Final report for 09/01/0 to 08/31/11

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Nuclear Physics from Lattice QCD

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Amount of unexpended funds

All funds where expended.

I. FINAL REPORT

A. Personnel: Postdoctoral research

Post-Doctoral Associate: Andre Walker-Loud was the postdoctoral research associate under this grant. Dr. Walker-Loud, joined William and Mary starting June 25, 2008. He was my first choice for this position. He is very active and promising young scientist in the field of Lattice QCD calculations for Nuclear physics, as his publication record shows (12 submitted and published papers since he joined William and Mary). He has been a great collaborator and a mentor for my graduate student. Dr. Walker-Loud was hired as research scientist at LBNL after his appointment at W&M.

B. Computer Hardware

Part of 2007-2008 grant was spent towards the extension of Lattice QCD computer cluster we purchased in collaboration with our experimental particle physics group. The total budget of the project which includes funds contributed from the College is about $400,000. During the period of 2008-2009 the computer became operational sustaining close to 1Tflop performance for Lattice QCD applications. We are currently utilizing more that 80% of the capacity of the machine with the rest being used by our experimentalist colleagues. The resource has being invaluable in supporting the research of Dr. Walker-Loud and of my Ph.D student.

C. Research accomplishments

The PI under this grant has accomplished the following research objectives of this grant.

- **Two meson scattering lengths:** Using the dynamical lattice QCD calculations with 2 light and 1 heavy (strange) dynamical flavors (within the context of NPLQCD collaboration) we have performed precision calculations of meson-meson scattering lengths. This includes $\pi - \pi$ in the I=2 channel, K-K in the I=1 channel and K-π I=3/2 channel. These results represent the most accurate lattice QCD determinations of such quantities and in the case of $\pi - \pi$ I=2 scattering our result is in agreement with experiment with an errorbar smaller than the experimental one. In the cases of K-K and K-π scattering the I=0 and I=1/2 scattering lengths were also determined using chiral effective theory and the low energy constants extracted from the I=1 (K-K) and I=3/2 (K-π) channels. For details see Ref. 1 which is a review of all our recent calculations, and the individual papers in Ref. 2 and 3. In all the above work essential input in understanding the systematics of our the calculations were the mixed meson masses determined together with Andre Walker-Loud (see Ref. 4). In this publication we set up the general formalism and performed the first determination of such parameter that enters mixed action calculations.

  The above results were obtained using one lattice spacing. We are in the process of analysing results from a second lattice spacing. This will allow us to control better our continuum extrapolation systematic error. In addition we will revisit previously done calculations of single particle properties (pseudoscalar meson decay constants and masses) at our coarse lattice spacing . These results combined with scattering observables will allow us to constrain and extract more reliably the chiral lagrangian low energy constants.

- **High statistics results from lattice QCD:** The study of (multi) baryon properties with lattice QCD is an exponentially more challenging task than the more well established computations of meson properties. To make a significant impact in the nuclear physics community, this challenge will need to be addressed by the lattice community. In a series of seminal papers, we (along with the rest of the NPLQCD Collaboration) have begun a high statistics study of the energy levels of one, two and three baryons with lattice QCD. Our calculations have increased the statistics by two orders of magnitude above typical lattice calculations, performing $\mathcal{O}(300,000)$ measurements on the newly generated anisotropic gauge ensembles produced by the *Spectrum Collaboration* led by Robert Edwards at Jefferson Lab. This work has allowed for a *road map* of the necessary computational resources for lattice calculations to have a significant impact in the study of multi-baryon interaction energies, and ultimately make the connection of nuclear physics with QCD.

  Using this high statistics data we developed new analysis techniques for extracting multiple energy levels from limited number of correlators. Unlike standard methods where a symmetric matrix of correlators is used to extract the spectrum in a given symmetry sector, we have access only to a limited set of correlators. Our focus is multi-hadron systems where the construction of the correlators require significant computation, hence large symmetric matrices of correlators, such as those used in simple one particle spectroscopy, cannot be constructed without enormous computational resources. Our new methodology, has similar performance with classic methods, provided that high statistics calculation of the correlators has been achieved. With current computational resources obtaining the needed high statistics is possible. During the next year we will further develop this methodology and apply it in realistic computations.

