Properties of the $\Lambda(1405)$ Measured at CLAS

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Abstract. The nature of the $\Lambda(1405)$, and its place in the baryon spectrum has remained uncertain for decades. Theoretical studies have shown that it may possess strong dynamical components which are not seen in other well-known baryons. Using the CLAS detector system in Hall B at Jefferson Lab, we have measured the photoproduction reaction $\gamma + \mathrm{p} \to K^+\Lambda(1405)$ with high statistics and over different $\Sigma\pi$ decay channels. The reconstructed invariant mass distribution (lineshape) has been measured, as well as the differential cross sections for the $\Lambda(1405)$, $\Sigma(1385)$, and $\Lambda(1520)$. Our analysis method is discussed and our near-final results for the $\Lambda(1405)$ lineshape and differential cross section are presented.

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The spectrum of baryons has in the past played an important role in the establishment of the quark model. Today it is known that this spectrum matches very well to the so-called constituent quark model at low excitation energies. The $\Lambda(1405)$ is unique in the sense that although it is only the first excited Λ state and has relatively low excitation energy, the nature of this resonance is not well established. Past experiments have shown a distortion of the invariant mass distribution ("lineshape") of the $\Lambda(1405)$ from a simple Breit-Wigner form. On the theoretical side, all analyses agree that the closeness of the nearby $N\overline{K}$ threshold plays a role in the distortion, there is no universally accepted explanation (see [1] for a review). For the constituent quark model, the $\Lambda(1405)$ has the largest discrepancy between the model prediction and experimental mass [2].

Until recently, there was not enough experimental data on the $\Lambda(1405)$ to gain further insight into its nature. Now, using the CLAS [3] detector system in Hall B at the Thomas Jefferson National Accelerator Facility, we have done a photoproduction measurement of the $\Lambda(1405)$ with unprecedented statistics. With the high statistics and good resolution of the CLAS system, we were able to extract the $\Lambda(1405)$ lineshapes and differential cross sections in all three of its $\Sigma\pi$ decay channels. Our measurements give a much improved quantitative description of the $\Lambda(1405)$, and may lead to further insights into its nature.

THEORY OF THE Λ(1405)

In recent years, there has been a renewed interest in the $\Lambda(1405)$, especially from the point of view of chiral dynamics [4, 5, 6], where the $\Lambda(1405)$ is dynamically generated. More recent developments show that there may be two poles for the $\Lambda(1405)$ [6, 7], which may lead to different lineshapes of the $\Lambda(1405)$ for different reactions. A paper

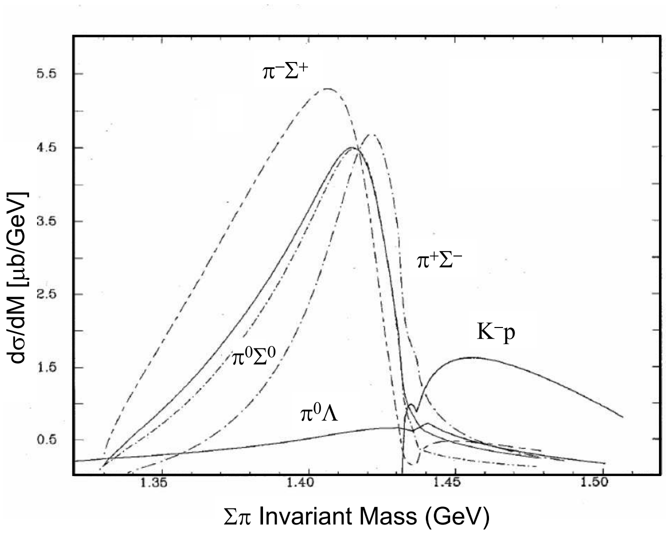

FIGURE 1: Theoretical lineshapes predicted [8] for the $\Lambda(1405)$ using one particular chiral unitary approach. Due to the interfering isospin 0 and 1 terms, the lineshapes are distorted from a simple Breit-Wigner form. In more recent years, attention has also focused on the possible two pole structure of the $\Lambda(1405)$ in the $I = 0$ channel alone. This too is expected to influence the lineshapes [6, 7].

by Nacher *et al.* [8] has predicted the lineshapes of the $\Lambda(1405)$ for photoproduction near threshold, which is shown in Figure 1. The prediction is that not only are the lineshapes of the $\Lambda(1405)$ distorted from a simple Breit-Wigner form, but different decay channels have different shapes due to the coupled channels mixing isospin contributions. Our main goal for this analysis has been on comparing the experimental data with this prediction.

