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η-production on the proton via electromagnetic and hadronic probes*

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Abstract The reactions $\pi^- p \to \eta n$ and $\gamma p \to \eta p$ are investigated within a dynamical coupled-channels model of meson production reactions in the nucleon resonance region. The meson-baryon channels included are πN, ηN, πΔ, σN, and ρN. The direct η-photoproduction process is studied within a formalism based on a chiral constituent quark model approach, complemented with a one-gluon-exchange mechanism, to take into account the breakdown of the $SU(6)\otimes O(3)$ symmetry. In the models search, the following known nucleon resonances are embodied: $S_{11}(1535)$, $S_{11}(1650)$, $P_{11}(1440)$, $P_{11}(1710)$, $P_{13}(1720)$, $D_{13}(1520)$, $D_{13}(1700)$, $D_{15}(1675)$, and $F_{15}(1680)$. Data for the $\pi^- p \to \eta n$ reaction from threshold up to a total center-of-mass energy of $W \approx 2$ GeV are satisfactorily reproduced. For the photoproduction channel, two additional higher mass known resonances, $P_{13}(1900)$ and $F_{15}(2000)$, are also considered. However, reproducing the data for $\gamma p \to \eta p$ requires, within our approach, two new nucleon resonances, for which we extract mass and width.

Key words multichannel scattering, meson production, baryon resonances

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1 Introduction

The complementary character of strong and electromagnetic production of baryon resonaces was recognized with the discovery of the first baryon resonance, Δ, when Fermi and collaborators[1] published their pioneer experimental results on the $\pi^{\pm}p$ interactions, followed by the data by Walker et al.[2] on the pion photoproduction.

Although the development of investigations on those channels continued more or less in parallel for the Δ-resonance, the other baryon resonances were mainly studied via the πN initial states. Actually, pion beams became available in 50's and culminated, both in intensity and resolution, in 80's. Nevertheless, the most extensively studied phase space concerned the Δ-resonance region. In the 90's, high intensity tagged photon beams started being operational and since about one decade, impressive copious and high precision data are being released from various laboratories, opening a new era in hadron physics.

In this paper we concentrate on the ηN final state. A common point to reactions $\pi N \to \pi N$, ηN, as well as to $\gamma N \to \pi N$, ηN, is that each final state is dominated by a single resonance in the relevant threshold region, namely Δ(1230) and $S_{11}(1535)$, in contrast to the case of the other pseudoscalar (kaon) or vector mesons. However the roughly 300 MeV mass differ-

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ence between the two resonances, led to a drastic unbalanced data base generated with pion beams. The reason for that uncomfortable situation is that the so-called pion factories (LAMPF, TRIUMF, SIN) in 80's provided high quality beams, but limited mainly to the Δ-resonance region (see e.g. Ref. [3]). Consequently, in studying the $\pi N \to \eta N$, we have to deal with rather poor and inconsistent[4] data sets[5—12]. However, since about one decade, the $\gamma N \to \eta N$ is subject to very extensive experimental investigations in JLab[13], ELSA[14—17], LNS[18], and GRAAL[19].

Theoretical approaches focused also on the $\pi N \to \pi N$ reactions in the Δ-resonance region and, besides extensive partial wave analysis[20—22], evolved to sophisticated approaches based on the isobaric effective Lagrangians, embodying meson-nucleon degrees of freedom. Those formalisms go beyond the direct channel mechanisms to include multi-step processes or coupled-channels treatments[23—30].

The main goal of the Excited Baryon Analysis Center (EBAC) investigations is to extend a powerful dynamical formalism[24], hereafter called MSL approach, to all significant final states needed for a comprehensive determination and description of the properties of baryon resonances via meson-production mechanisms. The first step in that effort was a coupled-channels study of the $\pi N \to MB \to \pi N$, with meson-baryon (MB) channels being

$$MB \equiv \pi N,\ \eta N,\ \pi\Delta,\ \rho N,\ \sigma N. \tag{1}$$

The 175 free parameters of that approach[25] are fitted on over 10000 data points, reproducing them very well and producing a model, hereafter referred to as JLMS[25] model. Those parameters include the needed ingredients to study other final states. The second step was then to study the $\pi N \to \eta N$ channel, for which only some 50 data points were fitted in constructing the JLMS model. A work dedicated to that channel[31], within the MSL formalism, showed that the 29 parameters (out of a total of 175) directly related to the ηN states, have to be better determined by fitting the relevant data. In this paper we present a more advanced version of our previous work[31] and report on a new model for the $\pi^- p \to \eta n$ reaction, hereafter called EBAC-Saclay-πη model.

