeized treatment which can interpolate the Regge case smoothly to the Feynman case. Such a hybrid approach has been successfully applied to reproduce the experimental data in Refs. [1,2,14,23], especially the falloff at forward angles. In Refs. [20,21], the local gauge invariance of the Regge trajectory was discussed. In the case of this work, the gauge invariance is kept because the Lagrangians for the $t$ channel produce an amplitude which keeps gauge invariance by itself. So we need not make extra treatment to restore the gauge invariance. The interpolated Reggeized form factor can then be written as

$$F_t \to \mathcal{F}_{R,t} = \mathcal{F}_t R(t) + F_t[1 - R(t)], \tag{13}$$

where $R(t) = R_s(s)R_t(t)$, with

$$R_s(s) = \frac{1}{1 + e^{-(s-s_R)/s_0}}, \qquad R_t(t) = \frac{1}{1 + e^{-(t+t_R)/t_0}}. \tag{14}$$

Here, $s_R$ and $t_R$ describe the centroid values for the transition from non-Regge to Regge regimes while $s_0$ and $t_0$ provide the respective widths of the transition regions. The four parameters of this function will be fitted to the experimental data.

## III. NUMERICAL RESULTS

With the preparation in the previous section, the differential cross section of the $f_1(1285)$ photoproduction will be calculated and compared with the CLAS data released recently. The differential cross section in the center of mass (c.m.) frame is written with the amplitudes obtained in the previous section as

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s}\frac{|\vec{k}_2^{\text{c.m.}}|}{|\vec{k}_1^{\text{c.m.}}|}\left(\frac{1}{4}\sum_\lambda|\mathcal{M}|^2\right), \tag{15}$$

where $s = (k_1 + p_1)^2$, and $\theta$ denotes the angle of the outgoing $f_1(1285)$ meson relative to beam direction in the

TABLE II. Fitted values of free parameters and corresponding reduced $\chi^2$/d.o.f. value.

| | | | |
|---|---|---|---|
| $s_0$ (GeV$^2$) | $s_R$ (GeV$^2$) | $t_0$ (GeV$^2$) | $t_R$ (GeV$^2$) |
| $3.99 \pm 0.23$ | $6.61 \pm 0.59$ | $0.95 \pm 0.07$ | $0.3 \pm 0.08$ |
| $\kappa_{f_1}$ | $\Lambda_t$ (GeV) | $\Lambda_s = \Lambda_u$ (GeV) | $\chi^2$/d.o.f. |
| $1.94 \pm 0.39$ | $0.92 \pm 0.04$ | $0.68 \pm 0.06$ | 1.27 |

c.m. frame. $\vec{k}_1^{\rm c.m.}$ and $\vec{k}_2^{\rm c.m.}$ are the three-momenta of the initial photon beam and final $f_1(1285)$, respectively.

### A. Fitting procedure

The CLAS data [13] for the $f_1(1285)$ photoproduction will be fitted with the help of the MINUIT code in the CERNLIB. In the current work, we minimize $\chi^2$ per degree of freedom (d.o.f.) for the differential cross sections $d\sigma/d\cos\theta$ of the CLAS data by fitting seven parameters, which include four parameters for the Regge trajectory ($s_0$, $t_0$, $s_R$, $t_R$), the anomalous magnetic moment $\kappa_{f_1}$, and the cutoffs $\Lambda_t$ and $\Lambda_u$. Here the cutoff $\Lambda_s$ for the $s$ channel is chosen to be the same as $\Lambda_u$ for the $u$ channel for simplification because the $s$-channel contribution is usually small. The CLAS experimental data include 45 data points at center-of-mass energy bin $W = 2.35$ 2.45, 2.55, 2.65, and 2.75 GeV at nine angle bins [13]. In the fitting, both statistical and systematic uncertainties are considered.

The fitted values of the free parameters are listed in Table II, with a reduced value $\chi^2/\text{d.o.f.} = 1.27$, which indicates the CLAS [13] data can be reproduced quite well in the current model with only $s$-, $u$-, and $t$-channel Born terms. It suggests that the intermediate $s$-channel nucleon resonances are not essential to reproduce the experimental data. Moreover, the best fitted result is achieved with reasonable cutoff values $\Lambda_x (x = s, u, t)$ around the usual empirical 1 GeV value.