- **Multi-meson systems:** During the last year we have performed the first numerical calculations of the energy levels of multi-pion systems and multi-kaon systems in a box (up to 12 pions). This allowed for the extraction of the three pion and three kaon interaction term at low energies. In addition, we calculated the chemical potential of these systems as a function of the density. Our results are in surprising good agreement with leading order chiral perturbation theory. Currently we are working in extending these calculations to include multi-meson systems containing kaons as well as pions.

- **Octet baryon Axial couplings and form factors:** Together with Huey-Wen Lin the PI published the first lattice calculation of octet baryon axial couplings. These results allowed us to extract the axial couplings F and D and study the effects of SU(3) flavor symmetry breaking. One interesting conclusion of our work is that the SU(3) flavor symmetry breaking is rather large at the physical pion mass point (about 20%). In addition, we published our results on the electromagnetic form factors of octet baryons. These calculation are the first in full QCD (unquenched) with light pion masses. Although, the quark masses are still at the edge of validity of heavy baryon chiral perturbation theory, we were able to extrapolate to the physical point charge radii and magnetic moments. Our results are in good agreement with experiment within the systematics of our calculation.

  During the next year we are continuing to pursue these calculations and we are working in modifying our computational approach in order to better control our statistical and systematic errors.

- **Charm and Bottom baryon spectrum and interactions:** Recently there have been exciting developments in heavy-hadron physics both theoretically and experimentally. Along with exciting discoveries of charmonium states, considerable progress has been made in studying bottom mesons and baryons. While the B factories, such as Belle and Babar, have investigated the bottom mesons, recent experiments at Fermilab have reported the discoveries of a few bottom baryon states. It is anticipated that in the upcoming dedicated bottom physics experiment LHCb at CERN, there will be many more discoveries in the bottom-hadron spectrum, significantly enhancing our knowledge about these states. Most recently D0 and CDF have observed Ω_b^-, however their results seem to be in disagreement. Lattice determinations of the flavored baryon spectrum could be useful and complementary to the on going experimental program in this field.

During this last year we targeted both the charm and the bottom sector with two different computational approaches. In the bottom sector we worked with the static approximation since the bottom quark is heavy and the leading term in the Heavy Quark Effective Theory (HQET) is sufficient reliable computations of several quantities. In the charm sector (a project primarily pushed by my graduate student Liuming Liu) we used the Fermilab relativistic action in order to reduce discretization errors and capture the relevant relativistic effects in the charm sector.

Our results in the bottom sector are in good agreement with experiment. In the case of Ω_b^- our result is in good agreement with the CDF result and several standard deviations away from the D0 observation. In addition, we also predict the mass for the as yet unobserved Ξ_b' to be 5955(27) MeV.

In the charmed sector, we have published in conference proceedings preliminary results for the baryon (spin 1/2) sector. In addition, we compute the scattering lengths of charmed mesons and charmonia scattering with light hadrons. The scattering processes of chamonia (η_c and J/Ψ) with light hadrons (π, ρ and N). As it has been pointed out in the literature such interaction has a direct relation to possible charmonium-nucleus bound states with binding energy of a few MeV. Unlike the traditional nuclear force that binds nucleons, in this case, there are no quark exchange diagrams, and only gluons are responsible for the binding. In other words, the charmonium nucleon force is purely a gluonic van der Waals force. D meson scattering can also provide useful insight to nucleon nucleon interactions since the low energy effective theory describing the D meson interaction through the exchange of pions is related to this of the nucleon-nucleon interaction. These calculations are pursued for the first time in the full QCD.

Currently we are working on finalizing a publication of our results for both the spectroscopy and scattering lengths in the charmed sector. During the next year we plan to extend these calculations to the cases where coupled channels exist and study the formalism needed to extract scattering lengths in such cases (where the application of the simple Luscher formula is not possible).

