

# The search for missing baryon resonances

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## **Abstract.**

Experiments with electromagnetic probes are promising to search for baryon resonances that have been predicted by quark models but have not yet been observed. Data sets from different experiments show interesting resonance structures possibly due to so far unknown states. This might indicate that at least some of the missing baryon resonances start to show up.

## **Introduction**

At medium energies, our present understanding of QCD is still very limited. Here, in the energy regime of meson and baryon resonances the strong coupling constant is large and perturbative methods can no longer be applied. One of the key issues in this energy regime is to identify the relevant degrees-of-freedom and the effective forces between them. A necessary step towards this aim is undoubtedly a precise knowledge of the experimental spectrum of baryon resonances and of their properties. Their comparison with different models may lead to a deeper understanding of QCD in the non-perturbative regime. Quark models are in general amazingly successful in describing the spectrum of existing states. However, constituent quark models usually predict many more resonances than have been observed so far. Different explanations have been suggested to explain this observation:

1) The "missing" states may not exist. Nucleon resonances could e.g. have a quark-diquark structure [1]. This reduces the number of internal degrees-of-freedom, and therefore, the number of existing states. Of course, one might also think of other hidden symmetries. At a first glance, this explanation seems to be rather exotic but it is interesting to notice that the Regge trajectories for mesons and baryons are parallel. The similar dependence of the mass squared on the angular momentum seems to indicate that also the acting force is similar. This behavior could be easily understood in terms of a quark-diquark picture, with a diquark in a baryon replacing the antiquark in the meson (see also [2]).

2) The "missing" states may not have been observed so far because of a lack of high quality data in channels different from  $\pi N$ . Most available experimental data stem from  $\pi N$  scattering experiments. If the missing states decouple from  $\pi N$  they would not have been observed so far. This conjecture seems reasonable following quark model predictions [3]. Many of these unobserved states are expected to couple significantly to channels like  $N\eta$ ,  $N\eta'$ ,  $N\omega$ ,  $\Delta\pi$ ,  $N\rho$  or  $K\Lambda$  and also to  $\gamma p$  [3, 4]. Therefore photo-production experiments investigating these channels have a great discovery potential if

these resonances really exist.

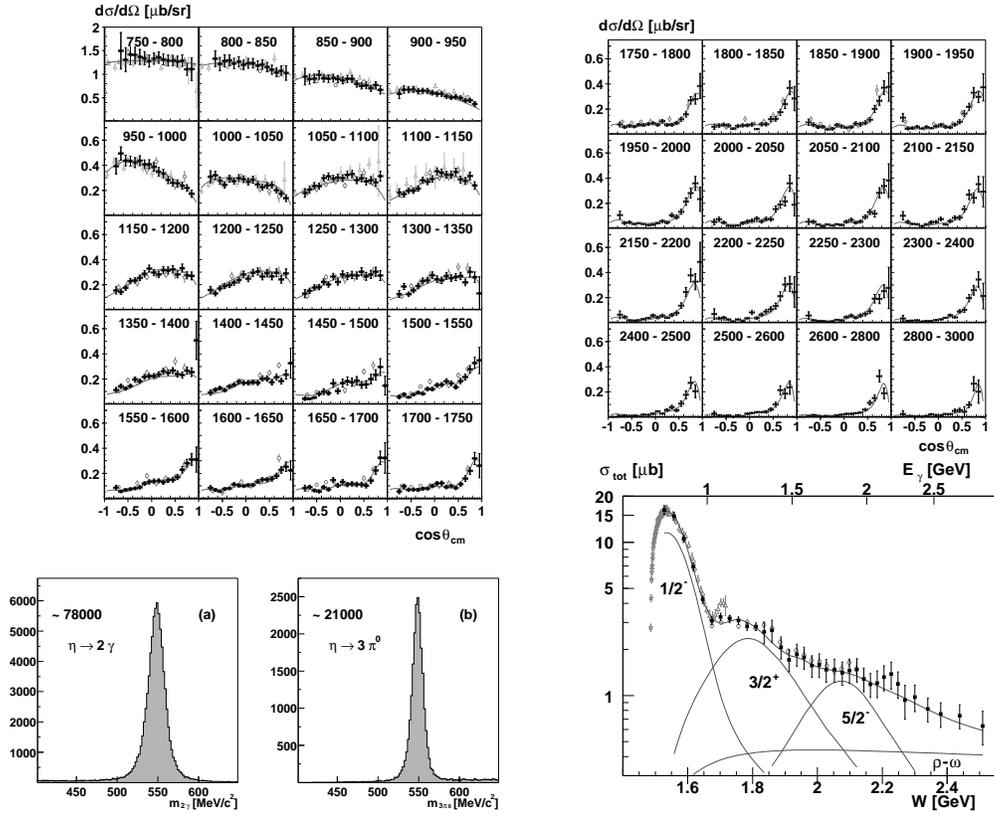
Experiments with electromagnetic probes are not only interesting to search for unknown states but also to determine the properties of resonances like photo-couplings and partial widths. These provide additional information which can be compared to model predictions. The properties of a resonance are also of big importance for an interpretation of its nature. One immediate debate in the light of the possible observation of a pentaquark is e.g. whether the  $P_{11}(1710)$  and the  $P_{11}(1440)$  might be pentaquarks rather than 3-quark states. A good understanding of their production and decay properties may help to elucidate their nature. In the following, different final states, where interesting resonance structures have been observed, will be discussed.