We also make a fitting with the coupling constant of the radiative decay of the $f_1(1285)$ $g_{\rho f_1\gamma}$ as a free parameter to test the radiative decay width we adopted to calculate the coupling constant. The fitted values of free parameters are listed in Table III. One can obtain a similar result with a little smaller $\chi^2/\text{d.o.f.} = 1.21$. The parameters are close to these with fixed $g_{\rho f_1\gamma} = 0.56$ GeV$^{-2}$. The corresponding decay width $\Gamma_{f_1\to\rho\gamma} \simeq 259 \pm 12$ keV, which is within the margin of the CLAS experimental value. Compared with the results with the coupling constant fixed at the CLAS value, we can say that our fitting of the differential cross section is consistent with the radiative decay of the $f_1(1285)$ observed by the CLAS Collaboration.

TABLE III. Fitted values of free parameters with the coupling constant $g_{\rho f_1\gamma}$ as a free parameter. Here, $\chi^2/\text{d.o.f.} = 1.21$.

| | | | |
|---|---|---|---|
| $s_0$ (GeV$^2$) | $s_R$ (GeV$^2$) | $t_0$ (GeV$^2$) | $t_R$ (GeV$^2$) |
| $3.99 \pm 0.57$ | $5.00 \pm 0.77$ | $0.92 \pm 0.02$ | $0.3 \pm 0.07$ |
| $\kappa_{f_1}$ | $\Lambda_t$ (GeV) | $\Lambda_s = \Lambda_u$ (GeV) | $g_{\rho f_1\gamma}$ |
| $1.92 \pm 0.06$ | $0.87 \pm 0.02$ | $0.68 \pm 0.01$ | $0.42 \pm 0.01$ |

### B. Differential cross section for the $f_1(1285)$ photoproduction

In this subsection, we will present the best fitted results with the fixed coupling constant $g_{f_1\rho\gamma}$. The fitted values of the free parameters are listed in Table II, and the reduced value $\chi^2/\text{d.o.f.} = 1.27$. As shown in Fig. 2, the differential cross section $d\sigma/d\cos\theta$ reported by the CLAS Collaboration is well reproduced in our model. It is found that the $t$-channel vector-meson exchange plays a dominant role in the $f_1(1285)$ photoproduction. Its contribution corresponds to the enhancement at forward angles. The $u$ channel with nucleon exchange plays a very important role at backward angles, in particular, at the high-energy end of the data range. The differential cross section in the full model is almost from these two contributions. Since the contribution from the $s$ channel with nucleon exchange is very small and can be negligible, it is not shown in Fig. 2.

To show the importance of introducing the interpolated Reggeized form factor in Eq. (13), in Fig. 2 we present the

