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Impact of recent data on N* structure

Steven A. Dytman

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260 USA

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Abstract. Many modern experiments are posed with the issue of physics interpretation of their data when the theory is complicated. Certainly, experiments studying N* resonances are in this category. This short paper presents examples of interpretation made by inspection of the data, Breit-Wigner analyses, and coupled channels analysis. There are significant advantages to all three, but only a coupled channels analysis can provide the checks needed for a complete analysis. Examples from the S_{11} and P_{13} partial waves are discussed.

PACS. 13.30.-a Baryon decays – 13.60.Le Meson production in electromagnetic reactions – 13.20.Gk Baryon resonances with S=0

1 Introduction

The study of N* resonances has gotten a large boost from results from CEBAF, GRAAL, Mainz, Bonn and Spring8 in the last few years. These labs were all represented in talks at this conference. Experimenters are blessed with many reactions that feed into N^* states, but this also makes analysis more of a challenge. It is possible to learn about a given N^* state from a single reaction as long as there is a large enough coupling to the initial and final channels that a bump in the total cross section is produced. However, what if 2 reactions give contradictory results? (Is there a way to choose a correct interpretation?) What if a state is not seen in another reaction? (Does that mean the state doesn't really exist?) Unitary coupled channel analyses provide the formalism to get the necessary understanding. They simultaneously account for all possible decay channels in all reactions with various theoretical constraints.

Data alone can also provide insights into the underlying states. Is there a peak in the total cross section? This most likely has a resonance associated with it. However, peaks can come from threshold effects and low statistics and/or broad peaks have a way of disappearing when more accurate experiments are done. Simple Breit Wigner analyses are the natural way to first analyze experimtental results. This gives a common language to present results. However important these studies may be, assumptions must be made in absence of the bigger picture because there is no well-established link between the Breit-Wigner models and coupled channel models. This talk provides a few examples where new data gets a clearer interpetation when viewed through a coupled channel picture [1]. Although the new data can seldom be directly incorporated into a coupled channel fit, comparisons with full fits can provide important tests of tentative interpretations of new data. Unfortunately, the simple Breit-Wigner interpretation is shown to be incomplete in some cases.

2 S_{11} partial wave

The S_{11} resonances are important to study. The lowest state ($S_{11}(1535)$) is so close to ηN threshold (1.486 GeV for a proton target) that many papers assumed the strong features in the data come from strong final state interactions. If so, the long-standing interpretation of the data as the quark model state would be in doubt. It also has a transition form factor with a very slow falloff with Q^2 that is very hard for quark models to reproduce. Finally, this partial wave is an excellent place to search for N^* states beyond the quark model because it has no states in the mass range 1.7-2.0 GeV. Thus, experiments can provide many ways to test models of these states.

Unfortunately, the lowest state has a very unusual energy dependence in πN elastic scattering and photoproduction because of the strong threshold effect when the ηN channel opens up. A Breit-Wigner shape is wrong for these interactions unless the threshold cusp is properly included. A speed plot is misleading because the most rapid change comes at ηN threshold (also where the total cross section peaks). Thus, one must be very careful in the choice of analyses to be used for this state. The PDG summary [2] shows significant doubt in its properties showing a strong need for new, better data and for more consistent analyses. On the other hand, the 2nd state ($S_{11}(1650)$) is prominent in πN elastic scattering. A third state ($S_{11}(2090)$) was seen in older πN data.

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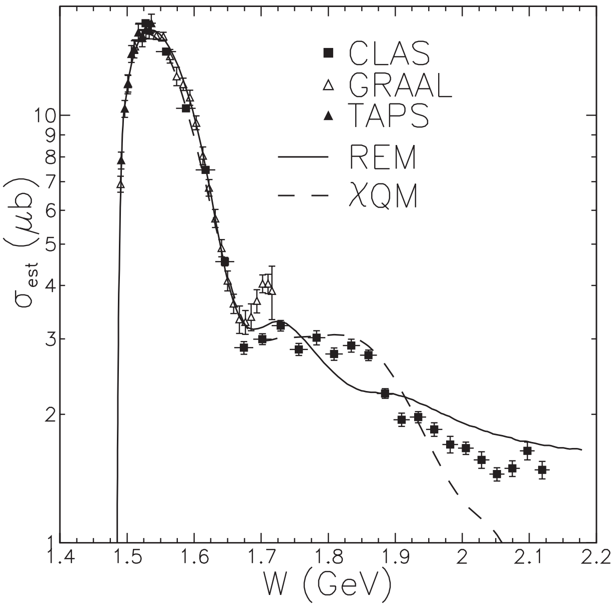

