DOE/FG02-07ER41525

Photoproduction of Multiply-Strange Hyperons at CLAS
Final Technical Report

Period of Award:
05/01/2012 — 04/30/2015

August 2016

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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
OFFICE OF SCIENCE
UNDER CONTRACT NO. DE-FG02-07ER41525

Abstract

The activities of the California State University, Dominguez Hills (CSUDH) Hadronic Structure Laboratory, undertaken with the support of the U.S. Department of Energy's Office of Science under grant DE-FG02-07ER41525, are described. This grant was originally awarded in 2007, and then renewed in 2009 and 2012, before it expired in 2015. The work was performed primarily at the home institution on the CSUDH campus in Carson, CA. A significant portion of the work was carried out at the Thomas Jefferson National Accelerator Facility (JLab) in Newport News, VA. The work covered in this award involves the study of the structure of the proton, which is done indirectly by looking at the Ξ particle. This is a particle with a spin and spatial structure similar to that of the proton, but with a different quark structure. Their properties are expected to be related due to $SU(3)_F$ symmetry. Additional work performed under this grant involved the construction of the High Threshold Čerenkov Counter, which was done by CSUDH undergraduate students in collaboration with JLab staff scientists.

1 Introduction

The California State University, Dominguez Hills (CSUDH) Hadronic Structure Laboratory was created in 2006, for two main purposes:

1. To contribute to our understanding of the structure of the proton and other hadrons, by using the complementary approach of a study of the Ξ hyperons; and
2. To create an environment in which undergraduate students are introduced to research in experimental nuclear physics, and to enhance their opportunities for advanced study beyond the bachelor's degree.

The physics program undertaken by the Hadronic Structure Laboratory was designed with both of these goals in mind. It is meant to be straightforward enough so that the salient features are accessible to undergraduate researchers, while still being of sufficient importance to merit serious study.

The main thrust of our work is in the study of the structure of the nucleon, undertaken primarily by studying the physics of the Ξ hyperons, which are related to the proton by $SU(3)_F$ symmetry. This program seeks to exploit the narrow widths of the Ξ hyperons to detect them in the process $\gamma p \to K^+K^+\Xi^-$. In principle, the entire Cascade spectrum can be studied with this process; the Ξ^- here can be either the ground state or any of the excited states. This technique was pioneered by the PI using data from the CLAS *g6a* dataset, for the photon energy range $3.2 < E_\gamma < 3.9\,\text{GeV}$.[1] A subsequent measurement by the CLAS collaboration extended the photon energy range to 4.75 GeV, and additionally measured the differential cross section, the mass splitting between the two charge states of the Ξ, and the cross section for the photoproduction of the first excited state $\Xi^-(1530)$.[2] In 2008, the CLAS *g12* dataset was taken, with the intention to extend the photon energy range even further.

During the analysis of the *g12* dataset, we realized that CLAS produces copious amounts of Λ particles via the photoproduction process $\gamma p \to K^+\Lambda$. With the right experimental setup, it should be possible to utilize this as a tagged Λ source. Such a source could prove immensely useful in studies of nucleon structure. We began looking for the simplest process using such a source, namely elastic scattering on the proton ($\Lambda p \to \Lambda p$).

Looking to the future, we are part of the "Very Strange" collaboration within CLAS which seeks to measure the photoproduction of the Ω^- hyperon via the process $\gamma p \to K^0K^+K^+\Omega^-$. This

experiment, known as E12-11-005A, will begin taking data when CLAS12 comes back online in late 2017.

The final part of our program involves our work with the upgrade of the CLAS detector. For several years, CSUDH undergraduate students have worked on the design and construction of the High Threshold Čerenkov Counter (HTCC) during the summer months between academic years. More recently, as the construction phase winds down, we are moving our focus to software development, both in the definition of the geometry of the detector in our software, and in the understanding of particle reconstruction. This latter project is connected to our work with the Ω experiment. The analysis of this process will depend critically on our ability to reconstruct the neutral K^0 from its decay $K^0 \to \pi^+\pi^-$. This is also of general interest to the collaboration, since a large fraction of the particles produced in CLAS12 will be detected by their decay products. I am therefore working with the software group to understand the quality of this reconstruction.