- **Meson Baryon interactions:** The $\pi^+\Sigma^+$, $\pi^+\Xi^0$, K^+p, K^+n, and $K^0\Xi^0$ scattering lengths are calculated in mixed-action Lattice QCD with domain-wall valence quarks on the asqtad-improved coarse MILC configurations at four light-quark masses, and at two light-quark masses on the fine MILC configurations. Heavy Baryon Chiral Perturbation Theory with two and three flavors of light quarks is used to perform the chiral extrapolations. We find no convergence for the kaon-baryon processes in the three-flavor chiral expansion. Using the two-flavor chiral expansion, we find $a_{\pi^+\Sigma^+}$ =?0.197 ± 0.017 fm, and $a_{\pi^+\Xi^0}$ =?0.0980.017 fm, where the comprehensive error includes statistical and systematic uncertainties.

D. Andre Walker-Loud's Research accomplishments

Andre Walker-Loud worked on a variety of projects on his own and in collaboration with others not including the PI of this grant. Here is a description of his research accomplishments.

1. *Lattice Field Theory*

- **Strong isospin breaking with lattice QCD:** One of the four major methods of including dynamical quarks in lattice field theory calculations is known as *twisted mass lattice QCD*. This formulation of lattice QCD has proven to be a competitive in terms of numerical cost and the ability to perform lattice calculations with realistically light quark masses. However, it was previously not known how practically include strong isospin breaking ($m_u \neq m_d$) in twisted mass lattice QCD.

  This year, we proposed a new method for including strong isospin breaking in twisted mass lattice calculations, while preserving flavor identification. We utilized a partially quenched construction in which the sea quarks are given by the standard twisted mass lattice action while the valence quarks have an additional strong isospin breaking mass term. This construction allows for a practical use with existing twisted-mass gauge ensembles. Additionally, we constructed the relevant partially quenched twisted mass chiral perturbation theory for both mesons and baryons to $\mathcal{O}(m_q^2, m_q a, a^2)$, providing explicit expressions for the pion, nucleon and delta masses, as well as the corresponding mass splittings. Finally, we demonstrated how the application of this idea can be used, with mild approximations, to determine the values of both the up and down quark masses.

- **Nucleon Electromagnetic Self Energy and $m_d - m_u$:** A precise determination of the light quark masses necessarily includes effects from electromagnetism. Presently, most lattice computations do not explicitly include the effects of electromagnetism. However, the value of the nucleon electromagnetic self energy (or the difference between the neutron and proton electromagnetic self energy) is comparable in size to the contribution from the strong isospin breaking parameter, $m_d^{(0)} - m_u^{(0)}$ (the *super* $^{(0)}$ denotes zeroth order in electromagnetic effects). In order to precisely determine the quark masses, the electromagnetic effects must be accounted for. In collaboration with Carl Carlson (faculty at William and Mary), Ian Cloët (postdoc at Univ. of Washington, Seattle) and Will Detmold, we have computed the electromagnetic self energy of the neutron and proton, making use of the Cottingham formula and modern data on the nucleon form factors and structure functions. This will allow for a direct lattice calculation of $m_d^{(0)} - m_u^{(0)}$.

