In this work we present the results of a theoretical analysis of the data on photoproduction of the $f_0(980)$ meson in the laboratory photon energy between 3.0 and 3.8 GeV. A comparison is done to the measurements performed by the CLAS Collaboration at the JLab accelerator for the exclusive reaction $\gamma p \rightarrow pf_0(980)$. In the analysis the partial $S$-wave differential cross section is described by a model based on the Regge approach with reggeized exchanges and distinct scenarios for $f_0(980) \rightarrow V\gamma$ coupling considered. It is shown that such a process can provide information on the resonance structure and production mechanism.
II. MODEL AND CROSS SECTION CALCULATION

We focus on the $S$-wave analysis of nondiffractive $f_0(980)$ photoproduction and its decay on the $\pi^+\pi^-$ final state. According to the Regge phenomenology, one expects that only the $t$-channel meson exchanges are important in such a case. The $\rho$ and $\omega$ reggeized exchanges are to be considered in the present analysis. To obtain mass distribution for the scalar $f_0(980)$ meson, one represents it as relativistic Breit-Wigner resonance with energy-dependent partial width. The differential cross section for the production of a scalar with invariant mass $M$ and its decay to two pseudoscalars, masses $m_a$ and $m_b$, can be written as

$$
\frac{d\sigma}{dt dM} = \frac{d\hat{\sigma}(t, m_S)}{dt} \pi \left( \frac{m_a^2 - M^2}{4} + (M \Gamma_{\text{tot}})^2 \right)^2,
$$

where $d\hat{\sigma}/dt$ is the narrow-width differential cross section at a scalar mass $M = m_S$ and $\Gamma(M)$ being the pseudoscalar-pseudoscalar final state partial width, which can be computed in terms of the $SPP$ coupling $g_i$. A note is in order at this point. Although the main decay of the $f_0(980)$ is $\pi \pi$, this state resides at the $K\bar{K}$ threshold. Therefore, following Ref. [7] we use the Breit-Wigner parametrizations obtained in the analysis of $\phi$ radiative decays [18]. In such a case, the Breit-Wigner width takes the form

$$
\Gamma(M) = \frac{g_{2\pi}^2}{8\pi M^2} \sqrt{\frac{M^2}{4} - M_{\pi\pi}^2} + \frac{g_{K\bar{K}}^2}{8\pi M^2} \sqrt{\frac{M^2}{4} - M_{K\bar{K}}^2 + \frac{M_{K\bar{K}}^2}{4} - \frac{M_{K\pi\pi}^2}{4}},
$$

where we set the following parameters: $M = 984.7$ MeV, $g_{K\bar{K}} \equiv g_{K^+K^-} = g_{K^0\bar{K}^0} = 0.4$ GeV, and $g_{\pi\pi} = \sqrt{2}g_{\rho\rho} = 1.31$ GeV for the scalar meson $f_0(980)$ considered here. However, when we consider the $f_0(980)$ cross section below the $K\bar{K}$ threshold, the total width cannot be written as in Eq. (2). Thus, in this case we should use the Flatté formula [19] when computing our numerical results in the next section.

Let us proceed; the reaction proposed here is $\gamma p \to p f_0(980)$. Within the Regge phenomenology the differential cross section in the narrow-width limit for a meson of mass $m_S$ is given by [13]

$$
\frac{d\hat{\sigma}}{dt}(\gamma p \to p M) = \frac{|M(s, t)|^2}{64\pi (s - m_p^2)^2},
$$

where $M$ is the scattering amplitude for the process, $s$ and $t$ are usual Mandelstan variables, and $m_p$ is the proton mass. For the exchange of a single vector meson, i.e., $\rho$ or $\omega$, one has

$$
|M(s, t)|^2 = -\frac{1}{2}A^2(s, t)[s(t - t_1)(t - t_2) + \frac{1}{t}[t^2 - 2(m_S^2 + s) t + m_S^4]] - A(s, t)B(s, t)m_p s(t - t_1)(t - t_2) - \frac{1}{8}B^2(s, t)s(4m_p^2 - t)(t - t_2).$$

where $t_1$ and $t_2$ are the kinematical boundaries

$$
t_{1,2} = \frac{1}{2\sqrt{s}}[-(m_p^2 - s)^2 + m_p^2(m_p^2 + s) \pm (m_p^2 - s)\sqrt{(m_p^2 - s)^2 - 2m_p^2(m_p^2 + s) + m_S^4}],
$$

and where one uses the standard prescription for Reggeizing the Feynman propagators assuming a linear Regge trajectory $\alpha_V(t) = \alpha_V(0) + \alpha_V'(t)$ for writing down the quantities $A(s, t)$ and $B(s, t)$:

$$
A(s, t) = g_A \left( \frac{s}{s_0} \right)^{\alpha_V(0) - 1} \frac{\pi \alpha_V'}{\sin[\pi \alpha_V(t)]} 2 \Gamma[\alpha_V(t)],$$