As already mentioned, those formalisms employ meson-nucleon degrees of freedom. However, in 70's, formalisms embodying subnucleonic degrees of freedom started getting developed in this realm. The early works by Copley et al.[32] and Feynman et al.[33] on the pion photoproduction, provided the first clear evidence of the underlying $SU(6)\otimes O(3)$ structure of the baryon spectrum. More recently, a unified formalism for pseudoscalar mesons photoproduction, based on a QCD Lagrangian[34] and chiral constituent quark model[35], was developed. Advanced versions of that formalism embody in general also the quark states configuration mixings in baryons, generated by the $SU(6)\otimes O(3)$ symmetry breaking due to, e.g. the one-gluon-exchange mechanism[36]. Those approaches have been successful in investigating photoproduction of pseudoscalar mesons: π[37], η[38—42] and kaon[43, 44], as well as of vector mesons[45]. The electroproduction of the η-meson at low Q^2 has also been studied[46]. Moreover, the CQM has been extended[42, 47] to the strong channel, allowing a reasonable description of the $\pi^- p \to \eta n$ data. In all those works, only the direct channel processes are studied. The only exception concerns the $\gamma p \to K^+\Lambda$, for which a coupled-channels approach has been developed[43]. In that approach a χCQM is used for the direct channel, while the intermediate and final state meson-baryon interactions are handled with an isobaric effective Lagrangian coupled-channels approach[48], embodying πN and KY channels, with $KY \equiv K^+\Lambda,\ K^+\Sigma^\circ,\ K^\circ\Sigma^+$.

In this paper, we describe the direct η-photoproduction channel with a recent χCQM model[41], proven to reproduce satisfactorily all available data, including polarization observables. In that work the spectrum of the known nucleon resonances (N^*)[49] is well reproduced with only 7 adjustable parameters. Moreover, that study, in line with previous CQM works[50—52], predicts the so-called missing resonances. Actually, as mentioned above, our main source of knowledge on N^*s comes from reactions with πN final states. Accordingly, processes with mesons, other than pion, in the final states are expected to reveal yet unknown baryon resonances. So, a strong motivation of the present work is to search for such 3-quark states.

The paper is organized as follows. In Section 2 we briefly present the chiral constituent quark model, for the direct photoproduction channel, as well as the dynamical coupled-channels formalism for both $\pi N \to \eta N$ and $\gamma N \to \eta N$ reactions. Section 3 is devoted to our results for $\pi^- p \to \eta n$ and $\gamma p \to \eta p$ processes, where we compare the outcome of the present work to the data. Conclusions are given in Section 4.

2 Theoretical frame

In order to present briefly the theoretical formalisms of our approach, we start with the expression for the coupled-channels T-matrix describing the η meson photoproduction on the nucleon

$$T_{\gamma N\to\eta N} = (v^{NR}_{\gamma N\to\eta N}+v^{R}_{\gamma N\to\eta N})\times (1+G_{\eta N}t^{NR}_{\eta N\to MB\to\eta N})+ v^{NR}_{\gamma N\to\pi N}G_{\pi N}t^{NR}_{\pi N\to MB\to\eta N}. \quad (2)$$

2.1 Constituent quark model

The first two terms in Eq. (2) are the non-resonant and resonant terms for the direct channel $\gamma p\to\eta p$, calculated[41] within a chiral constituent quark model, complemented with a one-gluon-exchange model, to take into account the breakdown of the $SU(6)\otimes O(3)$ symmetry.

For s-channel, the amplitudes are given by the following expression[35, 39]:

$$\mathcal{M}_{N^*}=\frac{2M_{N^*}}{s-M^2_{N^*}-iM_{N^*}\Gamma(\boldsymbol{q})}e^{-\frac{\boldsymbol{k}^2+\boldsymbol{q}^2}{6\alpha^2}}\mathcal{O}_{N^*}, \quad (3)$$

where $\sqrt{s}\equiv W=E_N+\omega_\gamma=E_f+\omega_m$ is the total centre-of-mass energy of the system, and $\mathcal{O}_{N^*}$ is determined by the structure of each resonance. $\Gamma(\boldsymbol{q})$ in Eq. (3) is the total width of the resonance, and a function of the final state momentum $\boldsymbol{q}$.