2. *Hadron Properties and Interactions from Lattice QCD*

- **Electromagnetic properties of hadrons:** In collaboration with Will Detmold and Brian Tiburzi we have begun an exploration of the low energy electromagnetic properties of hadrons. Our first in a planned series of publications concerned the calculation of pion and kaon polarizabilities. This is of timely interest as there is currently a discrepancy between the last published pion polarizabilities and their two-loop chiral perturbation theory predictions, and the COMPASS experiment is expected to release new results soon. We are also calculating the magnetic moments and polarizabilities of the baryons, in anticipation of the high statistics measurements of these quantities from the HIγS experiment at TUNL. In addition to making a timely calculation of these quantities for comparison with these experimental efforts, the study of the polarizabilities can potentially teach us much about low energy QCD. From chiral perturbation theory, the hadron polarizabilities are predicted to diverge in the chiral limit, as a hadrons electromagnetic deformation is due principally to the interaction with the pion cloud. This non-analytic chiral behavior should be very pronounced in lattice calculations as one reduces the light quark masses, providing stringent checks of chiral perturbation theory predictions. In lattice QCD we use background electric fields to extract the polarizabilities. As the magnetic moments of baryons affect their relativistic propagation in constant electric fields, electric polarizabilities cannot be determined without knowledge of magnetic moments. This is analogous to the experimental situation, for which determination of polarizabilities from the Compton amplitude requires subtraction of Born terms. With the background field method, we devised combinations of nucleon correlation functions in constant electric fields that isolate magnetic moments and electric polarizabilities. Using an ensemble of anisotropic gauge configurations with dynamical clover fermions, we demonstrate how both observables can be determined from lattice QCD simulations in background electric fields. We obtained results for the neutron and proton, however, our study is currently limited to electrically neutral sea quarks. The value we extract for the nucleon isovector magnetic moment is comparable to those obtained from measuring lattice three-point functions at similar pion masses.

- **$\pi\pi$ scattering in twisted mass chiral perturbation theory:** In collaboration with Jiunn-Wei Chen (Prof. at National Taiwan University) and Michael Buchoff (graduate student at Univ. of Maryland), we determined the form of two pion interactions with twisted mass chiral perturbation theory. It was demonstrated that the $I = 2\ \pi^+\pi^+$ scattering length is free of discretization errors up to next-to-leading order in the combined chiral–lattice-spacing expansion. Conversely, we demonstrated that the isospin breaking inherent in the twisted mass lattice QCD formulation precludes the study of $I_3 = 0$ states, for example the $|I = 2, I_3 = 0\rangle$ and $|I = 0\rangle$ states mix non-perturbatively. This work is currently being used by the *European Twisted Mass Lattice Collaboration* to perform an extrapolation of $I = 2\ \pi^+\pi^+$ scattering calculations to the physical point.

- **Restless pions from orbifold boundary conditions: An Explicit construction for noise reduction in lattice QCD:** Along with Paulo Bedaque (Prof. at Univ. of Maryland) we have been exploring the use of new boundary conditions in lattice QCD calculations with the goal of mitigating, at least in part, the exponential problem of calculating (multi) baryon energy levels, mentioned above. We have formulated an explicit construction which can be implemented during the calculation, and presently, in collaboration with Robert Edwards (Staff Scientist at Jefferson Lab) we are working to implement this new idea.

3. Effective Field Theory for Lattice QCD

- **Chiral behavior of the nucleon mass:** Efforts to reproduce the known hadron spectrum with lattice QCD serve two purposes; first they provide a necessary check that the systematic approximations made in the lattice calculation are under control, second by performing the extrapolation to the physical values of the light quark masses, utilizing chiral perturbation theory, we can gain much insight into the low energy behavior of QCD. These chiral extrapolations are predicted to have stringent functional forms, with a small set of unknown *low energy constatns*, or LECs. These LECs are universal, so that determined from one observable, they can then be used to make predictions of other observables whose chiral perturbation theory expressions share the same LECs. Importantly, they can be used to make predictions of quantities which are difficult or impossible to calculate with lattice QCD, or to measure experimentally.

To this end, in addition to performing a calculation of the light hadron spectrum, we have performed a detailed study of the chiral extrapolation of the nucleon mass (as well as that of the lambda, sigma and cascade). One striking feature of our work was the finding that the nucleon mass displays unexpected behavior as a function of the pion mass, scaling linearly in m_π. Given this unexpected phenomenon, we (along with the LHP Collaboration) compared our results to those of other current lattice calculations, finding this linear pion mass dependence present in all dynamical lattice calculations. This unexpected chiral behavior has provided a new theoretical puzzle, which we continue to explore (see also the invited plenary talk by A. Walker-Loud at the 2008 Lattice Field Theory Conference).

