Lattice Hadron Physics Collaboration

Nucleon Structure in the Chiral Regime with Domain Wall Fermions

February 15, 2007

Abstract

We propose a comprehensive set of calculations of nucleon structure in the chiral regime using 2+1 flavors of dynamical domain wall fermions. Physical observables will include moments of structure functions, nucleon electromagnetic and generalized form factors, the nucleon sigma term, the neutron electric dipole moment, quark distribution amplitudes, the nucleon to Delta transition form factors, and spectroscopic quantities. Operators will be renormalized nonperturbatively. Calculations will be performed on $a = 0.123$ fm lattaces at $m_\pi = 517$, 389, and 305 MeV and on $a = 0.093$ fm lattices at $m_\pi = 315$ and 261 MeV, making use of lattices already provided by the RBC and UKQCD collaborations and new lattices currently proposed on USQCD facilities and leadership class facilities. Propagators calculated in this project will be made available to the lattice community.

Total Request: 3.6 million 6n-equivalent node-hours on clusters

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1 Physics Goals

Introduction

From the inception of the SciDAC lattice QCD project, one of the strategic goals of the USQCD Collaboration articulated in each of its proposals to the DOE has been understanding hadron structure from first principles and calculating key experimental observables in the DOE experimental program revealing this structure. The proposed calculations of nucleon form factors, moments of parton, helicity, and transversity distributions as a function of momentum fraction, and the moments of generalized parton distributions(GPD's) are all specified as Nuclear Physics 2014 milestones in Hadronic Physics. These first principles calculations will have direct impact on key experimental measurements at Jefferson Lab and RHIC-spin, including the 2008 milestone of extracting accurate information on GPD's, the 2010 milestone of determining electromagnetic and electroweak form factors, and the 2013 milestone of measuring flavor-identified contributions to the proton spin. Thus, we believe that our proposed strategic analysis will achieve essential goals of the USQCD Collaboration and of the DOE research program and thus justifies the substantial investment of DOE resources required to accomplish it.

The ultimate goal in hadron structure calculations has always been a consistent, unitary treatment of dynamical and valence chiral fermions in the chiral regime of light quark masses where chiral perturbation theory is applicable. Chiral symmetry on a discrete lattice is essential in avoiding operator mixing among the twist-two operators relevant to structure functions and generalized parton distributions. Furthermore, the clear control of systematic errors provided by unitary treatment of valence and dynamical quarks and the intrinsic order a^2 error will be invaluable in achieving the high precision required for decisive impact on experiment.

Now, for the first time, we have the opportunity to achieve this goal of using chiral fermions in the chiral regime. As a result of DOE investment in lattice QCD resources, international collaboration between RBC and UKQCD in sharing domain wall configurations, and a joint collaboration between LHPC, RBC, and UKQCD to generate domain wall configurations and propagators, we now have an unprecedented opportunity to calculate hadron structure using dynamical domain wall fermions with two lattice spacings at pion masses down to 261 MeV with high statistics.

It is important to note that calculation of hadron observables using domain wall fermions does not fit the normal preconception that "analysis" of configurations only requires small amounts of resources and that the only expensive task is generating configurations. The emerging dynamical domain wall configurations are an important national resource, but utilizing their full potential requires expensive calculations of observables. One important step in addressing this issue is the decision by the LHPC, RBC, and UKQCD collaborations to include the generation of standard fermion propagators calculated with a smeared Gaussian source as well as lattices. This both avoids duplication of the cost of generating expensive propagators needed for many applications and significantly reduces the cost of calculating hadronic matrix elements, where we now only have to bear the cost of sequential or "backward" propagators. Nevertheless, utilizing the configurations that will be available during the next allocation year requires the full 3.6M 6n node-hours requested in this proposal. If sufficient resources are not allocated to extract the physics from configurations as they become available, then the national program will become unbalanced as un-utilized configurations accumulate. This would be analogous to building a first-rate accelerator, but failing to fund the detectors required to do physics with it. In the spirit of the call for proposals, in addition to the specific request for resources, we have also listed the configurations that are being proposed to be generated at ANL under INCITE and early use opportunities, and show the Teraflops-years required to calculate nucleon observables on them as well. When INCITE and early use opportunities are evaluated, we believe that physics analysis should be considered as an important component complementary to lattice generation.

In considering the impact on the field, it is useful to note that there are several competing efforts in hadron structure under way internationally. Using algorithmic developments comparable to those that have made the dynamical domain wall project feasible, the QCDSF collaboration is actively generating and analyzing computationally less demanding clover improved Wilson configurations, and the twisted-mass collaboration is embarking on a hadron structure project. In the short term, the lower computational cost of those approaches will likely enable them to complete higher statistics studies than feasible for us on the same time scale. Hence, it is important to aggressively pursue domain wall calculations so that sooner rather than later, we can acquire sufficient statistics to take advantage of the intrinsic advantages of domain wall fermions to achieve higher precision results with smaller systematic error.

Previous accomplishments with domain wall fermions on a staggered sea

Previous calculations on $a = 0.125$ fm lattices with dynamical improved staggered quarks generated by the MILC collaboration provided the first entree to the chiral regime in full QCD with domain wall valence quarks. These calculations with pion masses down to 359 MeV enabled us to develop all the computational and analysis technology needed for the present calculation, produced chiral extrapolations in impressive agreement with experiment, and highlight current challenges and opportunities.