The transition amplitude for the n^{th} harmonic-oscillator shell, under $SU(6)$ symmetry, is

$$\mathcal{O}_n=\mathcal{O}^2_n+\mathcal{O}^3_n. \quad (4)$$

The first (second) term represents the process in which the incoming photon and outgoing meson, are absorbed and emitted by the same (different) quark.

In the present work, we use the standard multipole expansion of the CGLN amplitudes[53], and obtain the partial wave amplitudes of resonance $l_{2I,2l\pm1}$. Then, the transition amplitude takes the following form:

$$\mathcal{O}_{N^*}=if_{1l\pm}\sigma\cdot\epsilon+f_{2l\pm}\sigma\cdot\hat{\boldsymbol{q}}\sigma\cdot(\hat{\boldsymbol{k}}\times\epsilon)+ if_{3l\pm}\sigma\cdot\hat{\boldsymbol{k}}\hat{\boldsymbol{q}}\cdot\epsilon+if_{4l\pm}\sigma\cdot\hat{\boldsymbol{q}}\epsilon\cdot\hat{\boldsymbol{q}}. \quad (5)$$

where

$$f_{1l\pm}=f_0[\mp A^{N^*}_{1/2}-\sqrt{\frac{l+1/2\mp1/2}{l+1/2\pm3/2}}A^{N^*}_{3/2}]P'_{\ell\pm1},$$
$$f_{2l\pm}=f_0[\mp A^{N^*}_{1/2}-\sqrt{\frac{l+1/2\pm3/2}{l+1/2\mp 1/2}}A^{N^*}_{3/2}]P'_{\ell},$$
$$f_{3l\pm}=\pm f_0\frac{2A^{N^*}_{3/2}}{\sqrt{(l-1/2\pm1/2)(l+3/2\pm1/2)}}P''_{\ell\pm1},$$
$$f_{4l\pm}=\mp f_0\frac{2A^{N^*}_{3/2}}{\sqrt{(l-1/2\pm1/2)(l+3/2\pm 1/2)}}P''_{\ell}. \quad (6)$$

The f_0 and $A^{N^*}_\lambda$ in the above equations can be related to the matrix elements of the electromagnetic interaction Hamiltonian[32] as in Ref. [42]

$$A_\lambda = \sqrt{\frac{2\pi}{k}}\langle N^*;J\lambda|H_e|N;\frac{1}{2}\lambda-1\rangle, \quad (7)$$
$$A^m_\nu = \langle N;\frac{1}{2}\nu|H_m|N^*;J\nu\rangle. \quad (8)$$

2.2 Dynamical coupled-channels approach

The remaining terms in Eq. (2) are due to intermediate and final state interactions, allowing to go beyond the direct channel approximation. Actually, the pion photoproduction cross-section being roughly one order of magnitude larger than that of the η-photoproduction, it is a priori mandatory to consider the reactions initiated by $\gamma N\to\pi N$ and leading to the ηN final states. Accordingly, the T-matrix (Eq. (2)) contains the pion photoproduction contribution $v^{NR}_{\gamma N\to\pi N}$. That non-resonant term is calculated in line with Ref. [23].

Meson-baryon channels (MB) are handled[24] using the transition amplitudes in each partial wave

$$T_{MB,M'B'}(E)=t^{NR}_{MB,M'B'}(E)+t^{R}_{MB,M'B'}(E), \quad (9)$$

where MB ≡ πN, ηN, πΔ, ρN, σN. The non-resonant amplitude $t^{NR}_{MB,M'B'}$(E) in Eq. (9) is defined by the coupled-channels equations,

$$t^{NR}_{MB,M'B'}(E)=V_{MB,M'B'}(E)+ \sum_{M''B''}V_{MB,M''B''}(E)\,G_{M''B''}(E)t^{NR}_{M''B'',M'B'}(E), \quad (10)$$

with $G_{M''B''}(E)$ meson-baryon propagators and

$$V_{MB,M'B'}(E)=v_{MB,M'B'}+Z^{(E)}_{MB,M'B'}(E). \quad (11)$$

The energy independent interactions $v_{MB,M'B'}$ are derived from tree-level processes by using a unitary transformation method. $Z^{(E)}_{MB,M'B'}(E)$ is induced by the decays of the unstable particles (Δ, ρ, σ). Here, the 3-body ππN states are neglected.