- **Hyperons in two flavor chiral perturbation theory:** The $SU(3)$ chiral perturbation theory for baryons is poorly convergent at best, while the $SU(2)$ chiral extrapolations in the light quark masses tends to work quite well, in particular when compared with modern lattice calculations with pion masses $m_\pi \lesssim 400$ $\texttt{MeV}$. Given the wealth of new lattice QCD calculations which can be used to constrain the greater number of LECs in the $SU(2)$ chiral perturbation theory, along with Brian Tiburzi, I developed the two flavor chiral perturbation theory for hyperons. This work has been further extended by others, and is now being used to explore the light quark extrapolations of hyperon observables.

- **Mixed action effective field theory:** In collaboration with Jiunn-Wei Chen (Prof. at National Taiwan Univ.), Maarten Golterman (Prof. at SanFrancisco State University) and Donal O'Connell (postdoctoral fellow at the Institute for Advanced Study, Princeton) we corrected a mistake in the literature regarding mixed action effective field theories for lattice QCD.

- **Lattice test of $1/N(c)$ baryon mass relations:** In collaboration with Elizabeth Jenkins (Faculty at U.C. San Diego), Aneesh Manohar (faculty at U.C. San Deigo) and John Negele (faculty at MIT), we have begun an extensive quantitative exploration of the predictions of large N_c using lattice QCD. To begin the project, the $1/N_c$ baryon mass relations are compared with lattice simulations of baryon masses using different values of the light-quark masses, and hence different values of $SU(3)$ flavor-symmetry breaking. The lattice data clearly display both the $1/N_c$ and $SU(3)$ flavor-symmetry breaking hierarchies. The validity of $1/N_c$ baryon mass relations derived without assuming approximate $SU(3)$ flavor-symmetry also can be tested by lattice data at very large values of the strange quark mass. The $1/N_c$ expansion constrains the form of discretization effects; these are suppressed by powers of $1/N_c$ by taking suitable combinations of masses. This $1/N_c$ scaling was explicitly demonstrated in this first project. This work may significantly impact the manner in which lattice computations of baryon quantities are extrapolated to the physical value of the light and strange quark masses.

- **Kaon thresholds and Two-flavor chiral expansions for hyperons:** In collaboration with Brian Tiburzi and Fu-Jiun Jiang (faculty at National Taiwan University), we extended our work on the two-flavor chiral expansion for hyperons. This framework provides a useful perturbative framework to study hadron properties. Such expansions should exhibit marked improvement over the conventional three-flavor chiral expansion. Although one can theoretically formulate two-flavor theories for the various hyperon multiplets, the nearness of kaon thresholds can seriously undermine the effectiveness of the perturbative expansion in practice. We investigate the importance of virtual kaon thresholds on hyperon properties, specifically their masses and isovector axial charges. Using a three-flavor expansion that includes SU(3) breaking effects, we uncover the underlying expansion parameter governing the description of virtual kaon thresholds. For spin-half hyperons, this expansion parameter is quite small. Consequently virtual kaon contributions are well described in the two-flavor theory by terms analytic in the pion mass-squared. For spin three-half hyperons, however, one is closer to the kaon production threshold, and the expansion parameter is not as small. Breakdown of SU(2) chiral perturbation theory is shown to arise from a pole in the expansion parameter associated with the kaon threshold. Estimating higher-order corrections to the expansion parameter is necessary to ascertain whether the two-flavor theory of spin three-half hyperons remains perturbative. We find that, despite higher-order corrections, there is a useful perturbative expansion for the masses and isovector axial charges of both spin-half and spin three-half hyperons.

E. Service work / advancement of DOE goals

The PI served as the chairman of the Local Organizing committee of the XXVI International Symposium on Lattice Field Theory (Lattice 2008) which will be held at the College of William and Mary, Williamsburg Virginia, July 14-19, 2008. This is the major international conference on Lattice Field Theory. The subject of this conference is techniques and results in field theory on a spacetime lattice. This includes spin systems important to condensed matter physics, non-perturbative studies of the Higgs mechanism and studies of the electroweak phase transition in the early universe. However, the largest part of the conference is devoted to numerical studies of QCD. These calculations are essential to interpreting the results of accelerator experiments. Lattice QCD will produce first principles computations of hadron masses and hadron structure and interactions, eventually leading to an understanding of nuclear forces from QCD. We had about 303 participants more than half of them being international.