Figures 1-3 show the results for low moments of quark distributions $\langle x\rangle_{u-d}$ and helicity distributions, $g_A = \langle 1\rangle_{\Delta u-\Delta d}$, $\langle x\rangle_{\Delta u-\Delta d}$, $\langle x^2\rangle_{\Delta u-\Delta d}$, compared with experiment. Already with the limited statistics available last year, finite volume chiral perturbation theory including both nucleon and Delta degrees of freedom predicted g_A with an error of 6.8 % in agreement with experiment [1]. One-loop chiral perturbation theory using the measured values of f_π and g_A produced chiral fits which in all cases were consistent with experiment as shown in the Figures [2]. Although that is reassuring, the Figures clearly show the need to perform calculations at lower pion masses to actually measure the pronounced curvature expected from chiral perturbation theory. The proposed calculations at $m_\pi = 261$ MeV will have decisive impact in measuring these moments midway between the lowest point and the physical pion mass, where one both expects to clearly observe chiral logs and to highly constrain them by lattice measurements.

Figures 4-5 show electromagnetic vector and axial vector form factors compared with experiment. Again, the fact that the lattice form factors appear to be extrapolating correctly to the experimental form factors is gratifying, but also highlights the need for calculating at the lighter mass $m_\pi = 261$ MeV. In addition, a key goal is to explore form factors at the highest Q^2 possible, and decreasing the lattice spacing from 0.125 fm to 0.093 fm will increase the accessible Q^2 on the lattice by a factor of 1.8. Finally, our overconstrained analysis combines different combinations of initial and final nucleon momentum corresponding to similar Q^2. Although these should agree in the continuum limit, they suffer from different finite-a lattice artifacts. Hence, we expect going to a finer lattice spacing to significantly decrease these discrepancies.

The origin of the nucleon spin is an area of intense experimental and theoretical interest, and Figures 6-7 show the present results for the contribution from the quark spin and quark angular momentum. Although, as a separate issue, it is also important to calculate the presently omitted disconnected diagrams, it will again be valuable to constrain the chiral extrapolation more accurately with lower pion masses.

Finally, Figure 9 shows the increasing agreement, as the pion mass gets lighter, of lattice calculations of generalized form factors, corresponding to moments of GPD's, and a phenomenological parameterization of GPD's constrained by a large amount of experimental data[3]. This is an important opportunity for lattice QCD to provide complementary information to that provided by experiment. Since lattice QCD specifies moments of GPD's and experiment measures convolutions, combined analysis can provide significantly greater constraints than either can separately.

Four papers describing these and other results are nearly complete and will be submitted shortly. Our plan is to complete our analyses of the $a = 0.125$ fm MILC lattices with the remainder of our allocation for the present production period, and starting in July 2007, concentrate our effort on domain wall calculations. We will begin with the domain wall configurations described below at $a = 1.123$ fm, which beautifully overlap the masses and lattice sizes used with MILC configurations. Hence, we will be able to observe in detail any physics differences as well as any lattice technology differences between domain wall and staggered dynamical configurations, before we go on to the finer a= 0.093 fm lattices.

Research Topics

A central feature of the LHPC hadron structure research program is the coordination of a large number of separate research projects to calculate a minimal common set of propagators and operator building blocks for all the required observables as efficiently as possible. The building blocks include all the combinations of gamma matrices and up to three covariant derivatives required for twist-two operators. Here we summarize the principal observables we plan to calculate.

Moments of Structure Functions Nucleon matrix elements of the twist-2 operators

$$\langle P'S'|\mathcal{O}^{\mu_1\cdots\mu_n}|PS\rangle \quad \text{with} \quad \mathcal{O}^{\mu_1\cdots\mu_n} = \bar{\psi}\Gamma iD^{\mu_1}\cdots iD^{\mu_n}\psi \tag{1}$$

specify moments of the parton distributions and generalized parton distributions that have been measured extensively in high energy scattering experiments. Diagonal matrix elements, $P = P'$, correspond to the moments of the light cone quark distribution, longitudinal spin distribution, and transversity distribution for $\Gamma = \gamma_\mu, \gamma_5\gamma_\mu$, and $\sigma_{\mu\nu}$ respectively, and will be calculated using the methodology we developed in Ref. [4]. As seen in Figures. 1-2, understanding the chiral behavior of these moments will be an important challenge. The zeroth moment of the spin dependent structure function, $\langle 1\rangle_{\Delta q}$, specifies the contribution of the quark spin to the total nucleon spin shown in Figs. 6-7, and thus lies at the heart of the proton "spin crisis".

Form Factors and Generalized Form Factors Off-diagonal matrix elements of the twist-two operators given in Eq.(1) for $P \neq P'$ yield a hierarchy of generalized form factors $A_{nm}(t), B_{nm}(t)$, and $C_n(t)$ for the spin independent case and $\tilde{A}_{nm}(t), \tilde{B}_{nm}(t)$ for the spin-dependent case, where $n-1$ equals the number of covariant derivatives[5]. The form factors $A_{10}(t)$ and $B_{10}(t)$ correspond to the familiar electromagnetic form factors F_1 and F_2, which are of great interest as a result of the F_2 measurements and apparent early onset of scaling in recent JLab experiments, as well as strangeness form factors studied extensively at Bates and JLab. Figures 4-5 show form factors for the vector and axial vector currents.