The second term in the right-hand-side of Eq. (9) is the resonant term defined by

$$t^{R}_{MB,M'B'}(E)=\sum_{N^*_i,N^*_j}\frac{\bar{\Gamma}_{MB\to N^*_i}(E)\bar{\Gamma}_{N^*_j\to M'B'}(E)}{(E-M^0_{N^*_i})\delta_{i,j}-\bar{\Sigma}_{i,j}(E)}, \quad (12)$$

where $M^0_{N^*}$ is the bare mass of the resonant state N*, and the self-energies are

$$\bar{\Sigma}_{i,j}(E)=\sum_{MB}\Gamma_{N^*_i\to MB}G_{MB}(E)\bar{\Gamma}_{MB\to N^*_j}(E). \quad (13)$$

The dressed vertex interactions in Eqs. (12) and (13) are (where we define $\Gamma_{\rm MB\to N^*}=\Gamma^{\dagger}_{\rm N^*\to MB}$)

$$\bar{\Gamma}_{\rm MB\to N^*}(E)=\Gamma_{\rm MB\to N^*}+\sum_{\rm M'B'}t^{\rm NR}_{\rm MB,M'B'}(E)G_{\rm M'B'}(E)\Gamma_{\rm M'B'\to N^*}\,, \qquad (14)$$

$$\bar{\Gamma}_{\rm N^*\to MB}(E)=\Gamma_{\rm N^*\to MB}+\sum_{\rm M'B'}\Gamma_{\rm N^*\to M'B'}G_{\rm M'B'}(E)t^{\rm NR}_{\rm M'B',MB}(E)\,, \qquad (15)$$

with $G_{\rm M'B'}$ meson-baryon propagators.

In order to solve the coupled-channels equations, Eq. (10), we regularize the matrix elements of $v_{\rm MB,M'B'}$ by introducting at each meson-baryon-baryon vertex a form factor of the following form:

$$F(\vec{k},\Lambda)=\left[\frac{\Lambda^2}{\vec{k}^2+\Lambda^2}\right]^2, \qquad (16)$$

with $\vec{k}$ being the meson momentum. For the meson-meson-meson vertex of $v^{\rm t}$, the form factor in Eq. (16) is also used with $\vec{k}$ being the momentum of the exchanged meson. For the contact term $v^{\rm c}$, we regularize it by $F(\vec{k},\Lambda)F(\vec{k'},\Lambda')$.

With the nonresonant amplitudes generated from solving Eq. (10), the resonant amplitude $t^{\rm R}_{\rm MB,M'B'}$ in Eq. (12) then depends on the bare mass $M^0_{\rm N^*}$ and the bare $\rm N^*\to MB$ vertex functions, parameterized in the following form:

$$\Gamma_{\rm N^*,MB(LS)}(k)=\frac{1}{(2\pi)^{3/2}}\frac{1}{\sqrt{m_{\rm N}}}C_{\rm N^*,MB(LS)}\left[\frac{\Lambda^2_{\rm N^*,MB(LS)}}{\Lambda^2_{\rm N^*,MB(LS)}+(k-k_{\rm R})^2}\right]^{(2+L)}\left[\frac{k}{m_\pi}\right]^L, \qquad (17)$$

where L and S are the orbital angular momentum and the total spin of the MB system, respectively. $C_{\rm N^*,MB(LS)}$ measure the meson-nucleon-$\rm N^*$ coupling strength for a specific LS combination of the MB system and are treated as free parameters, and $k_{\rm R}$ are parameters fixed by the $\pi N\to\pi N$ analysis in Ref. [25].

3 Results and discussion

In this section we first report on our results for the process $\pi^-p\to MB\to\eta n$. The known resonances embodied in the reaction mechanism are: $S_{11}(1535)$, $S_{11}(1650)$, $P_{11}(1440)$, $P_{11}(1710)$, $P_{13}(1720)$, $D_{13}(1520)$, $D_{13}(1700)$, $D_{15}(1675)$, and $F_{15}(1680)$. The obtained model is then used to investigate the $\gamma p\to MB\to\eta p$ reation, where in addition to the above resonances, we include also $P_{13}(1900)$ and $F_{15}(2000)$. Finally, for the photoproduction channel, possible contributions from missing and/or new resonances are studied.

3.1 $\pi^-p\to\eta n$

The procedure in building a model for this channel is in line with our previous work[31], with a significant difference with respect to the ηNN coupling constant, which constitues the only common adjustable parameter for both channels. Notice that, the coupling extracted from the $\pi^-p\to\eta n$, and reported in Ref. [31], turns out to be about one order of magnitude larger than the coupling extracted via the photoproduction process (Ref. [41]). Accordingly, we went back to the $\pi^-p\to\eta n$ reaction, and imposed a coupling compatible with its photoproduction value. As explained in Ref. [31], our formalism embodies a total of 29 adjustable parameters for this channel. A series of minimizations were then performed, with strong constraints on $g_{\eta NN}$, and a new model is obtained, EBAC-Saclay-πη model.