$$
B(s, t) = -\frac{g_B}{g_A}(s, t).
$$

It is assumed nondegenerate $\rho$ and $\omega$ trajectories $\alpha_V(t) = \alpha_V(0) + \alpha_V'(t)$, with $\alpha_V(0) = 0.55(0.44)$ and $\alpha_V' = 0.8(0.9)$ for $\rho$ ($\omega$). In Eq. (6) above, one has that $g_A = g_\gamma(g_V(\rho + 2m_p g_T)$ and $g_B = 2g_g g_T$. The quantities $g_V$ and $g_T$ are the vector-nucleon-nucleon ($VNN$) vector and tensor couplings, and $g_\gamma$ is the $\gamma V N$ coupling. For the $\omega NN$ couplings we have set $g_{\omega V}^V = 15$ and $g_{\omega T}^T = 0$ [13], and for the $\rho NN$ couplings we used $g_{\rho V}^V = 3.4$ and $g_{\rho T}^T = 11$ GeV$^{-1}$. The $SV\gamma$ coupling $g_S$ can be obtained from the radiative decay width through [20]

$$
\Gamma(S \to V \gamma) = \frac{g_S^2 m_S^3}{32\pi} \left( 1 - \frac{m_V^2}{m_S^2} \right)^3.
$$

This model was applied to $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$ mesons which are considered as a mixing of $n\bar{n}$, $s\bar{s}$, and glueball states [21]. In this case their radiative decays into a vector meson are expected to be highly sensitive to the degree of mixing between the $q\bar{q}$ basis and the glueball. In Ref. [13] three distinct mixing scenarios were considered. The first one is the bare glueball being lighter than the bare $n\bar{n}$ state; the second scenario corresponds to the glueball mass being between the $n\bar{n}$ and $s\bar{s}$ bare state; and finally the third one is where the glueball mass is heavier than the bare $s\bar{s}$ state. The numerical values for the widths having effects of
mixing on the radiative decays of the scalars on $\rho$ and $\omega$ can be found in Table 1 of Ref. [13]. This way it is clear that the width is strongly model dependent, and different approaches can be taken into account. For instance, we refer the work in Ref. [22], where the decays of a light scalar meson into a vector meson and a photon, $S \to V \gamma$, are evaluated in the tetraquark and quarkonium assignments of the scalar states. The coupling now reads

$$\Gamma(S \to \gamma V) = g_S^2 \frac{(m_S^2 - m_V^2)^3}{8 \pi m_S^2}. \quad (8)$$

The different nature of the couplings corresponds to distinct large-$N_c$ dominant interaction Lagrangians. In the next section we compare those approaches discussed above for the direct $f_0(980)$ photoproduction in the CLAS energies.

### III. RESULTS AND DISCUSSIONS

In what follows we present the numerical results for the direct $f_0(980)$ photoproduction considered in the present study and the consequence of the tetraquark and quarkonium assignments of the scalar states discussed in the previous section. The results presented here will consider five distinct scenarios, three of them assuming that $f_0(980)$ is a quarkonium and two assuming that $f_0(980)$ is a tetraquark. In scenarios 1, 2, and 3 the $f_0(980)$ will be interpreted as a ground-state nonet and in scenarios 4 and 5 as a tetraquark. The $g_S$ coupling can be obtained from the radiative decay width in Table I using Eq. (7) for scenario 1 and Eq. (8) for the remaining scenarios. The values for scenario 1 in Table I were extracted from Refs. [7,20] and from Ref. [22] for the remaining ones. The radiative decay in scenarios 3 and 5 have considered the $f_0$ resonance as a quarkonium and a tetraquark, respectively, including vector meson dominance, as discussed in Ref. [22].

The partial $S$-wave differential cross sections for the $f_0(980)$ are presented in Fig. 1 at $E_{\gamma} = 3.4 \pm 0.4$ GeV and integrated in the $M_{\pi\pi}$ mass range $0.98 \pm 0.04$ GeV. As a general picture, the typical pattern is a vanishing cross section towards the forward direction (it does not appear in the plot as we are showing the region $|t| \geq 0.4$ GeV$^2$) due to the helicity flip at the photon-scalar vertex and the dip at $|t| \approx 0.7$ GeV$^2$ related to the reggeized meson exchange. The scenarios 1 and 4 are represented by the solid and dot-dashed lines, respectively. Both fairly reproduce the trend of the CLAS data. The scenario 2 is denoted by the dashed curve. In this case the result overestimates the CLAS data points by a factor of 50. The scenarios 3 and 5 are represented by the dotted and dot-dot-dashed lines, respectively. Now, the results underestimate the data by the same factor.