The total quark contribution to the nucleon spin is given by the extrapolation to $t = 0$ of $A_{20}^{\mathrm{u+d}}(t)$ and $B_{20}^{\mathrm{u+d}}(t)$. Combined with $\langle 1\rangle_{\Delta q}$, one can decompose the nucleon spin into the contributions from quark spin and orbital angular momentum, with the remainder arising from gluons. Figures 6 and 7 show the total contribution of quark spin and quark angular momentum to the nucleon spin and the separated contributions of up and down quarks respectively.

Generalized parton distributions explore the quark distribution in three dimensions, $q(x, \vec{r}_\perp)$, as a function of the longitudinal momentum fraction x and the transverse spatial coordinate $\vec{r}_\perp$. It turns out that several of the generalized form factors, which can be calculated on the lattice, measure moments of the Fourier transform of $q(x, \vec{r}_\perp)$: $A_{n0}(-\Delta_\perp^2) = \int d^2r_\perp \int dx\, x^{n-1} q(x, \vec{r}_\perp)\, e^{i\vec{r}_\perp\cdot\vec{\Delta}_\perp}$. Figure 8 shows the ratio A_{30}/A_{10} indicating a striking variation in the slope, and therefore the rms radius, as the moment increases from $n = 1$ to $n = 3$. With this methodology, we expect to measure the transverse structure of the nucleon in the chiral regime[6].

Quark Distribution Amplitudes According to perturbative QCD, the form factors at asymptotic Q^2 are determined by quark distribution amplitudes. The moments of these amplitudes involve nucleon-to-vacuum matrix elements,

$$\langle 0|\epsilon^{ijk} u_i^c \gamma_\mu D^{\alpha_1}\cdots D^{\alpha_n} u_j D^{\alpha_{n+1}}\cdots D^{\alpha_\ell}\gamma_5\gamma^\mu d_k|P\rangle, \tag{2}$$

which can be calculated in terms of two-point functions. Given the widely differing models prevalent in the literature, definitive lattice calculations are expected to be useful.

N - Δ Transition Form Factors The experimental method of choice to reveal the presence of deformation in the low-lying baryons is measuring the N - Δ transition amplitude, where the dominant transition is the magnetic dipole (M1) and non-vanishing electric quadrupole (E2) and Coulomb quadrupole (C2) amplitudes are a signature of deformation in the nucleon, Delta, or both. Extensive measurements have been completed at Bates, JLab, and Mainz. To the extent that external resources are available to calculate the additional sequential propagators for these transition form factors, we will continue an ongoing collaboration [7, 8] to calculate these transition form factors at lower masses.

Nucleon Sigma Term Low-energy pion-nucleus scattering data allow one to determine the $\pi - N$ sigma term, $\sigma = \frac{1}{2}(m_u + m_d)\langle P|\bar{u}u + \bar{d}d|P\rangle$. Combined with chiral perturbation theory analysis of the baryon octet mass splitting, the σ term implies that a large fraction of the nucleon mass arises from the strange quark mass term: $m_s\langle P|\bar{s}s|P\rangle$. A definitive lattice calculation will be quite valuable in clarifying whether this matrix element is indeed large, or if that experimental analysis is flawed.

Neutron Electric Dipole Moment The neutron electric dipole moment places a fundamental limit on the strong CP Θ-angle, so it is of great interest to have a first principles calculation of it. Since the unambiguous topology associated with domain wall fermions enables a conceptually clean calculation, this calculation has the potential for significant physics impact.

Spectroscopy A natural component of this project is careful extraction of hadron masses, quark masses and the decay constants f_π and f_K. Having observed the problem with negative norm states arising from the four different-mass pions in the staggered sea, it will be interesting to calculate the a_0 propagator for dynamical domain wall lattices and verify that the unitary theory is working properly.

2 Computational Strategy

Lattice action

We will use the standard action and domain wall parameters utilized by the RBC and UKQCD collaborations in generating the dynamical domain wall configurations [9]. They chose the Iwasaki gauge action to provide reasonable suppression of chiral symmetry breaking and adequate tunneling between topological sectors. For $a = 0.123$ fm, we will use $24^3 \times 64$ lattices at $m_\pi = 517$, 389, and 305 MeV, and for $a = 0.093$ fm we will use $32^3 \times 64$ lattices at $m_\pi = 315$ and 261 MeV. In all cases $L_s = 16$ and the valence masses will be identical to the sea masses.

Hadron Observables

For the $a = 0.123$ fm lattices, we will use the same strategy for computing hadronic matrix elements as we developed and used successfully for the $a = 0.125$ fm MILC lattices. Our projections for the $a = 0.093$ lattices are based on the same strategy, but clearly we will have to verify key aspects explicitly and modify the approach as dictated by the results.

As described in Ref. [4], we use Wuppertal smeared sources (equivalent to Gaussian smeared sources) and sinks, with the degree of smearing optimized to yield an overlap with the nucleon greater than 50%. Forward propagators are used to construct the sink, which is typically calculated for 2 distinct momenta and 2 flavors. A set of forward propagators from the source and backward propagators from the sink are then combined to calculate a set of building block operators for the tower of twist-2 operators. These building block operators consist of all relevant gamma matrices multiplied by zero, one, two, or three link variables and are Fourier transformed with each of the values of the momentum transfer that will be used to calculate form factors. These building blocks are stored and used to calculate all the nucleon matrix elements and generalized form factors described in Section 1. To economize, we retain only the upper two Dirac components, decreasing the number of propagators by a factor of 2. In addition, by carefully analyzing the operators for generalized form factors, it is possible to calculate all the operators of interest with the nucleon source and sink having the same spin orientation, saving another factor of 2.