In Fig. 1 results of our model are compared to the data at four energies, spanning the energy range from close to threshold up to $W\approx 1.9$ GeV.

In the same Figure we show also the EBAC model, JLMS[25], where all 175 parameters, including the 29 relevant to the ηN final state, have been adjusted on the $\pi N\to\pi N$ data.

At the lowest energy, data are from the Crystal Ball collaboration[5, 6]. At other energies, data are from rather old measurements. Given the inconsistencies within the data base, our model gives a reasonable account of the differential cross section from close to threshold up to $W\approx 1.9$ GeV. The fitted data base embodies 255 differential cross section data points, for which the χ^2 turns out to be 2.32 for the EBAC-Saclay-πη model and 6.94 for the JLMS model. The extracted coupling constant, within our present model is $g_{\eta NN}$=1.59, to be compared to 13.41 for JLMS[25] and 17.24 in our previous work[31].

Discrepancies between the EBAC-Saclay-πη and JLMS models span almost the whole phase-space depicted in Fig. 1, emphasizing that $\pi N\to\pi N$ data do not put enough constraints on the free parameters related to final states other than πN. Moreover, the new values extracted for the 29 fitted parameters here, once replacing those reported in JLMS[25], within the complete set of 175 parameters, lead to a better agreement with πN total cross sections, as shown in Fig. 2.

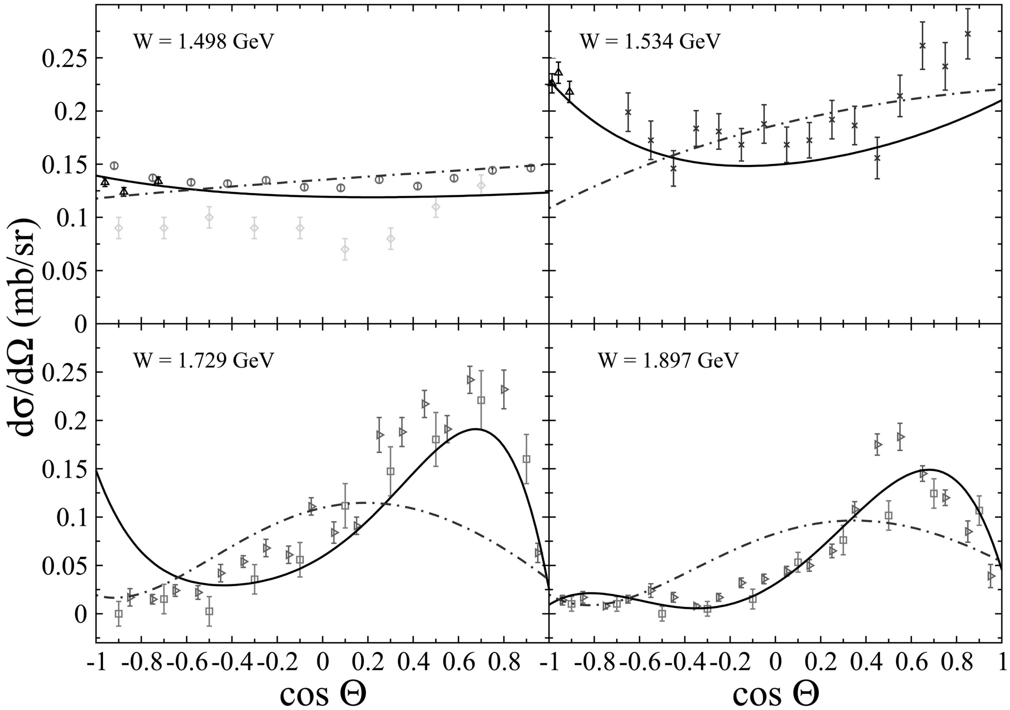

Fig. 1. Differential cross section for the reaction $\pi^-p\rightarrow\eta n$. The curves correspond to models EBAC-Saclay-πη (full), present work, and JLMS[25] (dash-dotted). Data are from Prakhov et al.[5] (empty circles), Morrison[6] (diamonds), Deinet et al.[7] (crosses), Debenham et al.[8] (up triangles), Richards et al.[9] (empty squares), and Brown et al.[10] (right triangles)