DATA ANALYSIS USING CLAS AND RESULTS

Using the CLAS detector at Jefferson Lab, we have obtained a large dataset containing $\Lambda(1405)$ events by tagging real photons from $K^+\Lambda(1405)$ threshold up to 2.84 GeV in center-of-mass energy. Charged particles decaying from the reaction $\gamma + \mathrm{p} \rightarrow K^+\Lambda(1405)$, $\Lambda(1405) \rightarrow \Sigma\pi$ were detected for the decay channels $\Sigma^+\pi^-$, $\Sigma^0\pi^0$, and $\Sigma^-\pi^+$.

In this analysis the main background reactions are $\gamma + \mathrm{p} \rightarrow K^+\Sigma(1385)$, where the $\Sigma(1385)$ overlaps significantly with the $\Lambda(1405)$ in the $\Sigma\pi$ invariant mass spectrum, and the reaction $\gamma + \mathrm{p} \rightarrow K^*\Sigma$, where the K^* can have kinematic overlap with the $\Lambda(1405)$. The $\Sigma\pi$ invariant mass spectrum was individually fit in bins of center-of-mass energy and center-of-mass kaon angles to Monte Carlo templates of the reactions of interest. The contributions thus determined for the $\Sigma(1385)$, K^*, and $\Lambda(1520)$ were subtracted to obtain the yield for the $\Lambda(1405)$, which was then acceptance-corrected.

A recent development in our analysis has been a final iteration of our Monte Carlo templates used for the $\Lambda(1405)$, where the results of our lineshapes determined from the data were used as direct input for generating our Monte Carlo events. This has helped in improving our fit quality for the $\Sigma\pi$ spectra, and we have confirmed that the templates used for the $\Lambda(1405)$ have little influence on our results. Another development includes taking into account the decay of ground state hyperons that decay outside of the CLAS Start Counter, which was part of our trigger. This mainly affects data for the $\Sigma(1385)$ in its decay to $\Lambda\pi^0$, and this raises the measured differential cross section of the $\Sigma(1385)$ by $\sim 3\%$.

Our results for the lineshape of the $\Lambda(1405)$ are summed over all center-of-mass kaon angles for each 100 MeV-wide energy bin we have in center-of-mass energy. Figure 2 shows the lineshape of the $\Lambda(1405)$ for each of the $\Sigma\pi$ decay channels that we have measured for $1.95 < W < 2.05$. Note that in this energy bin close to the $K^+\Lambda(1405)$ threshold, we are just below the edge of the nominal K^* threshold, and the K^* has very limited kinematic influence. The lineshapes are seen to be quite different from each other, with the $\Sigma^+\pi^-$ channel peaking at a mass of ~ 1420 MeV, and having a much more narrow structure than the $\Sigma^-\pi^+$ channel. This is in contrast to the theoretical prediction of Figure 1, where the $\Sigma^-\pi^+$ channel is expected to peak at a higher mass and have a narrow structure compared to the $\Sigma^+\pi^-$ channel.