Fig. 1. η photoproduction total cross section data from Mainz, CLAS, and GRAAL

This confusing picture at first became more uncertain with recent data. The Mainz eta photoproduction data at threshold (see Fig. 1) was one of the first reactions studied in the new generation of experiments. Quality was much higher than for the previous data. Although the energy region studied just reached the peak of $S_{11}(1535)$, these new data in conjunction with older data showed a prominent peak in the total cross section just above threshold that had the energy dependence of a single Breit-Wigner resonance. Breit-Wigner interpretations of these data gave a very large total width and proton photocoupling ($A_{1/2}$). These values were twice as large as the results of most previous πN analyses and caused an *apparent* controversy. The correct picture comes from a coupled channel analysis. The Breit-Wigner energy dependence is only valid near the peak and the coupled channel effects are large because the πN channel couples strongly to the ηN channel. Since the first two S_{11} states overlap, the quantum mechanical interference must be taken into account, also difficult to do with Breit-Wigner amplitudes. Thus, the πN and ηN asymptotic states and the 1535 and 1650 MeV intermediate states must all be included. Only a coupled channels model can do all of this with appropriate theoretical constraints. Therefore, only a coupled channel analysis can provide a consistent description of all the data. Our most recent result gives a full width of 122±20 MeV and $A^p_{1/2} = 91 \pm 6$ GeV$^{-1/2}$ [1].

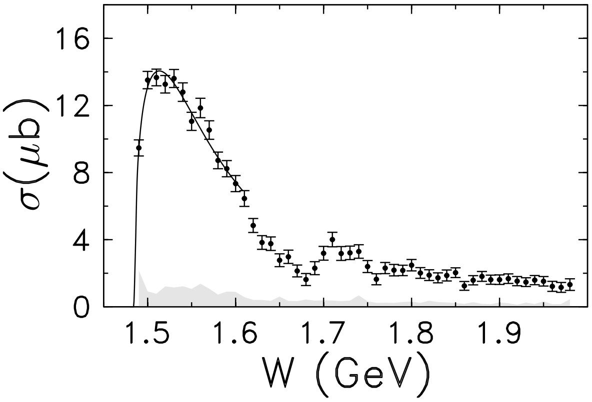

Fig. 2. Published η electroproduction total cross section data from CLAS for Q^2=0.625 (GeV/c)^2

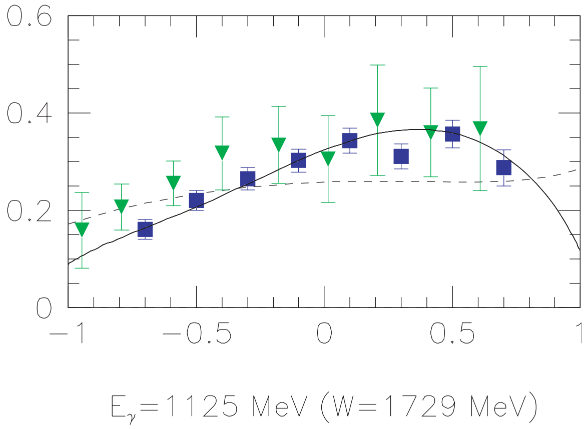

Fig. 3. η differential cross sections at W=1730 MeV for CLAS (squares) and GRAAL (diamonds), the energy where their total cross sections disagree