2 Cascade Photoproduction

The program in Cascade Photoproduction at Jefferson Laboratory continues to make progress. Present efforts are focused on the *g12* run, which took data in the Spring of 2008. The basic analysis is essentially complete, and has already resulted in the Ph.D. dissertations of several of the students in the *g12* analysis group, including John Goetz from UCLA. His dissertation, "Ξ Hyperon Photoproduction from Threshold to 5.4 GeV with the CEBAF Large Acceptance Spectrometer", was filed in November 2010. The analysis is now being finalized for publication.

One of the main analysis issues dealt with in the funding period of this award is related to the cross section normalization. This led us to revisit the basic analysis. To this end, we looked closely at the cross section for $\gamma p \to K^+\Lambda$, for which the cross section measurement is well-established. igure 1 shows the present state of the $K^+\Lambda$ cross section from the *g12* run. As can be seen in the figure, the comparison between our data and the previous result is reasonable at backward angles at low energy, but there seems to be an overall normalization issue at the higher energies. The analysis of this is nearing completion, and is not anticipated to delay our publication of these results.

We have produced a comprehensive analysis note that will be used by all members of the *g12* analysis group in the preparation of papers for publication. John Goetz from Ohio University is the primary author of this document; we are assisting with the editorial process. Figure 2 shows a representative plot from this analysis note. The plot shows the β vs. momentum of all charged particles in the CLAS detector, before and after timing cuts. The left plot, made before the cuts, shows not only the expected π^+, K^+, and p bands, but also several accidental bands for each particle, spaced $2ns$ apart. This is due to the $2ns$ structure of the beam. A particle in one of the "wrong" bands is the result of an event that was initiated by a photon that was *not* tagged by the CLAS photon tagger, perhaps because its energy was out of range. By requiring that all detected charged particles must be in coincidence with a photon detected in the tagger, these background events are much reduced, as seen in the plot on the right.

3 Λp Elastic Scattering

During the analysis of the *g12* dataset, it became clear that we were producing a copious amount of Λ's; a simple calculation, using an approximate total cross section for $\gamma p \to K^+\Lambda$ of $0.5\,\mu b$ and an integrated luminosity for the *g12* run of approximately $52\,\mathrm{pb}^{-1}$ gives an estimated total of 26 million Λ's produced. This makes possible the development of a tagged Λ source, in which the

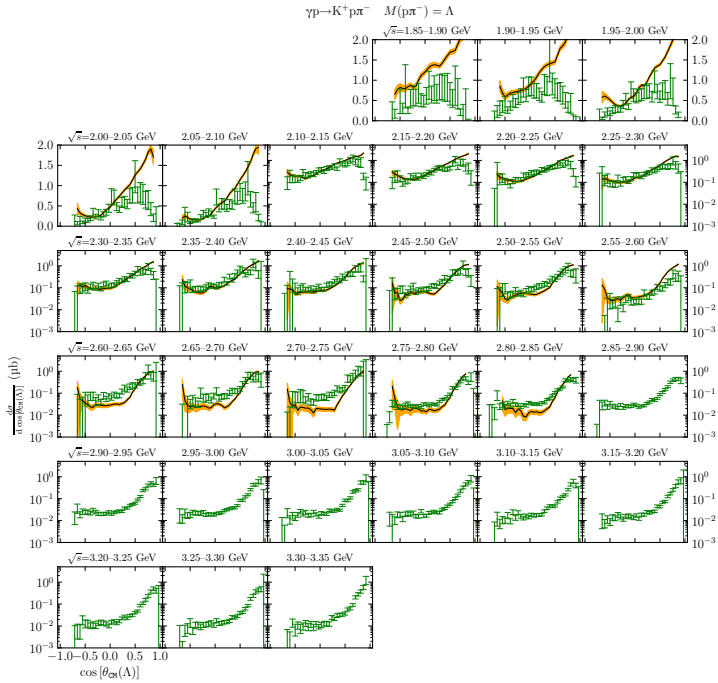

Figure 1: The cross section for the process $\gamma p \to K^+\Lambda$ from the *g12* dataset for $1.85 < \sqrt{s} < 3.35\,\mathrm{GeV}$, compared with previous results.