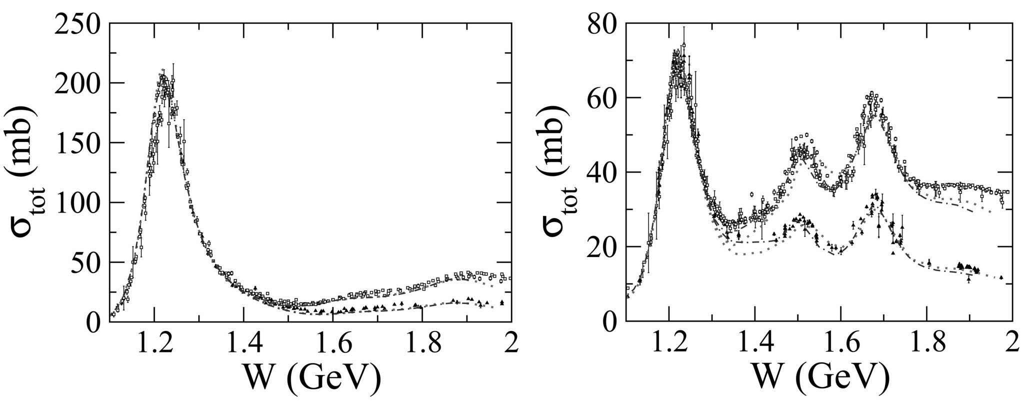

Fig. 2. Comparisons between the models EBAC-Saclay-πη (dash-dotted), and JLMS[25](dotted) for $\pi N\rightarrow X,\pi N$ processes. Left panel: Predicted total cross section for the reactions $\pi^+p\rightarrow X$ (upper set) and $\pi^+p\rightarrow\pi^+p$ (lower set). Right panel: Predicted total cross section for the reactions $\pi^-p\rightarrow X$ (upper set) and $\pi^-p\rightarrow\pi^-p+\pi^\circ n$ (lower set). Data in both panels are from Refs. [49,54].

3.2 $\gamma p\rightarrow\eta p$

For the photoproduction channel, we use the above meson-baryon formalism, with the free parameters determined for the EBAC-Saclay-πη, as explained above. So, the adjustable parameters here are merely those of the photoproduction reaction. As starting value for those parameters, we use the direct channel values, reported in Ref. [41].

In Fig. 3, we show two sets of curves. The first one (dash-dotted) is obtained by including exclusively the twelve known N^*s in this energy range (Table 1). At all shown energies those curves miss the data, especially with increasing W. The obtained χ^2 per data point, after minimization, is 11.36. This shows clearly the need for additional resonances with masses roughly between 1.7 to 2 GeV.

Here, we wish to emphasize that the χCQM approach[41], summarized in Section 2.1, allows reproducing the mass spectrum of known N^*s and predicts additional ones (missing resonances), Table 1. We have checked for possible contributions from the latter set of resonances, but found no significant effects.

However, in that energy range, two new resonances, namely S_{11} and D_{13}, have been reported by several authors[22,30,39,44,55—63]

In Figs. 3 and 4, the results of our model (full curves), hereafter called EBAC-Saclay-γη, are depicted and compared successfully with the relevant data. The full model is obtained by fitting 10 free parameters on a data base including 870 data points, and leading to a χ^2 per data point of 1.44. That model includes all the twelve known resonances, but also two new resonances. Within our full model, we extract mass and width of the new resonances, namely, $S_{11}[M{=}1.707\ \text{GeV}, \Gamma{=}222\ \text{MeV}]$ and $D_{13}[M{=}1.950\ \text{GeV}, \Gamma{=}139\ \text{MeV}]$.

In Fig. 4, our results for single polarization observables are reported at two energies, in vicinity of the first S_{11} resonance and the third one (new). All the shown data are well reproduced with the full model. Notice that the polarized target asymmetry data were not included in the data base fitted and, hence, the shown curves in the right panel are predictions. Here, again we remark that the new resonances are indispensible to describe the polarization measurements.