The 3rd PDG state (at high energy) is not seen in newer πN elastic partial wave analyses [4]. Instead, tentative evidence for a bump was seen at ~1.8 GeV in both GRAAL eta photoproduction [5] (see Fig. 1) and CLAS electroproduction [8] (see Fig. 2) cross section data. (At the same time, both the full width and photocoupling of $S_{11}(1535)$ got smaller in Breit-Wigner analyses as the higher energy data became available.) This would be a particularly interesting state as the quark model has no place for it. The picture for the 3rd state became quickly confusing when photoproduction data from CLAS [7] (Fig. 1) further extended the energy range covered. No peak in the *total cross section* was seen even though the *differential cross sections* from GRAAL and CLAS agreed at these energies. (see Fig. 3). The apparent contradiction is explained by the fact that neither of the experiments had complete angular coverage. Thus, a model was required to extrapolate to the most forward angles in order to determine the total cross section. GRAAL used a polynomial and CLAS used a model [6]. This issue is settled by looking at the more recent CLAS electroproduction data [9]. A very mild peak is seen in the total cross section (see Fig. 4) and the GRAAL extrapolation is shown to be more correct in the angular distributions (see Fig. 5. No strong conclusion can be made at this time.

A new third state should have repercussions in the interpretation of other data, especially the older, high quality πN elastic data. This author studied this issue in a series of fits with and without a third state. These fits included $\pi N \to \pi N$, $\pi N \to \eta N$, and $\pi N \to \pi\pi N$, $\gamma N \to \pi N$, and $\gamma p \to \eta p$ data including the recent GRAAL data. It gives very weak evidence for any third S_{11} state. Very

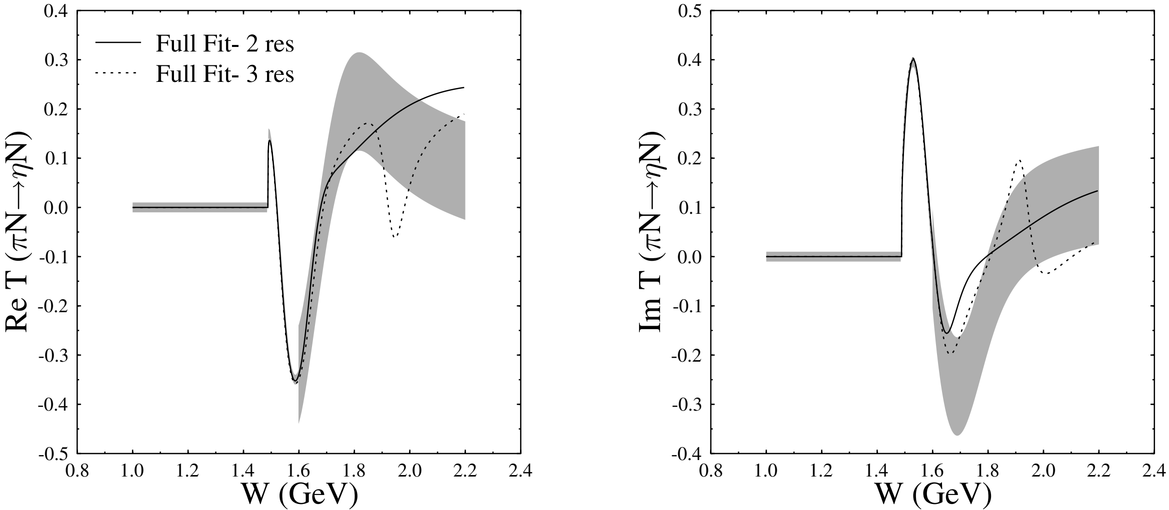

Fig. 6. Results from a fit to the S_{11} partial wave with and without a 3rd resonance

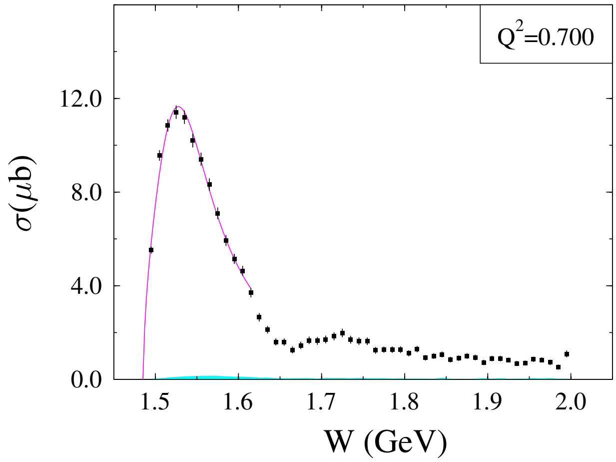

Fig. 4. New η electroproduction total cross section data from CLAS for Q^2=0.7 (GeV/c)^2