As explained in last year's proposal, to increase statistics, we calculate 4 temporally separated sets of 12-component forward propagators on configurations separated by 10 molecular dynamics time steps. These are indicated by "4F" in the table of resources. For each of two flavors and two momenta, 4 nucleon sinks 1.1 fm from each source are constructed from the forward propagators from the nearest source, and one set of 6-component nonrelativistic sequential backward propagators is calculated from the set of four sinks and used with the four sets of forward propagators to form 4 independent sets of building blocks for operators. An analogous calculation is performed for 4 antinucleon sinks on the opposite side of each source. The final cost of these 8 6-component propagators is the same as 4 standard 12-component propagators, so this whole set of nucleon and antinucleon propagators is indicated by "4N" in the table of resources. The set of 4F plus 4N propagators yields 8 independent measurements. Note that for the cases in which forward propagators are provided with the gauge fields, the computational cost is cut in half.

We have assumed the same technique could be used for the $a = 0.093$ fm lattices. In the event that the plateaus are no longer sufficiently independent, dropping to 3 intead of 4 plateaus would increase the cost for forward plus backward propagators by 12% and given 3 forward propagators, would increase the cost of backward propagators by 33%.

Generalized parton distributions are calculated using the overdetermined analysis described in Ref. [5]. For many observables of interest, the straightforward method of calculating a single lattice operator that yields the matrix element of interest requires such high statistics for a useful degree of precision that it is computationally impractical. Hence, we identify the largest set of physically equivalent operators we can calculate, and simultaneously least squares fit this overdetermined set.

The nucleon to Delta transition form factor is also calculated from an overdetermined analysis using a set of forward and backward propagators from a smeared nucleon source and a smeared Delta sink as described in Ref. [7]. In this case, to obtain an optimal signal, three different sinks are calculated, optimized for calculating the M1, C2, and E2 form factors respectively.

Renormalization

The axial and vector currents are renormalized simply using the 5-dimensional Noether current. We will calculate the renormalization factors for additional twist-2 operators nonperturbatively.

Disconnected Diagrams

A separate proposal is being submitted by James Osborn *et al.* for stochastic calculation of disconnected contributions to strange quark form factors. We will collaborate with that project in two ways. First, in a separately supported project using Wilson fermions on the same MILC configurations used for hadron structure calculations, Oliver Jahn at MIT is exploring a truncated eigenmode expansion for the necessary all-to-all propagators[10] with stochastic calculation of the contribution from the orthogonal subspace. We will continue to interact with Osborn, Brower and collaborators to determine which of the two approaches is the most computationally efficient. Second, in the future, when the technology is fully developed, we hope to combine efforts to evaluate the disconnected diagram contributions to all the twist-two operators addressed in this work, but no resources are being requested for this calculation as part of this present proposal.

3 Software

The proposed calculations will utilize Andrew Pochinsky's optimized SciDAC Level 3 domain wall inverter, which during the past year has been modified to enable economical single precision inversion to obtain a single precision approximation to a propagator, followed by a short restart in double precision to bring the propagator up to full double precision accuracy. A typical inversion on our current lattices involves several thousand single precision steps followed by the order of 20 double precision steps. The time requests are based on test runs on domain wall configurations with this inverter.

All the software for calculating sequential nucleon and antinucleon sinks and analysis software for all the major physics components of this proposal have been developed and tested.

4 Resources Requested

The computational resources requested for the hadron structure calculations described above are summarized in Tables 1 and 2. Table 3 lists additional opportunities to use resources on the ANL Blue Gene/P to calculate hadron structure observables concurrently with the generation of dynamical domain wall configurations and forward propagators proposed there.

The bulk of the computer time is used for calculating forward and backward domain wall propagators as described in Section 2. The times for domain wall conjugate gradient

Table 1: Resources requested, in millions of 6n processor-hours for the currently available $24^3 \times 64$ lattices with $a = 0.123$ fm. As explained in the text, the "Forward propagator" entry indicates that 4 forward propagators are calculated on each lattice, and the "Backward propagator" entry indicates that sequential backward propagators equivalent to 4 twelve-component propagators are calculated on each lattice.

$a = 0.123$ fm, $L_S = 16$

Run number	Volume	m_l/m_s	m_π (MeV)	Configs avail	Forward prop.	Backward prop.	M 6n pr hrs
5	$24^3 \times 64$	.02/.04	517	285	4	4	0.138
3	$24^3 \times 64$	.01/.04	389	373	4	4	0.313
1	$24^3 \times 64$	.005/.04	305	380	4	4	0.513
Total 6n processor-hours (millions)							0.964

Table 2: Resources requested, in millions of 6n processor-hours for $32^3 \times 64$ lattices with $a = 0.093$ fm. The notation is the same as Table 1.