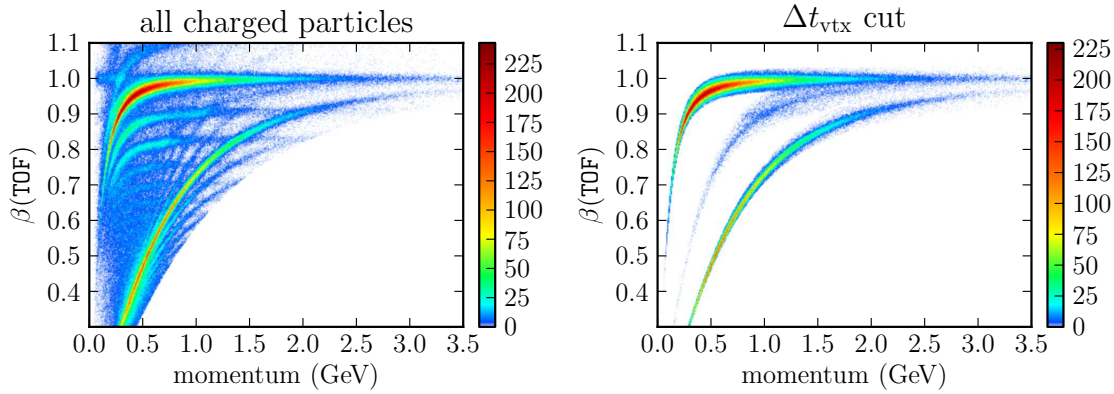

Figure 2: A representative plot from the analysis note. The left plot shows the β vs. momentum plot for all charged particles detected in the *g12* run. The extra structure in this plot is an artifact of the $2ns$ timing structure of the JLab beam. The right plot includes cuts on the vertex timing, in which the particle is required to be in time with a detected photon in the tagger. This cut cleans up the spectra considerably.

produced Λ is used as the incident "beam" particle in a secondary process which takes place on a second proton in the target. This study benefits from the long (40cm) liquid hydrogen target that was used in the *g12* run.

The simplest process to study with this new technique is the elastic scattering process $\Lambda p \to \Lambda p$. There have been several measurements of this process from 1959 through 1975, primarily with bubble chambers.[3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14] The *g12* run produced more Λ's than were used in any of the previous measurements, leading us to expect that we should be able to observe a sizeable signal for this process.

This is, however, a very challenging experiment. The CLAS Collaboration has never attempted to search for such a secondary process before. The CLAS detector was not designed for anything like this measurement. However, its large acceptance and ability to detect multi-particle final states make it an excellent device for such a study.

We can estimate the number of expected Λp events produced in the *g12* run with a simple calculation. We start with the number of Λ's produced N_Λ (2.6×10^7, from above). For simplicity, we assume that all the produced Λ's travel straight down the target, and we use the characteristic decay length $c\tau$ ($= 7.9\,\mathrm{cm}$) as the average distance the Λ will travel through the target to get the total luminosity. We normalize this with the density of the liquid hydrogen target ρ_{LH_2} ($= 0.071\,g/\mathrm{cm}^3$), Avogadro's number N_A, the atomic mass of hydrogen A_H, and the total cross section for Λp scattering from the Review of Particle Physics $\sigma_{\Lambda p}$.[15] Bringing all this together, we have

$$\begin{aligned} N_{\Lambda p} &= N_\Lambda \cdot c\tau_\Lambda \cdot \rho_{\mathrm{LH}_2} \cdot \frac{N_A}{A_H} \cdot \sigma_{\Lambda p} \\ &= (26,000,000) \cdot (7.9\,\mathrm{cm}) \cdot (0.071\,g/\mathrm{cm}^3) \cdot \frac{6.02 \times 10^{23}}{1.008\,g} \cdot (20 \times 10^{-27}\,\mathrm{cm}^2) \\ &= 175,000 \end{aligned}$$