The PI is also one of the organizers of the “Tenth Workshop on Non-Perturbative Quantum Chromodynamics” at l’Institut Astrophysique de Paris June 8-12, 2009. In particular he is one of the organizers of two sessions on non-perturbative results from Lattice QCD calculations. This is a broad workshop with talks covering recent results from experiment to pure mathematical methods on non-perturbative field theory and provides an excellent ground for interactions between theory, experiment and phenomenology.

The PI served as a member of the 2010 Nuclear Physics decadal review committee of the National Academies.

F. Publications and Talks

PI / investigator	publ.	prept./sub.	conf. rpts	talks
Orginos	15	3	4	11
Walker-Loud (Post-Doc)	9	5	5	7
total	24	8	9	18

Published papers:

1. H. -W. Lin, S. D. Cohen, N. Mathur and K. Orginos, "Bottom-Hadron Mass Splittings from Static-Quark Action on 2+1-Flavor Lattices," Phys. Rev. D **80**, 054027 (2009) [arXiv:0905.4120 [hep-lat]].

2. A. Torok, S. R. Beane, W. Detmold, T. C. Luu, K. Orginos, A. Parreno, M. J. Savage and A. Walker-Loud, "Meson-Baryon Scattering Lengths from Mixed-Action Lattice QCD," Phys. Rev. D **81**, 074506 (2010) [arXiv:0907.1913 [hep-lat]].

3. S. R. Beane, W. Detmold, T. C. Luu, K. Orginos, A. Parreno, M. J. Savage, A. Torok, and A. Walker-Loud, "High Statistics Analysis using Anisotropic Clover Lattices: (II) Three-Baryon Systems," arXiv:0905.0466 [hep-lat].

4. S. R. Beane, W. Detmold, T. C. Luu, K. Orginos, A. Parreno, M. J. Savage, A. Torok, and A. Walker-Loud, "High Statistics Analysis using Anisotropic Clover Lattices: (I) Single Hadron Correlation Functions," arXiv:0903.2990 [hep-lat].

5. H. W. Lin and K. Orginos, "Strange Baryon Electromagnetic Form Factors and SU(3) Flavor Symmetry Breaking," Phys. Rev. D **79**, 074507 (2009) [arXiv:0812.4456 [hep-lat]].

6. C. Aubin, K. Orginos, V. Pascalutsa and M. Vanderhaeghen, "Magnetic Moments of Delta and Ω^- Baryons with Dynamical Clover Fermions," Phys. Rev. D **79** 2R, (2009) [arXiv:0811.2440 [hep-lat]].

7. L. Liu, H. W. Lin and K. Orginos, "Charmed Hadron Interactions," PoS **LATTICE2008**, (2008) arXiv:0810.5412 [hep-lat].

8. C. Aubin, K. Orginos, V. Pascalutsa and M. Vanderhaeghen, "Finite Volume Study of the Delta Magnetic Moments Using Dynamical Clover Fermions," PoS **LATTICE2008**, (2008) arXiv:0809.1629 [hep-lat].

9. W. Detmold, K. Orginos, M. J. Savage and A. Walker-Loud, "Kaon Condensation with Lattice QCD," Phys. Rev. D **78**, 054514 (2008) [arXiv:0807.1856 [hep-lat]].

10. A. Walker-Loud, K. Orginos, *et al.*, for the LHP Collaboration, "Light hadron spectroscopy using domain wall valence quarks on an Asqtad sea," Phys. Rev. D **79**, 054502 (2009) arXiv:0806.4549 [hep-lat].

11. H. W. Lin and K. Orginos, "First Calculation of Hyperon Axial Couplings from Lattice QCD," Phys. Rev. D **79**, 034507 (2009) [arXiv:0712.1214 [hep-lat]].

12. S. R. Beane, T. C. Luu, K. Orginos, A. Parreno, M. J. Savage, A. Torok and A. Walker-Loud [NPLQCD Collaboration], "The K+K+ Scattering Length from Lattice QCD," Phys. Rev. D **77**, 094507 (2008) [arXiv:0709.1169 [hep-lat]].