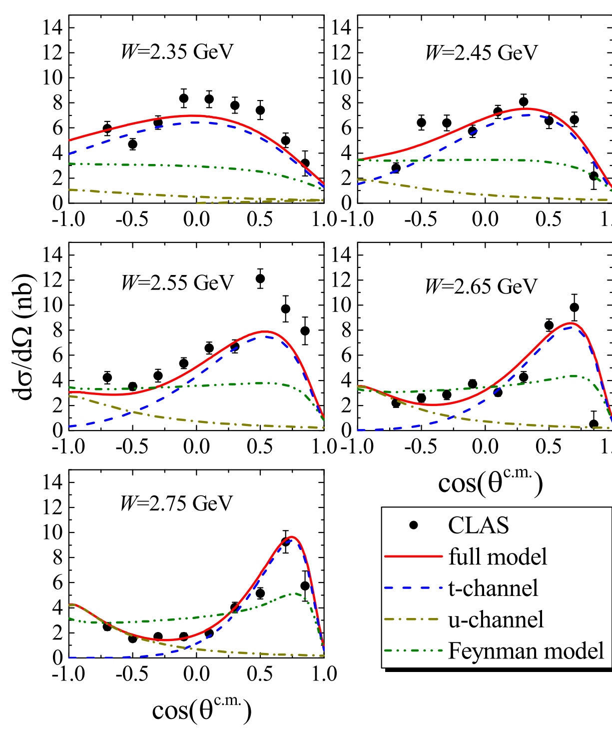


FIG. 2. The differential cross section $d\sigma/d\cos\theta$ for the $f_1(1285)$ photoproduction off a proton as a function of $\cos\theta$. The data are from Ref. [13]. The full (red), dashed (blue), dash-dotted (dark yellow) and dash-dot-dotted (green) lines are for the full model, $t$ channel, $u$ channel, and Feynman model, respectively. The curves have been scaled by the PDG [5] branching fraction for $f_1(1285) \to \eta\pi^+\pi^-$. In the figures, only statistical uncertainty is presented as in Ref. [13].

TABLE IV. Fitted values of free parameters with the Feynman model. Here $\chi^2/\mathrm{d.o.f.} = 6.31$.

| $\kappa_{f_1}$ | $\Lambda_t$ (GeV) | $\Lambda_s = \Lambda_u$ (GeV) | $g_{\rho f_1 \gamma}$ |
|---|---|---|---|
| $0.95 \pm 0.52$ | $0.98 \pm 0.01$ | $0.50 \pm 0.02$ | $0.99 \pm 0.01$ |

results in the Feynman model, in which the Feynman $t$ channel without inclusion of the interpolated Reggeized form factor, $u$ channel, and $s$ channel are considered. The best fitted parameters are listed in Table IV. A very large $\chi^2$/d.o.f of 6.31 suggests that the differential cross section observed at CLAS cannot be reproduced from the Feynman model. The most serious defect is that the sharp falloff at forward angle cannot be reproduced, which leads to the difficulty of reproducing the magnitude of the differential cross section. At the backward angles, the $u$-channel contribution shows its importance to reproducing the experimental data. After the interpolated Reggeized form factor is introduced, the CLAS data are well reproduced, as shown in Fig. 2.

In the work of Kochelev *et al.*, the Reggeized treatment has been considered in the $t$ channel. Because there was no experimental data when Kochelev *et al.* made the prediction about this process, the current results are much closer to the experimental data than the prediction in Refs. [11,13]. The main improvements in our model are the inclusion of the interpolating Reggeized treatment and the inclusion of the $u$-channel contribution. The $u$-channel contribution is essential to reproducing the enhancement at backward angles, which is absent in Refs. [11,13]. Kochelev *et al.* adopted an original Reggeized treatment without interpolation, so the differential cross section was predicted to be smaller than the experimental data at low energies, while the cross section at high energy was predicted closely [11,13]. The interpolating Reggeized treatment makes it possible to produce the relative magnitude of the differential cross section at both low and high energies. Further, the rapid falloff at forward angles can also be reproduced with the interpolating Reggeized treatment.

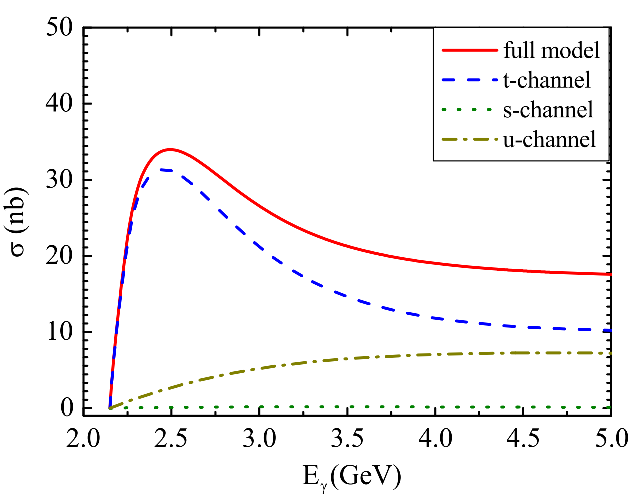


FIG. 3. Total cross section for $\gamma p \to f_1 p$ reaction. The full (red), dashed (blue), dotted (green), and dash-dotted (dark yellow) lines are for the full model, $t$ channel, $s$ channel, and $u$ channel, respectively.