The final state for this process, including the K^+ produced with the original Λ, is $K^+\pi^- pp$. If we use reasonable values of 60% acceptance for positively-charged particles, and 50% acceptance for negatively-charged particles, and include a 50% chance that the kaon will survive to the outer part of the detector before decaying, we expect a total acceptance of approximately

$$A_{\Lambda p \to \Lambda p} = 0.6 \cdot 0.5 \cdot 0.5 \cdot 0.6 \cdot 0.6 = 5.4\%,$$

for a total of slightly less than 9500 detected Λp rescattering events detected, which is very encouraging. The actual number detected will of course be smaller; one of the main assumptions in the above calculation, that the Λ stays within the target until it either decays or interacts, is certainly incorrect. This is still much larger than the existing world sample of approximately 1200 elastic scattering events published to date.

The analysis of the *g12* data for this process is underway. The initial work on this analysis was performed by CSUDH undergraduate student Alec Thompson, who graduated at the end of the Fall 2012 semester. He presented the results of this work at the 2012 CSUDH Student Research Day, where he won the award for the best talk in the Physical Sciences, and went on to represent CSUDH at the Statewide CSU competition in May 2012.

The search for this process began with a search for the initial "beam" Λ from the process $\gamma p \to K^+\Lambda$, by looking for a peak at the known Λ mass in the process $\gamma p \to K^+ X$. As of May 2015, we had not yet been successful in identifying this process. Fig. 3 shows the plot we had achieved by that point.

We believe that we understand the lack of a peak at the known Λ mass in this plot. The JLab electron beam has a 2ns microstructure; there is a very narrow timing window within this

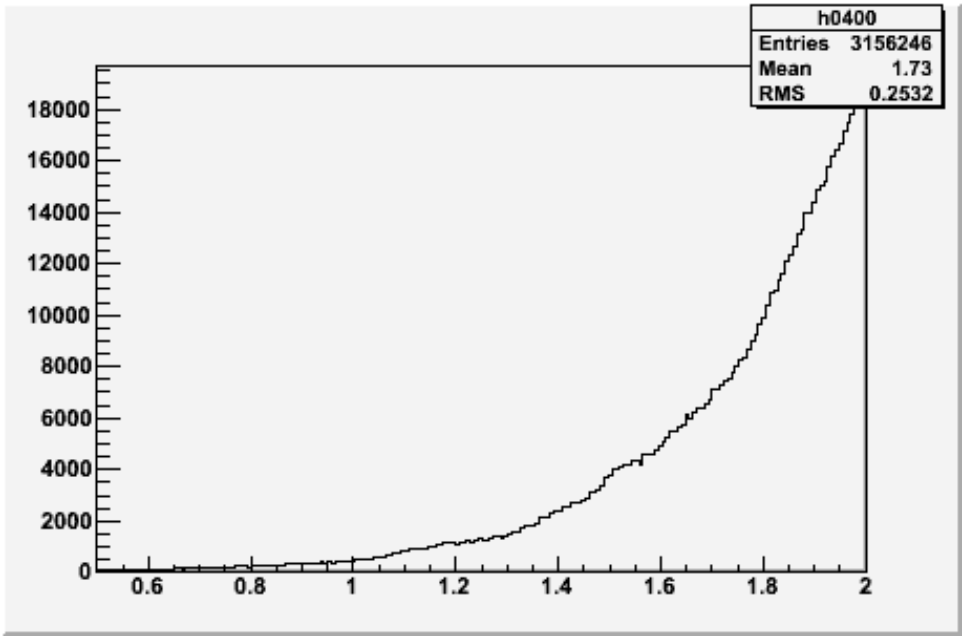

Figure 3: The missing mass in the process $\gamma p \to K^+X$ in the *g12* run. The data have been skimmed to contain only events with two candidate protons. The absence of a peak at the known Λ mass is attributed to the incorrect selection of the photon in the CLAS tagging system.

structure in which electrons can occur. The photon timing is identical to the electron timing, due to the nature of bremsstrahlung tagging systems. This means that, while the probability of having multiple photons in a single "beam bucket" is small, there is a reasonable chance of having photons in nearby beam buckets.