13. W. Detmold, M. J. Savage, A. Torok, S. R. Beane, T. C. Luu, K. Orginos and A. Parreno, "Multi-Pion States in Lattice QCD and the Charged-Pion Condensate," Phys. Rev. D **78**, 014507 (2008) [arXiv:0803.2728 [hep-lat]].

14. S. R. Beane, K. Orginos and M. J. Savage, Int. J. Mod. Phys. E **17**, 1157 (2008) [arXiv:0805.4629 [hep-lat]].

15. S. R. Beane, W. Detmold, T. CLuu, K. Orginos, A. Parreno, M. J. Savage, A. Torok and A. Walker-Loud, "High Statistics Analysis using Anisotropic Clover Lattices. II. Three-Baryon Systems," Phys. Rev. D **80**, 074501 (2009) [arXiv:0905.0466 [hep-lat]].

16. S. R. Beane, K. Orginos, A. Walker-Loud, *et al.* [NPLQCD Collaboration], "High Statistics Analysis using Anisotropic Clover Lattices: (III) Baryon-Baryon Interactions," Phys. Rev. D **81**, 054505 (2010) [arXiv:0912.4243 [hep-lat]].

17. L. Liu, H. -W. Lin, K. Orginos and A. Walker-Loud, "Singly and Doubly Charmed J=1/2 Baryon Spectrum from Lattice QCD," Phys. Rev. D **81** (2010) 094505 [arXiv:0909.3294 [hep-lat]].

18. H. -W. Lin, S. D. Cohen, L. Liu, N. Mathur, K. Orginos and A. Walker-Loud, "Heavy-Baryon Spectroscopy from Lattice QCD," Comput. Phys. Commun. **182**, 24 (2011) [arXiv:1002.4710 [hep-lat]].

The following are the publications of the Postdoctoral Associate excluding those that the PI is a co-author.

1. B. C. Tiburzi and A. Walker-Loud, "Hyperons in Two Flavor Chiral Perturbation Theory," Phys. Lett. B **669**, 246 (2008) [arXiv:0808.0482 [nucl-th]].

2. A. Walker-Loud, "New lessons from the nucleon mass, lattice QCD and heavy baryon chiral perturbation theory," PoS **LATTICE2008**, (2008) arXiv:0810.0663 [hep-lat].

3. M. I. Buchoff, J. W. Chen and A. Walker-Loud, "pi-pi Scattering in Twisted Mass Chiral Perturbation Theory," Phys. Rev. D **79**, 074503 (2009) arXiv:0810.2464 [hep-lat].

4. P. F. Bedaque and A. Walker-Loud, "Restless pions from orbifold boundary conditions: an explicit construction for noise reduction in lattice QCD," arXiv:0811.2127 [hep-lat].

5. W. Detmold, B. C. Tiburzi and A. Walker-Loud, "Extracting Electric Polarizabilities from Lattice QCD," Phys. Rev. D **79**, 074503 (2009) arXiv:0904.1586 [hep-lat].

6. A. Walker-Loud, "Strong isospin breaking with twisted mass lattice QCD," arXiv:0904.2404 [hep-lat].

7. J. W. Chen, M. Golterman, D. O'Connell and A. Walker-Loud, "Mixed Action Effective Field Theory: an Addendum," Phys. Rev. D **79**, 117502 (2009) arXiv:0905.2566 [hep-lat].

8. W. Detmold, B. C. Tiburzi and A. Walker-Loud, "Electric Polarizabilities from Lattice QCD," PoS LATTICE **2008** (2008) 147 arXiv:0809.0721 [hep-lat].

9. A. Walker-Loud, "Hadronic Interactions with Lattice QCD," PoS CONFINEMENT **8**, 144 (2008) arXiv:0812.2723 [nucl-th].