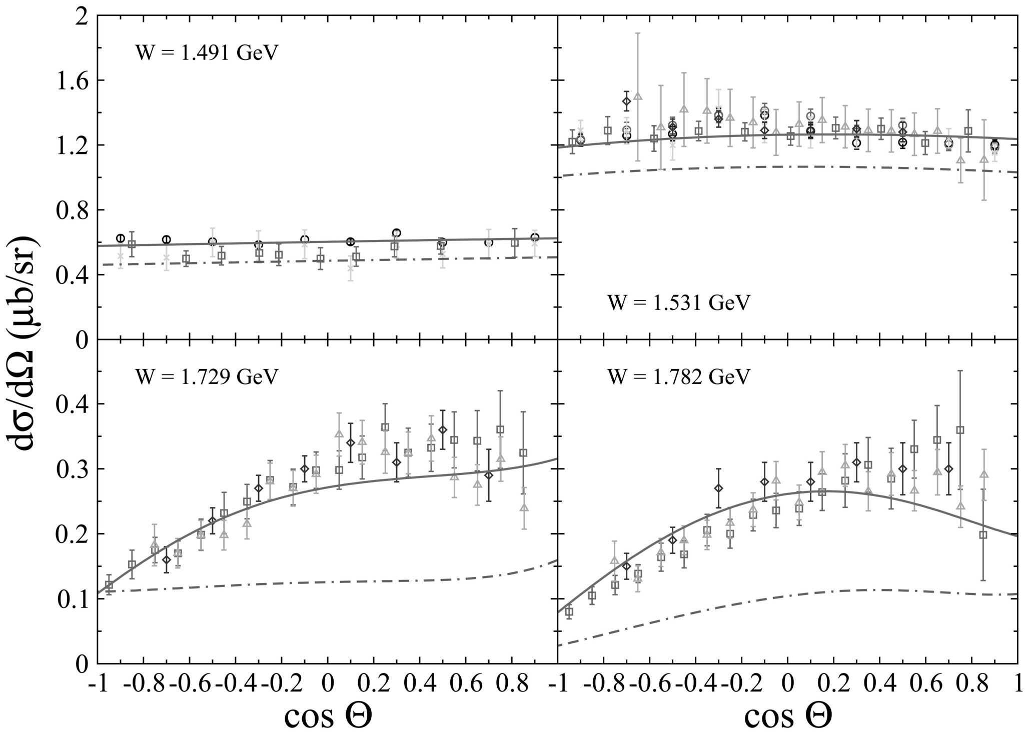

Fig. 3. Differential cross section for γp → ηp, at four values for W. The curves are: EBAC-Saclay-γη model (full), and a configuration embodying only known resonances (dash-dash-dotted). Data are from CLAS[13] (diamonds), LNS[18] (crosses), GRAAL[19] (squares), and ELSA[14] (triangles).

Table 1. Extracted masses for known resonances. For each resonance, results of the present work (M^{OGE}) are given in the first line, predictions from Isgur and Karl for negative-parity[50] and positive-parity[51] excited baryons in the second line, and PDG values[49] in the third line.

known N*	$S_{11}(1535)$	$S_{11}(1650)$	$P_{11}(1440)$	$P_{11}(1710)$	$P_{13}(1720)$	$P_{13}(1900)$
M^{OGE}	1473	1620	1428	1723	1718	1854
Refs. [50,51]	1490	1655	1405	1705	1710	1870
M^{PDG}	1535 ± 10	1655^{+15}_{-10}	1440^{+30}_{-20}	1710 ± 30	1720^{+30}_{-20}	1900
known N*	$D_{13}(1520)$	$D_{13}(1700)$	$D_{15}(1675)$	$F_{15}(1680)$	$F_{15}(2000)$	$F_{17}(1990)$
M^{OGE}	1511	1699	1632	1723	2008	1945
Refs. [50,51]	1535	1745	1670	1715	2025	1955
M^{PDG}	1520 ± 5	1700 ± 50	1675 ± 5	1685 ± 5	2000	1990
missing N*	P_{11}	P_{11}	P_{13}	P_{13}	P_{13}	F_{15}
M^{OGE}	1899	2051	1942	1965	2047	1943
Ref. [51]	1890	2055	1955	1980	2060	1955