The CLAS analysis software is designed to use the data in the CLAS detector to determine which is the "correct" photon, by tracking each detected particle back to the beamline, and determining the best match between the particle and the photon tagger. If there are multiple detected particles, then the average time is taken. For our events of interest, the only particle that will actually come from the same vertex as the beam photon is the K^+; all other particles emerge from later vertices. Future analysis will focus on the attempt to identify the correct photon by matching only the K^+ timing with the photon tagger.

After the end of the funding period, we were successful at identifying Λp elastic scattering, by reconstructing the final state particles. A more complete discussion of this success will be given in a future progress report. We are continuing our search for the correct photon at the start of the process, so that we can completely identify the event. This will be necessary for the extraction of the cross section, in order to get the flux of "beam" Λ's.

4 Photoproduction of the Ω^- Hyperon

Having successfully photoproduced the Ξ^-, the next logical step is to look for the photoproduction of the Ω^-. We are part of a group within the CLAS Collaboration that seeks to observe this process for the first time, using the upgraded CLAS12 detector. As of May 2015, this experiment has been approved, and is known by the designation E12-11-005A. It will take place as part of CLAS Run Group A, which is expected to start taking data in late 2017.

To prepare for this experiment, we have taken on the task of studying the reconstruction of the neutral kaon produced in $\gamma p \to K^+K^+K^0\Omega^-$. The K^0 will decay quickly to $\pi^+\pi^-$. While it is expected that our reconstruction efficiency and resolution will be sufficient for our purposes, this must be quantified before datataking begins. I have recently started working with a CSUDH undergraduate student to study this effect.

5 Service Work within the CLAS Collaboration

As a member of the CLAS Collaboration, I must contribute to the development and maintenance of the detector. For the last several years, I have sent 1–2 CSUDH undergraduate students to JLab in the summers to work with JLab staff members, primarily in the design, development, and construction of the High-Threshold Čerenkov Counter (HTCC). More recently, I have also started working with the CLAS12 Offline Software group, to help develop the software that will be used to analyze CLAS data once running begins.

In the summer of 2012, CSUDH undergraduate student Harneet Grewal continued the work he began the previous summer on the HTCC construction. His work focused on reflectivity tests for the mirror prototypes. This required the construction of a test stand designed specifically for this purpose. This work was carried out in large part by Grewal, working with Drs. Youri Sharabian and Andrew Puckett at JLab, in concert with JLab technicians and other students.

The results of this work were presented by Grewal in two separate talks. A report of the progress made during the summer of 2011 was presented on February 23, 2012 at the 2012 CSUDH Student Research Day, an annual competitive event which highlights student research done at CSU Dominguez Hills. His work during the summer of 2012 was first presented at the 2012 Annual meeting of the California Section of the American Physical Society at California Polytechnic State University in San Luis Obispo, CA. He also presented this work on February 21, 2013 at the 2013 CSUDH Student Research Day, where he was awarded the "Best Physical Science" talk.

In the summer of 2013, two CSUDH undergraduate students worked at JLab. Dylan Nicholas worked with JLab staff scientist Dr. Youri Sharabian and his group to build the superstructure that would eventually house the HTCC. Eddie Banuelos-Casillas worked with the CLAS12 offline software group on the development of ClaRA, the CLAS12 Reconstruction and Analysis Framework, which will be used in the offline data analysis of all CLAS12 data. They both presented their work at the 2013 Annual meeting of the California Section of the American Physical Society in Rohnert Park, CA, and at the 2014 CSUDH Student Research Day.

In the summer of 2014, CSUDH undergraduate students Shane Miller-Smith and Jeremiah Hankins worked at JLab. Miller-Smith worked with JLab staff scientist Dr. Youri Sharabian and his group to install the mirrors into the HTCC as part of the final construction phase of the project. He presented his work at the 2014 Southern California Conference on Undergraduate Research at CSU Fullerton in November 2014. Jeremiah Hankins worked with the CLAS12 offline software group, developing the geometry package which will be used both for simulation and data analysis for CLAS12. His work was presented to the CLAS Collaboration in August 2014.