### The $\gamma p \rightarrow p\eta$ -channel

Recently new data on  $\eta$ -photoproduction has been taken by the CB-ELSA experiment in Bonn [5]. Due to its electromagnetic calorimeter consisting of 1380 CsI(Tl) crystals covering 98% of the  $4\pi$  solid angle, the CB-ELSA detector is very well suited to measure photons. The  $\eta$  is observed either in its  $\gamma\gamma$ - or  $3\pi^0$ - decay. The two or six photons are detected in the calorimeter and the proton is identified in a 3-layer scintillating fiber detector. The invariant masses show a clear  $\eta$  signal over an almost negligible background (Fig. 1). The differential as well as the total cross section is shown in Fig. 1 in comparison to the TAPS [6], GRAAL [7] and CLAS [8] data. The new CB-ELSA data extends the covered angular and energy range significantly compared to previous measurements. The total cross section was obtained by integrating the differential cross sections. The extrapolation to forward and backward angles uses the result of the partial wave analysis (PWA) discussed below. The PWA is necessary to extract the contributing resonances from the data. Its result is shown as solid line in Fig. 1. In the fit the following data sets were included in addition to the CB-ELSA data on  $\gamma p \rightarrow p\eta$ : The CB-ELSA data on  $\gamma p \rightarrow p\pi^0$  [9], the TAPS data on  $\gamma p \rightarrow p\eta$  [6], the beam asymmetries  $\Sigma(\gamma p \rightarrow p\pi^0)$  and  $\Sigma(\gamma p \rightarrow p\eta)$  from GRAAL [10], and  $\Sigma(\gamma p \rightarrow p\pi^0)$  and  $\gamma p \rightarrow n\pi^+$  from SAID. Apart from known resonances a new state was found, an  $D_{15}(2070)$  with a mass of  $(2068 \pm 22)$  MeV and a width of  $(295 \pm 40)$  MeV. Its rather strong contribution to the data set is also shown in Fig.1. In addition an indication for a possible new  $P_{13}(2200)$  was found. No evidence was found for a third  $S_{11}$  for which claims have been reported at masses of 1780 MeV [11] and 1846 MeV [12].

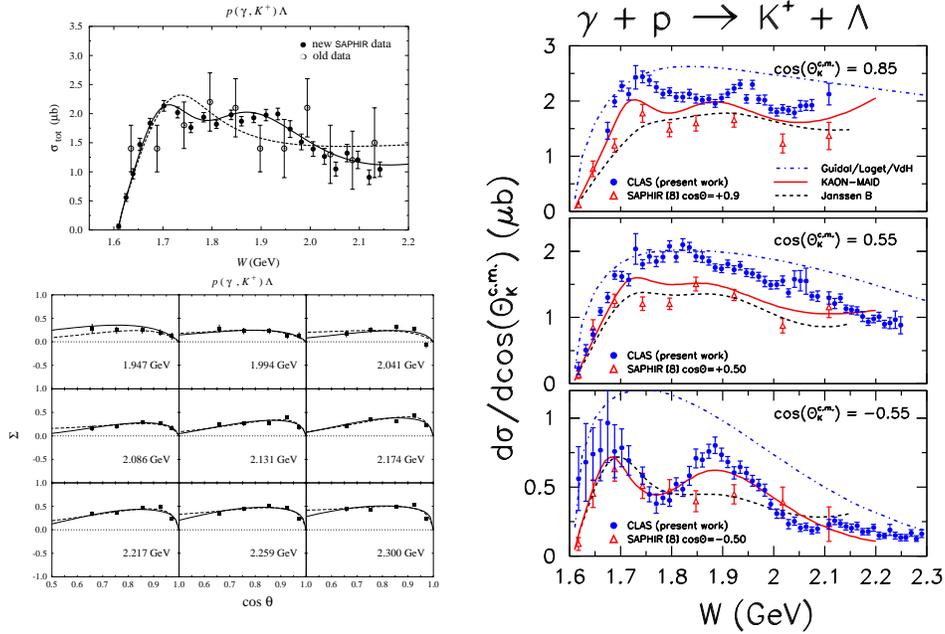
### The $\gamma p \rightarrow K^+\Lambda$ -channel