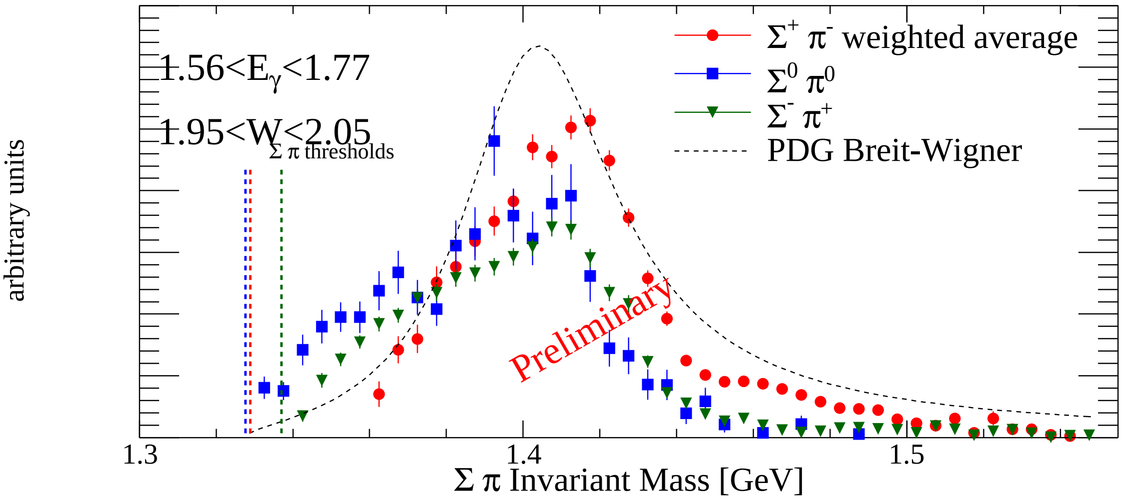

FIGURE 2. (Color online) The $\Sigma\pi$ invariant mass spectrum measured for the $\Lambda(1405)$ for the energy range $1.95 < W < 2.05$ GeV. The different decay channels are shown as $\Sigma^+\pi^-$ (red circles), $\Sigma^0\pi^0$ (blue squares), and $\Sigma^-\pi^+$ (green triangles). An example of a relativistic Breit-Wigner function using the PDG [9] values for the $\Lambda(1405)$ mass and width are shown as the dashed line.

By summing the lineshape over the $\Sigma\pi$ invariant mass range, we are able to calculate the differential cross section of the $\Lambda(1405)$. This is shown in Figure 3 for the same energy bin as Figure 2. The differential cross sections for each channel are shown in various symbols, and the behavior of the $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ channels are again seen to be different from each other. This complicated behavior of the differential cross section depending on decay channel may indicate that the strong dynamics that create the $\Lambda(1405)$ has dependence on the center-of-mass angle at which it is produced.

CONCLUSION

The photoproduction differential cross section of the $\Lambda(1405)$ has been measured using the CLAS detector system at Jefferson Lab's Hall B. Our lineshape results show a strong difference between each $\Sigma\pi$ decay channel, which has been predicted in the chiral unitary coupled channel approach, albeit with channels being interchanged from

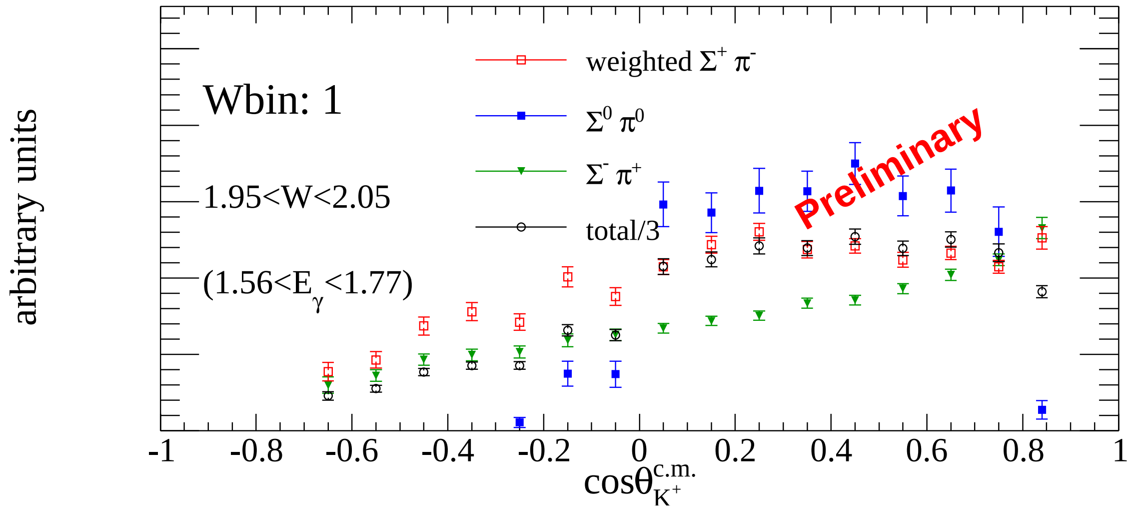

FIGURE 3. (Color online) The differential cross section $d\sigma/d\cos\theta_{K^+}^{c.m.}$ of the $\Lambda(1405)$ for the decay channels $\Sigma^+\pi^-$ (red empty squares), $\Sigma^0\pi^0$ (blue filled squares), and $\Sigma^-\pi^+$ (green triangles). The average of the three channels is shown as the black empty circles.

the prediction. The $\Lambda(1405)$ remains an exciting research topic, as recently there have also been studies of seeing how the lineshape can change depending on momentum transfer Q^2 in electroproduction [10]. The current photoproduction analysis is in the stages of collaboration review, and we hope to finalize and present our final results in the near future. Our data may help in shedding light on the nature of the $\Lambda(1405)$, and its production mechanism.

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