In the 2014-15 academic year, CSUDH undergraduate students Juan Cardenas and Hector Carranza began working in my group. Hector took charge of upgrading our computer cluster to a new software version, and tested its scalability. He showed that the analysis and simulation speed scaled linearly with the number of CPU cores installed, nearly to the maximum capability of the cluster, at which point slight deviations from linearity were observed. This indicates that the cluster is approximately the optimal size for the hardware we have available, and the tasks we use it for. Juan took over the work that had been started by Alec Thompson on Λp scattering in

CLAS, to attempt to determine why we had thus far been unable to isolate the $\Lambda p \to \Lambda p$ process. Their work was presented at the 2015 CSUDH Student Research Day in February 2015.

References

[1] J.W. Price *et al.* (CLAS Collaboration), Phys. Rev. C **71**, 058201 (2005).

[2] L. Guo *et al.* (CLAS Collaboration), Phys. Rev. C **76**, 025208 (2007).

[3] F.S. Crawford *et al.*, Phys. Rev. Lett. **2**, (1959).

[4] G. Alexander *et al.*, Phys. Rev. Lett. **7**, 348 (1961).

[5] T.H. Groves, Phys. Rev. **129**, 1372 (1963).

[6] P. Beillière *et al.*, Phys. Lett. **12**, 350 (1964).

[7] L. Piekenbrock and F. Oppenheimer, Phys. Rev. Lett. **12**, 625 (1964).

[8] B. Sechi-Zorn *et al.*, Phys. Rev. Lett. **13**, 282 (1964).

[9] D. Bassano *et al.*, Phys. Rev. **160**, 1239 (1967).

[10] G. Alexander *et al.*, Phys. Rev. **173**, 1452 (1968).

[11] B. Sechi-Zorn *et al.*, Phys. Rev. **175**, 1735 (1968).

[12] J.A. Kadyk *et al.*, Nucl. Phys. **B27**, 13 (1971).

[13] K.J. Anderson *et al.*, Phys. Rev. D **11**, 473 (1975).

[14] R.P. Mount *et al.*, Phys. Lett. **58B**, 228 (1975).

[15] K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014) and 2015 update.

Dissemination of Results

Recent Publications

1. L. El Fassi *et al.* (CLAS Collaboration), "Evidence for the onset of color transparency in ρ^0 electroproduction off nuclei", Phys. Lett. **B712**, 326 (2012).

2. F. Zehr *et al.* (Crystal Ball at MAMI and A2 Collaboration), "Photoproduction of $\pi^0\pi^0$ and $\pi^0\pi^\pm$ pairs off the proton from threshold to the second resonance region", Eur. Phys. J. **A48**, 98 (2012).

3. I. Bedlinskiy *et al.* (CLAS Collaboration), "Measurement of Exclusive π^0 Electroproduction Structure Functions and their Relationship to Transversity Generalized Parton Distributions", Phys. Rev. Lett. **109**, 112001 (2012).

4. V.I. Mokeev *et al.* (CLAS Collaboration), "Experimental study of the $P_{11}(1440)$ and $D_{13}(1520)$ resonances from CLAS data on $ep \to e'\pi^+\pi^-p'$", Phys. Rev. C **86**, 035203 (2012).

5. M. Anghinolfi *et al.* (CLAS Collaboration), "Comment on 'Observation of a narrow structure in $^1\mathrm{H}(\gamma, K^0_s)X$ via interference with ϕ-meson production' ", Phys. Rev. C **86**, 069801 (2012).

6. K. Park *et al.* (CLAS Collaboration), "Deep exclusive π^+ electroproduction off the proton at CLAS", Eur. Phys. J. **A49**, 16 (2013).

7. D.S. Carman *et al.* (CLAS Collaboration), "Separated structure functions for exclusive $K^+\Lambda$ and $K^+\Sigma^0$ electroproduction at 5.5 GeV measured with CLAS", Phys. Rev. C **87**, 025204 (2013).

8. Y. Maghrbi *et al.* (Crystal Ball at MAMI and A2 Collaboration), "Coherent photoproduction of π^0- and η-mesons off ^{7}Li", Eur. Phys. J. **A49**, 38 (2013).