The several theoretical predictions were compared to the CLAS analysis at Jefferson Lab [17], where the $\pi^+\pi^-$ photoproduction at photon energies between 3.0 and 3.8 GeV has been measured in the interval of momentum transfer squared $0.4 \leq |t| \leq 1.0$ GeV$^2$. There, the first analysis of $S$-wave photoproduction of pion pairs in the region of the $f_0(980)$ was performed. The interference between $P$ and $S$ waves at $M_{\pi\pi}$ $\approx$ 1 GeV clearly indicated the presence of the $f_0$ resonance. As a final comment on the compatibility of theoretical predictions and experimental results, the scenarios 1 and 4 fairly describe the data (they are parameter-free predictions as we did not fit any physical parameter). Moreover, the CLAS data have no

![FIG. 1. (Color online) The $S$-wave differential photoproduction cross sections for $f_0(980)$ photoproduction as a function of momentum transfer squared at CLAS experiment energy $E_\gamma = 3.4$ GeV. The statistical/systematic error bars for CLAS data [17] were summed in quadrature.](image1.png)

![FIG. 2. (Color online) $S$-wave $\pi^+\pi^-$ invariant mass distribution at $E_\gamma = 3.4$ GeV, $|t| = 0.55$ GeV$^2$. The results stand for $g_{\pi^+\pi^-} = 1.31$ GeV (solid curve) and $g_{\pi^+\pi^-} = 2.3$ GeV (dashed curve). In both cases, the value $g_{\pi\pi} = 0.4$ is considered.](image2.png)
indication of a minimum as predicted by the reggeized models. Here, we have two possibilities: there is no data point in the dip region (around $|t| \approx 0.7 \text{ GeV}^2$) to confirm the reggeized exchange prescription or some additional contribution, i.e., background effects or interference, is missing. The case seems to be the the first option based on the reasonable description of an $S$ wave by a nonreggeized meson exchange [15] as presented in Fig. 3 of Ref. [17].

As a complementary study, we also investigate the invariant mass distribution predicted by the theoretical models, taking the scenario 1 as a baseline. Another way to calculate the mass distribution is to use the branching fractions for the strong decay of $f_0(980)$ associated with the Breit-Wigner width for $f_0(980)$ to $\pi \pi$. In what follows two possibilities for the branching fractions will be used [7, 23]:

$$B[f_0(980) \rightarrow \pi \pi] = 85\% \quad (9)$$

and

$$B[f_0(980) \rightarrow \pi^+ \pi^-] = 46 \pm 6\% \quad (10)$$

On the other hand, it is possible to use the experimental value for the total width of $f_0(980)$ which is in the range of 40 to 100 MeV [24]. With this assumptions it is not necessary to calculate the $f_0(980) \rightarrow K \bar{K}$ width appearing in Eq. (2).

In Fig. 2 the $S$-wave $\pi^+ \pi^-$ invariant mass distribution at $E_{\gamma} = 3.4$ GeV and $|t| = 0.55 \text{ GeV}^2$ is shown. For the theoretical analysis we take the scenario 1. One considers the coupling $g_{SKK} = 0.4$ and two possibilities for the coupling $g_{S\pi \pi}$. The first one is $g_{S\pi \pi} = 1.31 \text{ GeV}$ (solid curve) presented in Ref. [7], and the second case $g_{S\pi \pi} = 2.3 \pm 2 \text{ GeV}$ (dashed curve) is given in Ref. [25]. The Flatté formula is used to obtain the $f_0(980)$ total width [19]. The results present a strong dependence of the mass distribution on the $g_{S\pi \pi}$ coupling.

In Fig. 3 we repeat the previous analysis using now the experimental values $\Gamma_{\text{tot}} = 40$ to 100 MeV for the $f_0(980)$ total width [24]. It can be also obtained by branching ratios for $f_0(980)$ into pions associated with the Breit-Wigner formula. The dot-dot-dashed and dot-dashed lines represent the invariant mass distribution for $\Gamma_{\text{tot}} = 40$ and $\Gamma_{\text{tot}} = 100 \text{ MeV}$, respectively. In this case, $\Gamma_{\pi^+ \pi^-} = 0.46\Gamma_{\text{tot}}$ following Eq. (10). The solid and dotted lines represent invariant mass distribution for $\Gamma_{\text{tot}} = \Gamma_{\pi^+ \pi^-}/0.85$ following Eq. (9) and where $\Gamma_{\pi^+ \pi^-}$ is given by Breit-Wigner formula. In the result represented by the dashed line $\Gamma_{\text{tot}} = \Gamma_{\pi^+ \pi^-}/0.46$ following Eq. (9) and $\Gamma_{\pi^+ \pi^-}$ is given by Breit-Wigner formula. As indicated in Fig. 2 there is a strong dependence on the coupling constant $g_{S\pi \pi}$. An interesting dependence on branching ratios is observed too.

In summary, we have studied the photoproduction of $f_0(980)$ resonance for photon energies considered in the CLAS experiment at Jefferson Lab, $E_{\gamma} = 3.4 \pm 0.4$ GeV. It provides a test for the current understanding of the nature of the scalar resonances. We have calculated the differential cross sections as function of effective masses and momentum transfers. The effect of distinct scenarios in the calculation of the coupling $S \rightarrow V\gamma$ was investigated. This study shows that we need to know more precisely the radiative decay rates for $f_0(980) \rightarrow \gamma V$ which are important in the theoretical predictions. Our predictions of the cross sections are somewhat consistent with the experimental analysis from the CLAS Collaboration, at least for scenarios 1 and 4. The present experimental data are able to exclude some possibilities for the $S \rightarrow V\gamma$ coupling. We show also the large dependence on the model parameters as $g_{S\pi \pi}$ values and branching fractions.

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