10. W. Detmold, B. C. Tiburzi and A. Walker-Loud, "Lattice QCD in Background Fields," arXiv:0908.3626 [hep-lat].

11. W. Detmold, B. C. Tiburzi and A. Walker-Loud, "Charged Hadron Properties in Background Electric Fields," PoS LAT **2009**, 158 (2009) [arXiv:0910.5148 [hep-lat]].

12. E. E. Jenkins, A. V. Manohar, J. W. Negele and A. Walker-Loud, Phys. Rev. D **81**, 014502 (2010) [arXiv:0907.0529 [hep-lat]].

13. F. -J. Jiang, B. C. Tiburzi and A. Walker-Loud, "Kaon Thresholds and Two-Flavor Chiral Expansions for Hyperons," Phys. Lett. B **695**, 329 (2011) [arXiv:0911.4721 [nucl-th]].

14. W. Detmold, B. C. Tiburzi and A. Walker-Loud, "Extracting Nucleon Magnetic Moments and Electric Polarizabilities from Lattice QCD in Background Electric Fields," Phys. Rev. D **81** (2010) 054502 [arXiv:1001.1131 [hep-lat]].

15. W. Detmold, B. C. Tiburzi and A. Walker-Loud, "Nucleon Magnetic Moments and Electric Polarizabilities," PoS LATTICE **2010**, 161 (2010) [arXiv:1008.2011 [hep-lat]].

G. Invited Talks

The following are invited talks the PI gave:

1. Generalized Parton Distributions from Lattice QCD,
   Invited talk at the Workshop on hard scattering processes and 3D parton distributions, DNP07, October 10-13, 2007.

2. Hadron Interactions from Lattice QCD,
   Seminar at Ohio University, Athens OH, October 16, 2007.

3. Lattice calculations of hadronic interactions: Prospects for the future,
   Seminar at Brookhaven National Laboratory, Upton, NY - January 29, 2008.

4. Scattering on the Lattice,
   Seminar at University of Kentucky, Lexington, KY - March 19, 2008.

5. Nucleon Structure form the Lattice,
   Invited talk at JLab Users Group Workshop, Newport News, VA - June 16-18, 2008.

6. Review of charm and beauty spectroscopy in Lattice QCD,
   Tenth Workshop on Non-Perturbative Quantum Chromodynamics, Paris June 8-12, 2009.

7. Algorithms: How to extract physics from Lattice QCD,
   Extreme Computing Workshop, Washington DC, January 26-28, 2009.

8. Hadron structure and interactions from Lattice QCD,
   University of Illinois at Urbana-Champain, November 3, 2008.

9. Lattice QCD results on Hadron scattering,
   ECT*, Trento Italy, September 29, 2008.

10. Introduction to Lattice Gauge Theory Five lectures at Hampton University Graduate School (HUGS), Jefferson Lab, June 2010.

11. Construction and analysis of two baryon correlation functions, XXVIII International Symposium on Lattice Filed Theory,July 2010, Villasimius, Sardinia.

The following are invited talks the AWL gave:

1. New lessons from the nucleon mass, lattice QCD and heavy baryon chiral perturbation theory
   Plenary talk at the 26th International Symposium on Lattice Field Theory,
   Williamsburg, VA, USA, July 2008.

2. Hadronic Interactions with Lattice QCD,
   Invited talk at Quark Confinement and the Hadron Spectrum,
   Mainz, Germany, September 2008.

3. Background Electric Fields and Charged Hadron Correlation Functions on the Lattice,
   Invited seminar at Jefferson Lab,
   Newport News, VA, USA, October 2008.

4. Background Electric Fields and Charged Hadron Correlation Functions on the Lattice,
   Invited seminar at Columbia University Theory Group,
   NewYork, NY, USA, December 2008.

5. Mixed Action Lattice QCD
   Invited seminar at University of Kentucky, Theoretical Physics Group,
   Lexington, KY, USA, April 2009.

6. Multi Baryon Interactions with Lattice QCD,
   Invited talk at Chiral Dynamics Conference,
   Bern, Switzerland, July 2009.

7. Charged Hadron Electromagnetic Properties with Lattice QCD,
   Invited talk at the 27th International Symposium on Lattice Field Theory,
   Beijing, China, July 2009.