9. K. Moriya *et al.* (CLAS Collaboration), "Measurement of the $\Sigma\pi$ photoproduction line shapes near the $\Lambda(1405)$", Phys. Rev. C **87**, 035206 (2013).

10. P. Khetarpal *et al.* (CLAS Collaboration), "Near-threshold neutral pion electroproduction at high momentum transfers and generalized form factors", Phys. Rev. C **87**, 045205 (2013).

11. C.S. Nepali *et al.* (CLAS Collaboration), "Transverse polarization of $\Sigma^+(1189)$ in photoproduction on a hydrogen target in CLAS", Phys. Rev. C **87**, 045206 (2013).

12. O. Hen *et al.* (CLAS Collaboration), "Measurement of transparency ratios for protons from short-range correlated pairs", Phys. Lett. **B722**, 63 (2013).

13. Y. Maghrbi *et al.* (Crystal Ball at MAMI and A2 Collaboration), "Double pion photoproduction off nuclei — Are there effects beyond final-state interaction?", Phys. Lett. **B722**, 69 (2013).

14. W. Tang *et al.* (CLAS Collaboration), "Cross sections for the $\gamma p \to K*^+\Lambda$ and $\gamma p \to K*^+\Sigma^0$ reactions measured at CLAS", Phys. Rev. C **87**, 065204 (2013).

15. M. Moteabbed *et al.* (CLAS Collaboration), "Demonstration of a novel technique to measure two-photon exchange effects in elastic $e^{\pm}p$ scattering", Phys. Rev. C **88**, 025210 (2013).

16. K. Moriya *et al.* (CLAS Collaboration), "Differential photoproduction cross sections of the $\Sigma^0(1385)$, $\Lambda(1405)$, and $\Lambda(1520)$", Phys. Rev. C **88**, 045201 (2013).

17. H.Y. Lu *et al.* (CLAS Collaboration), "First observation of the $\Lambda(1405)$ line shape in electroproduction", Phys. Rev. C **88**, 045202 (2013).

18. M. Dugger *et al.* (CLAS Collaboration), "Beam asymmetry Σ for π^+ and π^0 photoproduction on the proton for photon energies from 1.102 to 1.862 GeV", Phys. Rev. C **88**, 065203 (2013).

19. K. Moriya *et al.* (CLAS Collaboration), "Spin and parity measurement of the $\Lambda(1405)$ baryon", Phys. Rev. Lett. **112**, 082004 (2014).

20. W. Gohn *et al.* (CLAS Collaboration), "Beam-spin asymmetries from semi-inclusive pion electroproduction", Phys. Rev. D **89**, 072011 (2014).

21. S. Tkachenko *et al.* (CLAS Collaboration), "Measurement of the structure function of the nearly free neutron using spectator tagging in inelastic $^2\mathrm{H}(e, e'p_s)X$ scattering with CLAS", Phys. Rev. C **89**, 045206 (2014).

22. B. Dey *et al.* (CLAS Collaboration), "Data analysis techniques, differential cross sections, and spin density matrix elements for the reaction $\gamma p \to \phi p$", Phys. Rev. C **89**, 055208 (2014).

23. H. Seraydaryan *et al.* (CLAS Collaboration), "ϕ-meson photoproduction on hydrogen in the neutral decay mode", Phys. Rev. C **89**, 055206 (2014).

24. I. Bedlinskiy *et al.* (CLAS Collaboration), "Exclusive π^0 electroproduction at $W > 2\,\mathrm{GeV}$ with CLAS", Phys. Rev. C **90**, 025205 (2014), Phys. Rev. C **90**, 039901 (2014).

25. Y. Prok *et al.* (CLAS Collaboration), "Precision measurements of g_1 of the proton and of the deuteron with 6 GeV electrons", Phys. Rev. C **90**, 025212 (2014).

26. M. Gabrielyan *et al.* (CLAS Collaboration), "Induced polarization of $\Lambda(1116)$ in kaon electroproduction", Phys. Rev. C **90**, 035202 (2014).

27. M. Mestayer *et al.* (CLAS Collaboration), "Strangeness Suppression of $q\overline{q}$ Creation Observed in Exclusive Reactions", Phys. Rev. Lett. **113**, 152004 (2014).