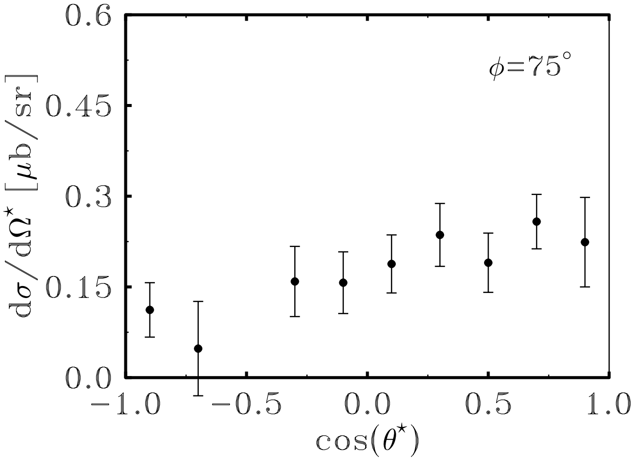

Fig. 5. New η electroproduction differential cross section data from CLAS for Q^2=0.8 (GeV/c)^2, W=1.72 GeV, and ϕ^*=75 degrees

inconclusive evidence for a state at ∼1.85 GeV is found. The only feature in the old data is a slight peak in the $\pi N \to \eta N$ amplitude at about 1.8 GeV that cannot be fit except with a new state (see Fig. 6). However, the overall impact on χ^2 is very small and the mass and width of this new state are very uncertain in this study. As the reader can see, the fit has more structure than the data. At present, the status of this tentative 3rd S_{11} state is still unclear. Full understanding will await a partial wave analysis of the eta photoproduction data.

3 P_{13} partial wave

States in this partial wave have been highlighted as a result of recent $\pi^+\pi^-$ electroproduction data from CLAS [10]. The data is far more accurate and has a much larger kinematical range than previous data.

They made a careful Breit-Wigner prediction for these data. This isn't trivial because the interference of the ρN, $\pi\Delta$ (both as decays from N^* resonances and as part of nonresonant amplitudes) and $\pi\pi N$ final states must be accounted for. Fits to the $\pi^+\pi^- N$ photoproduction data gave a good description of the nonresonant rho production in the t-channel. However, the modeling of the electromagnetic and hadronic couplings to the various N^* states had to be taken from previous results. (This probably introduces significant model dependence since the previous studies used different models.)

The prediction was a good match to the data except for a significant shortfall in a prominent peak in the total cross section at $W \sim 1.75$ GeV. They noted the large ρN coupling to P_{13} in PDG was probably inconsistent with the new data. Either the existing P_{13} state is greatly modified or there is a new P_{x3} (isospin is not determined) state in close proximity.

Potential uncertainties in the Breit-Wigner model cannot be ignored, but the uncertainties in the states at $W \sim 1.8$ GeV are also large, leading us to prefer the more con-