$a = 0.093$ fm, $L_S = 16$

Run number	Volume	m_l/m_s	m_π (MeV)	Configs avail	Forward prop.	Backward prop.	M 6n pr hrs
8	$32^3 \times 64$	.006/.03	315	140	4	4	0.336
11+13	$32^3 \times 64$	.006/.03	315	570	0	4	0.760
9	$32^3 \times 64$	.004/.03	261	140	4	4	0.486
10 + 12	$32^3 \times 64$	.004/.03	261	550	0	4	1.061
Total 6n processor-hours (millions)							2.644

inversions are based on interpolation between measured values using the relation

$$T = (A\frac{1}{m_l/m_s} + C)N_L^3 N_T N_5$$

and test measurements were made on $a = 0.123$ fm and $a = 0.093$ fm lattices to determine A and C. The only additional time is for building blocks, where we have estimated the cost of the building blocks associated with a specific source and sink with up to 3 covariant derivatives as 12 % of the cost of a 12-component propagator.

Table 1 shows the proposed production on the $24^3 \times 64$ lattices with $a = 0.123$ fm which have already been produced by RBC and UKQCD and are available now or in the immediate future. The run number refers to the run number listed in the current proposal *Simulations with Dynamical Domain Wall Fermions* submitted by Norman Christ. The listed number of configurations available assumes measurement every 10 molecular dynamics time steps. Since no propagators are provided with these configurations, as explained in Section 2, we would calculate 4 forward (12-component) propagators, sequential backward propagators

Table 3: Resources needed, in Teraflops-years to calculate nucleon structure observables on the $48^3 \times 64$ lattices with $a = 0.093$ fm proposed to be generated at ANL.

$a = 0.093$ fm, $L_S = 16$

Run number	Volume	m_l/m_s	m_π (MeV)	Configs avail	Forward prop.	Backward prop.	Tflops-yrs
16	$48^3 \times 64$	.004/.03	261	620	0	4	1.21
15	$48^3 \times 64$	.002/.03	193	730	0	4	2.60
14	$48^3 \times 64$	.0016/.03	178	920	0	4	5.89

corresponding to 4 additional 12-component propagators, and building blocks for the 8 plateaus associated with these propagators. The corresponding cost in millions of 6n processor-hours is given in the last column.

Table 2 shows the proposed production on the $32^3 \times 64$ lattices with $a = 0.093$ fm that are being produced by RBC and UKQCD and will be available by June 2007 (runs 8 and 9) and that are proposed to be generated in the current allocation period (runs 10, 11, 12, and 13). Note that forward propagators will be available for the latter configurations, so the production on them only requires backwards propagators and is correspondingly nearly twice as cost effective for us. The total time requested for the production in Tables 1 and 2 is 0.964 + 2.644 = 3.608 M 6n node-hrs, which we have rounded to 3.6 M in our request. Note that the configurations for half of this computer time will be available at the beginning of the year, enabling us to concentrate on analyzing them while the new configurations are accumulated.

One of the outstanding opportunities that has made it possible to embark on this dynamical domain wall project this year is the availability of substantial blocks of computer time for lattice QCD on the new DOE leadership class machines at ANL and ORNL. Hence, in addition to our request for time on the USQCD facilities, we have included Table 3 showing how we would propose to utilize resources on the ANL Blue Gene if they become available. It is our understanding that it is a high priority to produce high-impact physics with resources on these leadership class machines. Hence, only generating configurations that would be too expensive to analyze on any other accessible facilities would not fulfill this physics objective. Rather, a coordinated program of configuration generation coupled with strategic calculations of observables making a high impact on the DOE program would be optimal. In this spirit, we have estimated the amount of time required to calculate nucleon structure on the runs 14, 15, and 16 proposed for ANL. Again note that these calculations are cost effective by virtue of their use of forward propagators produced with the configurations. All the requisite software is currently running on the Blue Gene/L, and will be ported to the Blue Gene/P as soon as we obtain access.

5 Data Sharing

The domain wall propagators will be made available to the entire USQCD collaboration as they are produced and tested for use in projects other than the exclusive calculations listed below. In particular, the forward propagators for the existing sets of domain wall configurations for which they are not already available should be a valuable resource for everyone using the domain wall lattices. We will generate them with the same Gaussian smearing that is agreed upon by the RBC and UKQCD collaborations and store them in the same format, so that there will a consistent set of propagators for all domain wall configurations.

6 Exclusive Calculations

Subgroups of our collaboration plan to calculate each of the observables described under *Research Topics* in Section 1. Hence, we ask that moments of structure functions, form factors, generalized form factors, the nucleon to Delta transition form factor, distribution amplitudes, the nucleon sigma term, the neutron electric dipole moment, and the spectroscopic observables be treated as reserved calculations. We request that the propagators generated under this project not be used for these purposes by others until their release for unrestricted use by the US community in July 2009. However, these propagators will be made available as they are generated on a per request basis for those who wish to undertake specific projects that do not conflict with our plans.

References

[1] R. G. Edwards *et al.* [LHPC Collaboration], Phys. Rev. Lett. **96**, 052001 (2006) [arXiv:hep-lat/0510062].

[2] R. G. Edwards *et al.* [LHPC Collaboration], arXiv:hep-lat/0610007.

[3] M. Diehl, T. Feldmann, R. Jakob and P. Kroll, Eur. Phys. J. C **39**, 1 (2005) [arXiv:hep-ph/0408173].

[4] D. Dolgov *et al.* [LHPC collaboration], Phys. Rev. D **66**, 034506 (2002) [arXiv:hep-lat/0201021].