28. O. Hen *et al.* (CLAS Collaboration), "Momentum sharing in Imbalanced Fermi systems", Science **346**, 614 (2014).

29. E. Seder *et al.* (CLAS Collaboration), "Longitudinal Target-Spin Asymmetries for Deeply Virtual Compton Scattering", Phys. Rev. Lett. **114**, 032001 (2015).

30. D. Adikaram *et al.* (CLAS Collaboration), "Towards a Resolution of the Proton Form Factor Problem: New Electron and Positron Scattering Data", Phys. Rev. Lett. **114**, 062003 (2015).

31. S. Pisano *et al.* (CLAS Collaboration), "Single and double spin asymmetries for deeply virtual Compton scattering measured with CLAS and a longitudinally polarized proton target", Phys. Rev. D **91**, 052014 (2015).

32. K. Park *et al.* (CLAS Collaboration), "Measurements of $ep \to e'\pi^+ n$ at $1.6 < W < 2.0\,\mathrm{GeV}$ and extraction of nucleon resonance electrocouplings at CLAS", Phys. Rev. C **91**, 045203 (2015).

Recent Invited Talks and Conference Contributions

1. H. Grewal, J.W. Price, *et al.*, "Reflectivity Tests for the High-Threshold Čerenkov Counter Mirrors for the CLAS12 detector at JLab", 2012 Annual Meeting of the California/Nevada Section of the American Physical Society, San Luis Obispo, 2–3 November 2012.

2. E. Banuelos-Casillas, J.W. Price, *et al.*, "The CSUDH Hadronic Structure Laboratory", 2013 CSUDH Student Research Day, 21 February 2013.

3. H. Grewal, J.W. Price, *et al.*, "Reflectivity Tests for the High-Threshold Čerenkov Counter (HTCC) Mirror Assembly Located at the Thomas Jefferson National Accelerator Facility", 2013 CSUDH Student Research Day, 21 February 2013 (Physical Science Winner).

4. D. Nicholas, J.W. Price, "Breaking the Rules: The Parity of the Ξ Hyperon", 2013 CSUDH Student Research Day, 21 February 2013.

5. C. Jenkins, J.W. Price, "Cascade Physics at the CSUDH Hadronic Structure Laboratory", 2013 CSUDH Student Research Day, 21 February 2013.

6. J.W. Price, "The Discovery of the Higgs Boson...or was it...?", Osher Lifelong Learning Institute Seminar, California State University, Dominguez Hills, 8 March 2013.

7. J.W. Price, "Bending (not breaking!) the Rules: The parity of the Ξ hyperon", CSU San Marcos, 2 May 2013.

8. E. Banuelos-Casillas, J.W. Price, *et al.*, "ClaRA: The CLAS12 Reconstruction and Analysis Framework", 2013 Annual Meeting of the California/Nevada Section of the American Physical Society, Rohnert Park, CA, 1–2 November 2013.

9. D. Nicholas, J.W. Price, *et al.*, "Construction of the CLAS12 High-Threshold Cerenkov Counter", 2013 Annual Meeting of the California/Nevada Section of the American Physical Society, Rohnert Park, CA, 1–2 November 2013.

10. E. Banuelos-Casillas, J.W. Price, *et al.*, "ClaRA: The CLAS12 Reconstruction and Analysis Framework", 2014 CSUDH Student Research Day, 13 February 2014.

11. D. Nicholas, J.W. Price, *et al.*, "Construction of the CLAS12 High-Threshold Cerenkov Counter", 2014 CSUDH Student Research Day, 13 February 2014.

12. S. Miller-Smith, J.W. Price, *et al.*, "Final Construction Phase of the CLAS12 High-Threshold Cerenkov Counter", 2014 Southern California Conference on Undergraduate Research, CSU Fullerton, 22 November 2014.

13. J. Cardenas, J.W. Price, "Preparation for the Study of Λ Re-scattering on the Proton", 2015 CSUDH Student Research Day, 12 February 2015.

14. H. Carranza, J.W. Price, "The Upgrade of the CSUDH Hadronic Structure Laboratory", 2015 CSUDH Student Research Day, 12 February 2015.