Another interesting channel is the  $K^+\Lambda$  channel, where a structure around 1900 MeV was first observed in the SAPHIR data [13]. The total cross section shows two bumps, at about 1700 MeV, and 1900 MeV (Fig.2 upper left). Describing the data within different models it was found that the first peak is mainly due to the  $S_{11}(1650)$ ,  $P_{11}(1710)$ , and  $P_{13}(1720)$ . Within a tree level isobar model based on an effective lagrangian approach Mart and Bennhold found that a new resonance is needed to describe the second bump in the cross section [14]. This resonance was identified with a  $D_{13}(1895)$ . Fig.2, upper



**FIGURE 1.** Upper plots: Differential cross sections for  $\gamma p \rightarrow p \eta$ , for  $E_\gamma = 750 \text{ MeV}$  to  $3000 \text{ MeV}$ : CB-ELSA (black squares) [5], TAPS [6], GRAAL [7] and CLAS [8] data (in light gray). The solid line represents the result of our fit. Lower left: Invariant  $\gamma\gamma$  and  $3\pi^0$  invariant mass. Lower right: Total cross section (logarithmic scale) for the reaction  $\gamma p \rightarrow p \eta$ . For further details see [5].

left shows their best description of the data with and without this new state. Even though this picture looks quite convincing the existence of the state is controversially discussed. Saghai was e.g. able to describe the data within a chiral quark model without any new resonance [15]. In his model the enhancement is explained by hyperon exchange in the u-channel. Hyperon exchanges are also included in the model of Jannsen et al. [16] but still an additional state around  $1900 \text{ MeV}$  was needed. A similar improvement of the fit was obtained by resonances of different quantum numbers. In the Giessen coupled-channel model a negligible  $K\Lambda$  coupling was found for a  $D_{13}$  state which was introduced around  $1950 \text{ MeV}$  [17]. Recently new high statistics data on this final state became available. SAPHIR [18] and CLAS [19] did provide new data on cross sections and on the  $\Lambda$  recoil polarization and LEPS [20] on the beam-asymmetry. The differential cross sections as a function of  $\sqrt{s}$  for different  $K^-$ -angles are shown in Fig.2, right for the CLAS data. Again a structure around  $1900 \text{ MeV}$  is observed. It varies in width and position with the  $K^-$ -angle. This suggests an interference phenomenon between several resonant states, rather than a single resonance. This behaviour is not yet reproduced by the models shown, but the model parameters have not yet been adjusted to the new data. Some first preliminary results on an interpretation of the new data have been shown



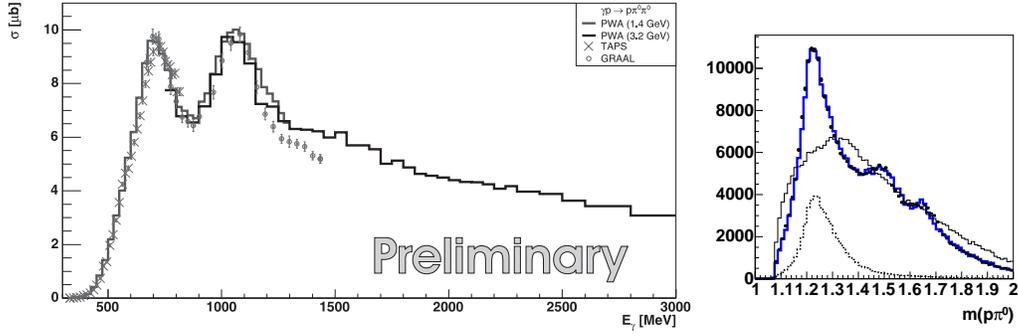
**FIGURE 2.** Left, upper plot: Total cross section for  $\gamma p \rightarrow K^+ \Lambda$  from SAPHIR [13]. Description of the data within the model [14] with and without including a new resonance around 1900 MeV. Right: Energy dependence of the  $\gamma p \rightarrow K^+ \Lambda$ -cross sections for different  $K^+$ -angles (CLAS-data [19]). Left, lower plot: Beam asymmetry for  $\gamma p \rightarrow K^+ \Lambda$  measured by LEPS [20].

by Mart and Bennhold [21]. Fitting the new SAPHIR data together with the beam asymmetry data from LEPS (Fig.2, lower left) they find that more than one resonance is needed to describe the mass region around 1900 MeV. This work is still in progress, so no definite statement on the existence of new resonances in this data could be made yet.