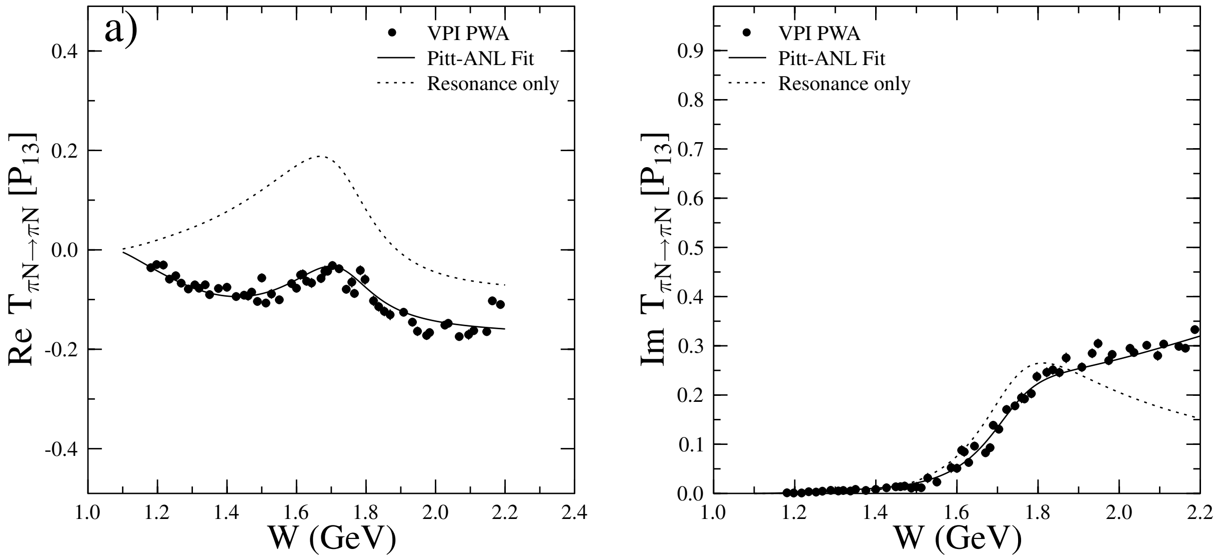

Fig. 7. P_{13} partial wave amplitude for πN elastic scattering. The full fit and the amplitude including only resonance couplings are shown

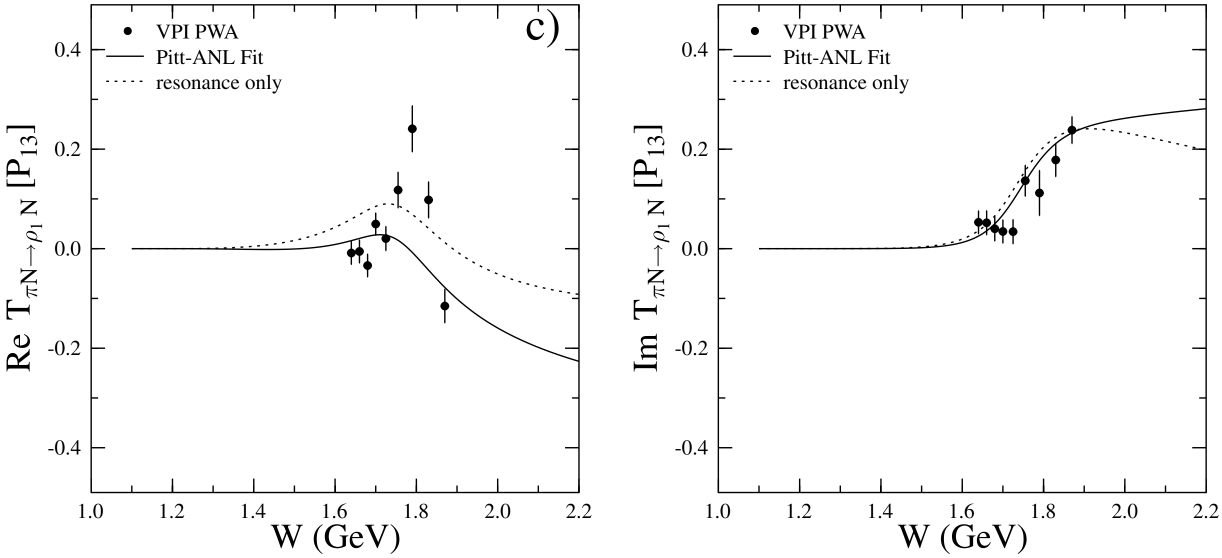

Fig. 8. P_{13} partial wave amplitude for $\pi N \to \rho N$ with $S_{\rho N}$=1/2

servative interpretation. About 5 N^* states of different quantum numbers will all contribute to most observables, making unambiguous identification very difficult in low quality older data. The most recent partial wave analysis of $\pi N \to \pi\pi N$ data [3] surprisingly found no contribution of $\pi\Delta$ to P_{13}. In addition, the $\pi N \to \rho N$ amplitudes are very uncertain (see Fig. 8); the energy range covered is very small and the structure in the real part is surprisingly sharp. (We've increased the error bars by a factor of 2 because any model has great difficulty fitting such sharp features.) Therefore, a likely result of any resonance analysis is an uncertain branching fraction for $P_{13} \to \rho N$. The PDG result is a very large BF for this decay with a surprisingly small uncertainty. It is also surprising that P_{13} is the only state in this region to have a large ρN decay while most of the others have a dominant $\pi\Delta$ decay. Fits to this partial wave are very difficult for these reasons despite doubling the estimated error bars.