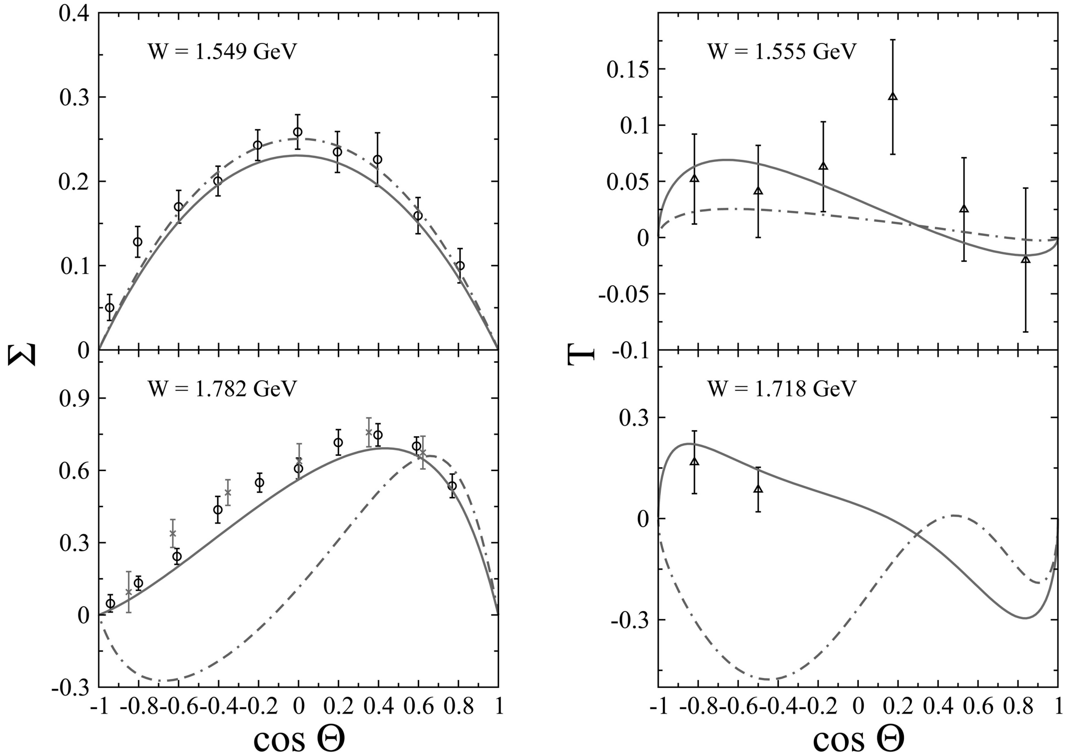

Fig. 4. Angular distribution for polarized beam asymmetry (left panel) and polarized taget asymmetry (right panel), for $\gamma p \rightarrow \eta p$; curves same as in Fig. 3. Data are: for Σ from GRAAL[19] (circles) and ELSA[16] (crosses), and for T from ELSA[17] (triangles).

4 Conclusions

We reported on the investigation of the reactions $\pi^- p \rightarrow \eta n$ and $\gamma p \rightarrow \eta p$, in the center-of-mass energy up to $W \approx 2$ GeV, reproducing well enough the relevant data. The formalisms used here are a combinations of a chiral constituent quark model[41] and a dynamical coupled-channels[24] based on meson-nucleon degrees of freedom.

With respect to our previous works, several new points emerge from the present work. For the $\pi^- p \rightarrow \eta n$ process, a new model is obtained, differing mainly from the previous one[31] by a significantly more realistic ηNN coupling constant, required by the χCQM approach[41]. Interstingly, the new set of parameters not only does not spoil the results of the original work[25] with respect to the $\pi N \rightarrow \pi N$ reactions, but it brings in some improvements, showing that in order to determine various parameters of electromagnetic and strong verticies, as well as properties of the resonances, it is mandatory to study reactions corresponding to the final states introduced, via coupled-channels, in intermediate and final states meson-baryons interactions.

The coupled-channels study of the reaction $\gamma p \rightarrow \eta p$ compared to the direct channel investigation[41], shows that the roles attributed to the most relevant resonances in the reaction mechanism become more coherent and hence realistic, while taking into account multi-step mechanisms. With respect to the new resonances, the coupled -channels approach confirms results provided by the direct channel study[41].

Finally, the present work shows that both reactions are by far dominated by the $S_{11}(1535)$ resonance, and the other significant components are the following ones: $S_{11}(1650)$, $P_{13}(1720)$, $D_{13}(1520)$, and $F_{15}(1680)$.

In order to deepen our knowledge of the properties of known resonances and, hopefully, to establish the existence of new baryon resonances, further investigations are needed. From theoretical point of view, a recent work[27] with respect to the ππN final states via a dynamical coupled-channels is a significant step and needs to be followed by studying other final states with kaon-hyperon and vector mesons production reactions. In the experimental realm, data using pion beams are highly desirable. Moreover, double polarization measurements in progress at JLab[64] and ELSA[65] are expected to put stronger constraints on the phenomenological models.

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