### The $\gamma p \rightarrow p\pi^0\pi^0$ -channel

The  $\gamma p \rightarrow p\pi^0\pi^0$  cross section was measured by TAPS [22] in the low energy range and by GRAAL [23] up to an incoming photon energy of about 1500 MeV; two peak-like structures are observed [22, 23]. The data has been interpreted within the Laget [24] and Valencia model [25], resulting in very different interpretations. In the Valencia-model, which is limited to the low energy region, the  $D_{13}(1520)$  decaying into  $\Delta(1232)\pi$  dominates the lower energy peak, while in the Laget-model the  $P_{11}(1440)$  decaying into  $\sigma p$  is clearly the dominant contribution. Even though both models lead to a reasonable description of the total cross section their interpretation of the data is rather different, in fact they are contradicting each other.

Recently data on  $\gamma p \rightarrow p\pi^0\pi^0$  has also been taken by the CB-ELSA experiment in Bonn extending the covered energy range up the  $E_\gamma=3.0$  GeV [26]. To extract the contributing resonances, their quantum numbers and their properties from the data, a PWA has been done. The formalism used is summarized in [27]. The fit uses Breit-Wigner resonances and includes  $s$ - and  $t$ -channel amplitudes. An unbinned maximum-likelihood



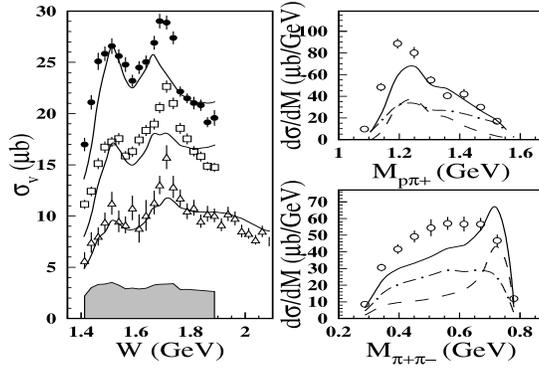
**FIGURE 3.** Left: Total cross section as obtained by integrating the result of the partial wave analysis over phase space (solid line), in comparison to the preliminary TAPS[28] and GRAAL[23] data. Right:  $p\pi^0$  invariant mass for  $E_\gamma=0.8-3.0$  GeV in comparison to the result of the PWA. The plots show the experimental data (points with error bars), the result of the PWA (solid gray curve), the contribution of the  $D_{13}(1520)$  (dashed black curve) and the phase space distribution (thin black line), preliminary.

fit was performed which has the big advantage of being event-based; it takes all the correlations between the five independent variables correctly into account. The fits include the preliminary TAPS data [28] in the low energy region in addition to the CB-ELSA data. Resonances with different quantum numbers were introduced in various combinations allowing, so far, for the following decay modes:  $\Delta(1232)\pi$ ,  $N(\pi\pi)_s$ ,  $P_{11}(1440)\pi$ ,  $D_{13}(1520)\pi$  and  $X(1660)\pi$ . For a good description of the data resonances like e.g. the  $P_{11}(1440)$ , the  $D_{13}(1520)$ , the  $D_{13}/D_{33}(1700)$ , the  $P_{13}(1720)$ , the  $F_{15}(1680)$  as well as several additional states are needed. One preliminary result of the PWA is a dominant contribution of the  $D_{13}(1520) \rightarrow \Delta\pi$  amplitude in the energy range, where the first peak in the cross section occurs. Fig. 3 shows the total cross section obtained by fitting the CB-ELSA and the TAPS data and by integrating the result of the combined fit over phase space.

In the CB-ELSA data baryon resonances not only decaying into  $\Delta\pi$  but also via  $D_{13}(1520)\pi$  and  $X(1660)\pi$  are observed for the first time. The enhancements at the corresponding  $p\pi$  invariant masses are clearly visible in Fig. 3, right. The observation of baryon cascades is also interesting with respect to the search for states which might not couple to  $\pi N$  and  $\gamma p$ ; they still could be produced in such baryon cascades.