[5] P. Hagler, J. Negele, D. B. Renner, W. Schroers, T. Lippert and K. Schilling [LHPC collaboration], Phys. Rev. D **68**, 034505 (2003) [arXiv:hep-lat/0304018].

[6] LHPC, P. Hagler, J. W. Negele, D. B. Renner, W. Schroers, T. Lippert and K. Schilling [LHPC Collaboration], Phys. Rev. Lett. **93**, 112001 (2004) [arXiv:hep-lat/0312014].

[7] C. Alexandrou *et al.*, Phys. Rev. D **69**, 114506 (2004) [arXiv:hep-lat/0307018].

[8] C. Alexandrou, T. Leontiou, J. W. Negele and A. Tsapalis, Phys. Rev. Lett. **98**, 052003 (2007) arXiv:hep-lat/0610107.

[9] C. Allton *et al.*, arXiv:hep-lat/0701013.

[10] H. Neff, N. Eicker, T. Lippert, J. W. Negele and K. Schilling, Phys. Rev. D **64**, 114509 (2001) [arXiv:hep-lat/0106016].

[11] J. J. Kelly, Phys. Rev. C **70**, 068202 (2004).

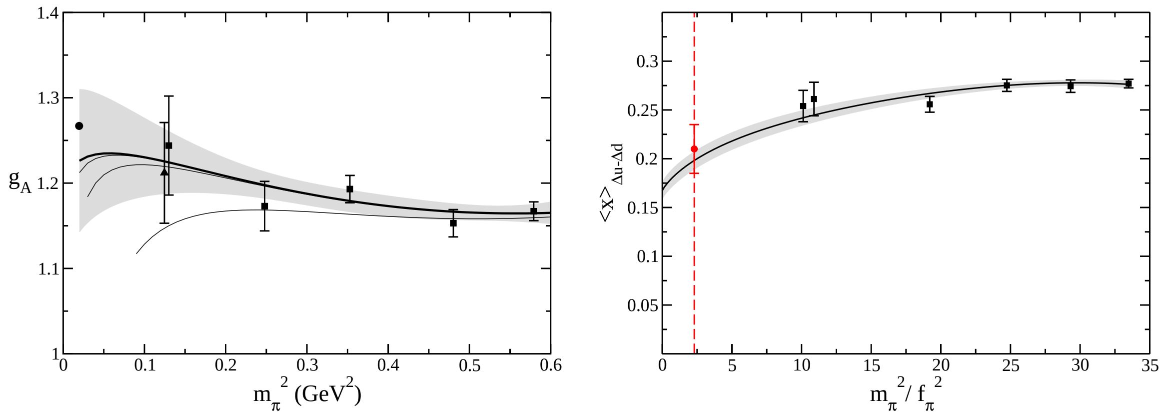

Figure 1: Nucleon axial charge $g_A = \langle 1 \rangle_{\Delta u - \Delta d}$ (left plot) and first moment of helicity distribution $\langle x \rangle_{\Delta u - \Delta d}$ (right plot) as a function of the pion mass. The heavy solid line and shaded error band in the left plot show the χPT fit to the finite volume g_A data on MILC lattices with pion masses down to 359 MeV evaluated in the infinite volume limit. The right plot shows the self-consistent improved one-loop fit to the lattice measurements of $\langle x \rangle_{\Delta u - \Delta d}$, which agrees with experiment at the physical pion mass.

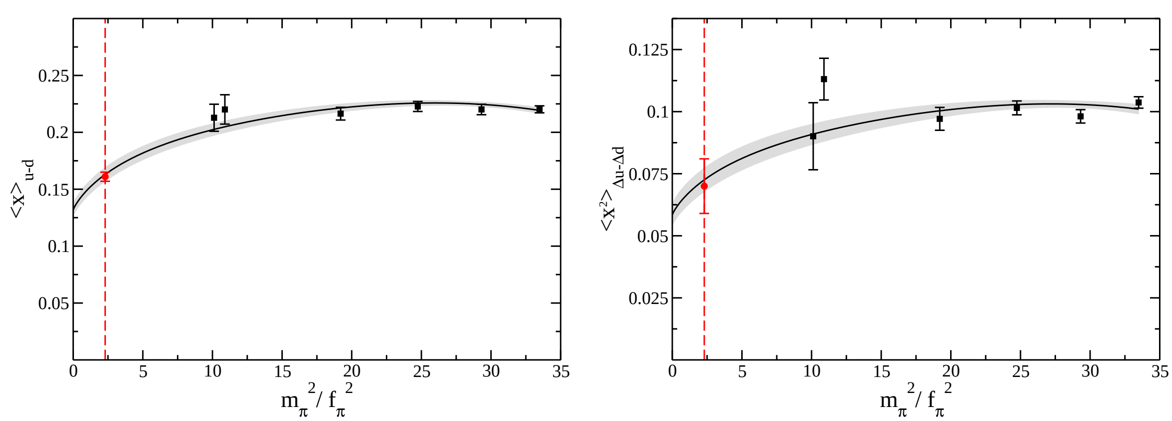

Figure 2: First moment of the unpolarized distribution, $\langle x \rangle_{u-d}$ (left plot) and second moment of the helicity distribution$\langle x^2 \rangle_{\Delta u - \Delta d}$ as a function of the pion mass. As in the right panel of Fig 1, the self-consistent improved one-loop fits to the lattice measurements agree with experiment at the physical pion mass.