We also present the total cross section of the $f_1(1285)$ photoproduction in Fig. 3. It is found that the $t$-channel vector-meson exchange is dominant at beam energy $E_\gamma$ from threshold up to 5.0 GeV. The contribution from the $u$ channel increases with the increase of energy. The contribution from the $s$-channel nucleon exchange is small and can be neglected. The total cross section of the $f_1(1285)$ photoproduction could be significant at higher energies.

## IV. SUMMARY AND DISCUSSION

Within an effective Lagrangian approach, a seven-parameter fitting is done to the CLAS data of the $f_1(1285)$ photoproduction off a proton with an interpolating Reggeized treatment. The numerical results show that the differential cross section is well reproduced by our model with $\chi^2/\mathrm{d.o.f.} = 1.27$. The fitting value of the decay width $\Gamma_{f_1 \to \rho\gamma}$ with the differential cross section is also consistent with the CLAS value.

The numerical results suggest that the $t$ channel is dominant in the reaction mechanism of the $f_1(1285)$ photoproduction and responsible for the behavior of the cross sections at forward angles. As expected, the contribution from the$s$-channel nucleon exchange is so small that it almost has no effect on the differential cross sections. The CLAS [13] data cannot be fitted very well using the usual Feynman-type $t$-channel exchange alone, even with the traditional Reggeized treatment, which suggests that the interpolating Reggeized treatment of the $t$ channel is essential to achieve the fit quality exhibited in Fig. 2. Further, the $u$ channel is responsible for the enhancement of the differential cross section at backward angles.

In the current work, $s$-channel intermediate nucleon resonances are not included in the fitting of the experimental data. The small $\chi^2$ suggests their contribution should not be very large, which indicates weak couplings of the $f_1(1285)$ and the nucleon resonances in the energy region considered in this work. Though the results of the differential cross section supported the small contribution from the nucleon resonance, it should be explained why there is a nucleon-resonance signal in the Dalitz plot. A explicit calculation is out of the scope of the current work. However, we would like to give some arguments to explain why an $s$-channel effect can be found within the $t$ channel–dominant interaction mechanism. In interpolating Reggeized treatment, we need to introduce an auxiliary function to interpolate the Regge case and Feynman case as shown in Eqs. (13) and (14). The $R_s(s)$ will introduce an $s$ dependence of the cross section. If we expand the exponential function (even with other forms) at $s_R$, we have $R_s(s) = 1/(1 + 1 - (s - s_R)/s_0) = -s_0/(s - s_R - 2s_0)$. Obviously, at the energies around $\sqrt{s_R}$, the amplitudes will exhibit some characteristics of the $s$ channel.

To describe more detailed structures of the cross sections of $f_1(1285)$ photoproduction, inclusion of $s$-channel resonances may be necessary, For example, some data points at forward angles with $W = 2.55$ GeV are larger than the theoretical result. However, the current data is not enough to make a meaningful analysis. To warrant expanding efforts in this direction, more precise data for $f_1(1285)$ photoproduction are necessary. The near future CLAS12@JLab experiment [24,25] may provide great opportunities for research in this direction.

*Note*: Just after the paper was submitted, we noticed that a work about the $f_1(1285)$ photoproduction based on new CLAS data has been released in arXiv [26]. In their work, besides the Reggeized $t$ channel, a nucleon resonance $N(2300)$ was introduced to reproduce the CLAS data; the nucleon resonance $N(2300)$ in their model plays a role similar to the interpolating Reggeized treatment and the $u$-channel contribution in our model. Quite good results can be obtained in their model with a $\chi^2 = 1.39$; however, this is larger than our $\chi^2$ value, 1.27. Besides, our results at extreme forward angles are better than the results in Ref. [26] in the energy region near the $N(2300)$. We made a refitting with the contribution from the nucleon resonance $N(2300)$, but no obvious improvement can be obtained in our model. Since the discrepancies are small, more precise experimental data are still needed to clarify the role of the nucleon resonance in the $f_1(1285)$ photoproduction.

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