### The $ep \rightarrow e'p\pi^+\pi^-$ -channel

Recently,  $2\pi$ -electroproduction was investigated by CLAS. The total cross section for different bins in momentum transfer  $Q^2$  is shown in Fig 4. The cross section changes with  $Q^2$  as one would expect since the helicity couplings of the resonances depend on  $Q^2$ . The data was investigated within an isobar model. The fit takes the  $\Delta\pi$  and the  $N\rho$  subchannels into account, in addition non-resonant contributions are allowed for. The fit included 12 known baryon resonances together with the non-resonant background amplitudes. If all known information on the resonances is included in the fit the mass region 1700 MeV is rather badly described while the fit agrees fairly well with the data at low  $W$  (Fig.4). At the same time, the fit clearly overshoots the data in the  $\rho$



**FIGURE 4.** Left: Total cross section for  $\gamma^* p \rightarrow p\pi^+\pi^-$  for  $Q^2=0.5-0.8$  (full points),  $0.8-1.1$  (open squares),  $1.1-1.5$   $(\text{GeV}/c)^2$  (open triangles) [29]. Right: Differential cross sections for  $W=1.7-1.75$   $\text{GeV}$ ,  $Q^2=0.8-1.1$   $(\text{GeV}/c)^2$ . The line corresponds to the fit which includes the known information on the resonances described in the text. For further details see [29].

region of the  $\pi^+\pi^-$  invariant mass in the  $W$ -bin around 1700 MeV. This behavior can be traced back to the  $P_{13}(1720)$  which has, following the PDG, a rather large  $N\rho$ -decay width of 70 to 85%. A better description of the data is reached by either changing the decay properties of the known  $P_{13}$  completely or by keeping the PDG-state and adding a new  $3/2^+$  state of slightly smaller width and a stronger  $\Delta\pi$  decay mode. For further details see [29]. A recent combined analysis of this data together with the CLAS  $p\pi^+\pi^-$ -photoproduction data seems to indicate that two state are needed to describe these two data sets consistently [30]. But this analysis is still in progress.

## Summary

Indications for new resonances are found in several final states. A  $D_{15}(2070)$  and possible indications for an  $P_{13}(2200)$ -state were found in a combined PWA of the new CB-ELSA  $\eta$ -photoproduction together with other data sets. In the old  $K^+\Lambda$ -SAPHIR data possible indications for a new state around 1900 MeV were observed, while the new higher statistics data on this final state from SAPHIR, CLAS and LEPS seems to indicate that even more than one resonance might contribute to the mass region around 1900 MeV.  $2\pi^0$ -photoproduction data has been taken by TAPS, GRAAL and CB-ELSA. The total cross section shows two clear peaks around  $E_\gamma=700$  MeV and 1100 MeV. The interpretation of the lower energy peak has been controversially discussed as either being mainly due to the  $P_{11}(1440) \rightarrow p\sigma$ , or due to the  $D_{13}(1520) \rightarrow \Delta\pi$  amplitude. A preliminary combined PWA of the CB-ELSA and TAPS data indicates a dominant contribution of the latter amplitude in this energy range. At higher energies, in addition to the  $\Delta\pi$  decay of baryon resonances, their decay via higher mass resonances like e.g. the  $D_{13}(1520)$  are observed for the first time. This observation opens up a new opportunity to search for baryon resonances which may decouple from  $N\pi$  and  $\gamma N$ ; they still might be produced in baryon cascades. The possible existence of an additional  $P_{13}$  state in the CLAS  $\pi^+\pi^-$ -electroproduction data around 1700 MeV also has been discussed recently. So the question is, whether the missing resonances are finally appearing. The  $D_{15}(2070)$

would nicely fit to one of the missing states and the same would also be true for the  $P_{13}(2200)$  and the  $D_{13}(1895)$  state, while a second  $P_{13}$  state in the mass range around 1700 MeV is not expected by the quark model.

Before the above question can be answered, a better understanding of the spectrum is obviously needed. One very important step towards this aim is the measurement of polarization observables. They provide additional constraints for models or PWA used to extract resonance information from the data. This increases the sensitivity on smaller contributions and helps to distinguish between ambiguous PWA solutions. Such polarization data has been taken recently by various experiments e.g. by GRAAL, at MAMI, by CLAS, by LEPS, and by CB-ELSA/TAPS. Additional new measurements will also take place, like e.g. the double polarization experiments planned at ELSA.

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