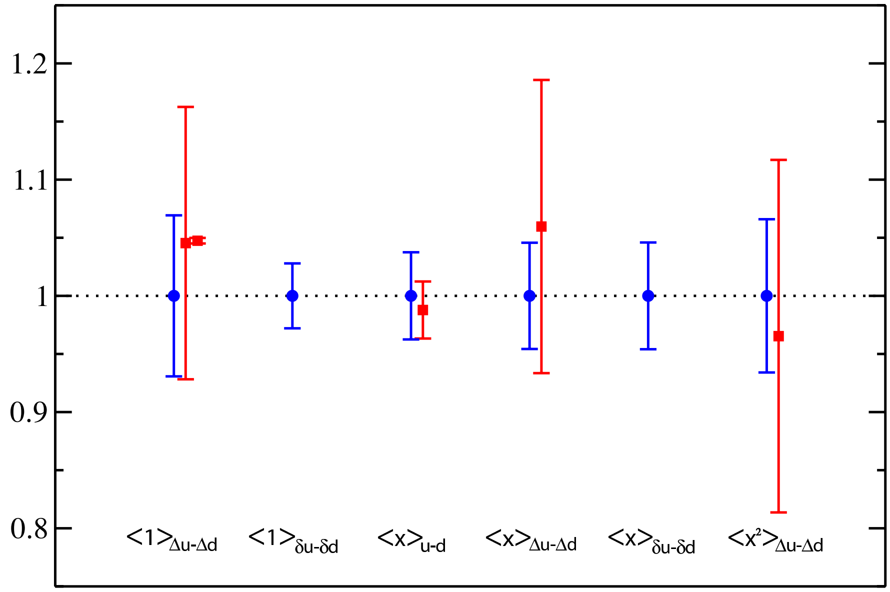

Figure 3: Six moments of quark distributions measured on MILC lattices with pion masses down to 359 MeV. Lattice results are shown in blue and experimental measurements in red, and each is normalized to the corresponding lattice result.

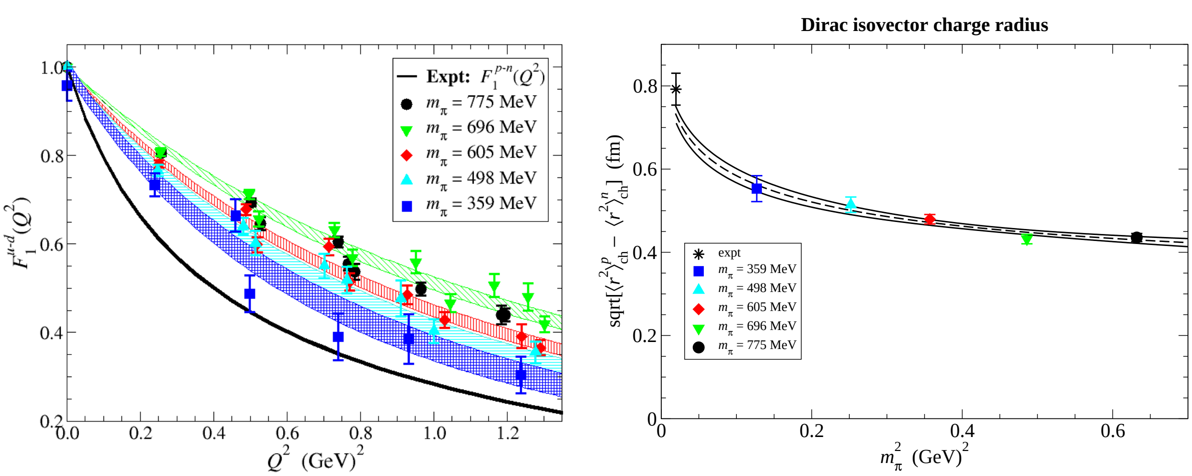

Figure 4: Isovector form factor F_1 at five masses compared with experiment [11] (left plot) and the chiral extrapolation of the corresponding form factor slopes compared with experiment (right plot).

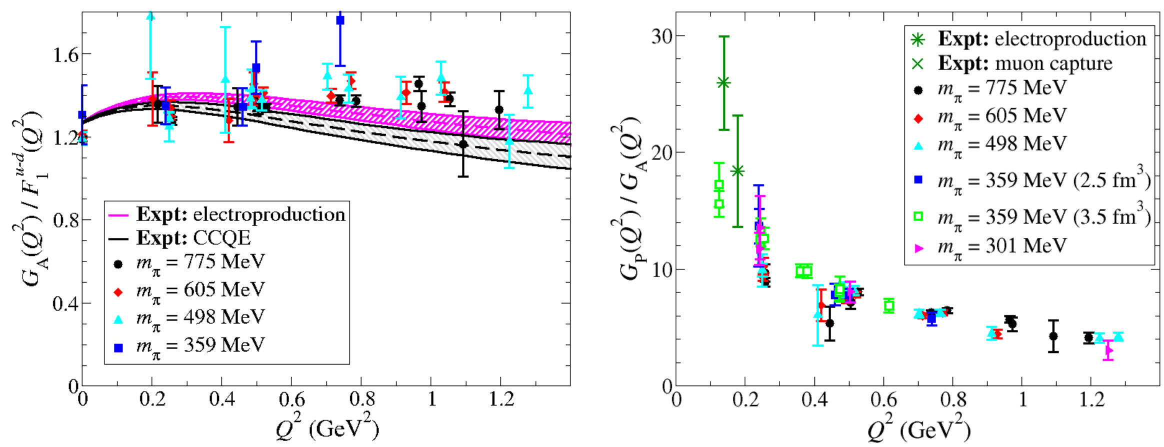

Figure 5: Isovector form factor ratio G_A/F_1 at four masses compared with experiment (left plot) and ratio G_P/G_A at five masses compared with experiment (right plot).