Difficulties with this partial wave led us to try new fits to the full set of partial wave amplitudes allowing a $\pi\Delta$ channel to be open even though there is no PWA result available. This fit gave better results than fits without the $\pi\Delta$ channel because the interferences were less complicated. In addition, the branching fractions for P_{13} decay to the two $\pi\pi N$ channels was much closer to the new values found in the Breit-Wigner analysis in the Ripani, et al. paper. Thus, we feel there is enough uncertainty in the old data to create significant doubt that a new state is seen in the new CLAS data. Nevertheless, the new data provide convincing evidence that the properties of $P_{13}(1720)$ require significant changes.

Another feature of the coupled channel fits is the importance of πN elastic scattering amplitudes (see Fig. 7, giving further concern for the Breit-Wigner fits. Although there is a prominent 'feature' at $W \sim 1.8$ GeV, the real amplitude has the peak while the normal Breit-Wigner shape has a peak in the imaginary amplitude. That and the large off-resonance amplitude are strong signals that the nonresonant amplitudes are also important. The πN nonresonant amplitude will therefore couple strongly into all inelastic reactions. While coupled channel models have this valuable constraint. the Breit-Wigner analysis of Ripani, et al. [10] has no ties to πN elastic scattering amplitudes.

4 Lessons learned

As new data come out, there will be many new opportunities for advancing knowledge of N^* states. There will also be potential mistakes to be made. Although Breit-Wigner analyses provide the obvious first way to extract physics from new data, the pitfalls of this approach should be recognized and appropriate caveats provided. The full problem is unfortunately complicated and much more sophisticated models are *sometimes* needed to learn the right physics interpretation. Previous coupled channel analyses provide an excellent guide to what truncations in channel space are appropriate. For example, the $S_{11}(1535)$ state can be studied with a minimum of πN and ηN channels because the $\pi\pi N$ channels aren't prominent. There are of course well established resonances such as the Delta and $D_{13}(1520)$ which can be studied using simple models with no theoretical difficulties as Breit-Wigner and coupled channels models give the same properties for these states. However, more complete studies are often required to know which simplifications are possible.

In the 2 examples given, the first Breit-Wigner analyses of exciting new data obtained results that are quite different than those obtained in published coupled channel work. This is due to the important constraints on any analysis that are provided by the new data, but also to the lack of theoretical constraints in any Breit-Wigner model. The coupled channel picture of $S_{11}(1535)$ is surprisingly different than the Breit-Wigner picture. The more complicated picture of S_{11} comes as the natural consequence of the strong coupling of $S_{11}(1535)$ to both πN and ηN. Further data and analyses will provide further clarification. In the case of P_{13}, even a careful Breit-Wigner analysis has to use both electromagnetic and hadronic couplings. This would provide a problem in any case. Here, the lack of good data for $\pi N \rightarrow \pi\pi N$ makes a Breit-Wigner interpretation more difficult. The first priority should be to understand the real characteristics of $P_{13}(1720)$; with this uncertainty it is difficult to suggest a new state. In addition, there is enough flexibility in the old data to allow a coupled channel interpretation which is consistent with the new data.

5 Conclusions

Although it is an interesting time for N^* structure studies with all the data coming out, the interpretations will not always be simple. In the long run coupled channel analyses have significantly more theoretical and data constraints and will be more viable. Since this can take a year or more to come about, a reasonable balance between single channel Breit-Wigner and coupled channel analyses will be most fruitful for the first results. The Breit-Wigner analyses can be improved by checking interpretations against what is known from previous coupled channel work.

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