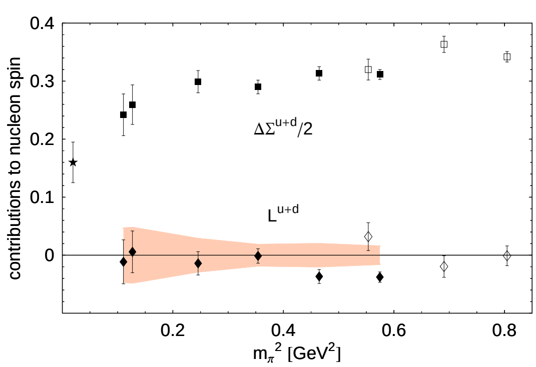

Figure 6: Nucleon spin decomposition. Squares denote $\Delta\Sigma^{u+d}/2$, the star indicates the experimental quark spin contribution, and diamonds denote L^{u+d}.

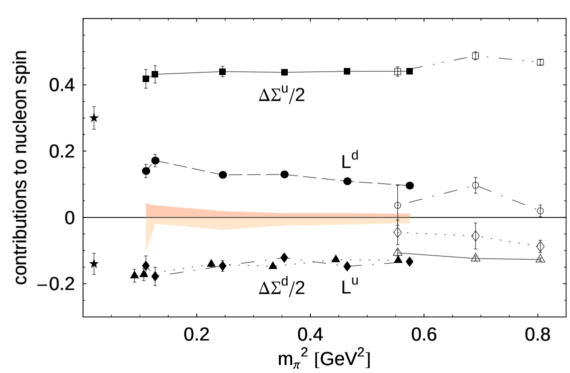

Figure 7: Nucleon spin decomposition by flavor. Squares denote $\Delta\Sigma^u/2$, triangles denote $\Delta\Sigma^d/2$, diamonds denote L^u, and circles denote L^d.

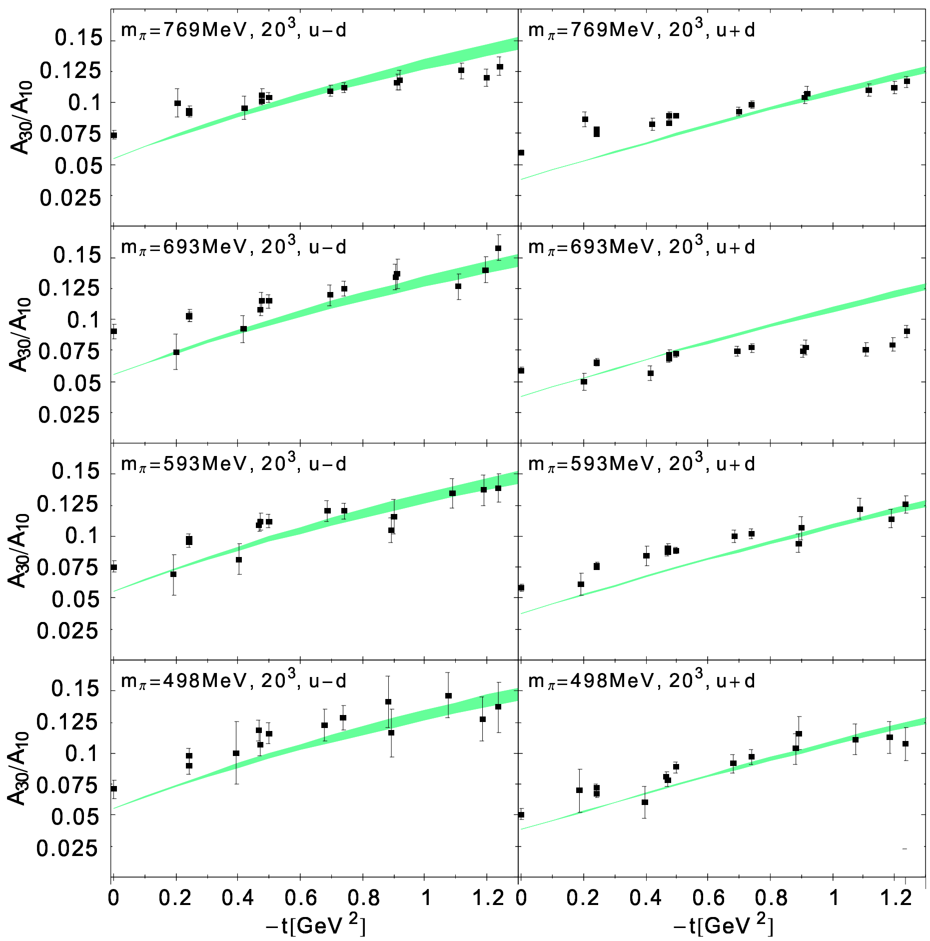

Figure 8: Comparison of the ratio A_{30}/A_{10} for $u-d$ and $u+d$ at four masses with a phenomenological fit to generalized parton distributions.