Illuminating the Origin of the Nucleon Spin

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Introduction

We propose, through a synergy between theory and experiment, to make a fundamental advance in our understanding of the origin of the nucleon spin. In a strategic partnership with Fermilab, we will carry out the world's first measurement of di-lepton production from a polarized proton target bombarded by a high-energy proton beam. LANL will design and construct a new high-luminosity polarized proton target for this measurement. We will also develop state-of-the-art theoretical and computational tools necessary to interpret the experimental results that will directly lead to a major breakthrough in our understanding of the structure of matter and the theory of strong interactions. This project will position our team of experts at LANL to take a leadership role in addressing this most urgent science question for the international spin physics community, which has become a top science priority for the US nuclear physics program [1,2,3]. A successful di-lepton measurement at the end of this LDRD DR project will determine new directions in the field of spin physics for the coming years.

Project Goals

Nucleons (protons and neutrons) are not fundamental constituents of matter, but are instead made up of quarks and gluons, the elementary particles of the strong interaction. There is compelling experimental evidence that the sum of the quark and gluon intrinsic angular momenta only contributes ~1/3 of the total proton spin. Thus, the majority of the proton spin is unaccounted for, which has been referred to as the "proton spin crisis" [4]. The missing fraction of the spin is likely carried by the orbital angular momentum of the quarks and gluons. The long-term goal of this project is to develop the experimental capability to measure the spin of the proton in terms of contributions from the spins of the quarks, gluons and their orbital angular momentum. An equally important goal is to understand the relative significance of these spin contributions in the theory of strong interactions, Quantum Chromodynamics (QCD), and how they manifest themselves in reactions with polarized proton beams and/or targets. To this end, we will determine the momentum distribution of quarks inside the proton, transverse to the proton momentum, from which one can deduce whether quark orbital motion contributes significantly to the proton spin.

To determine the distribution of quarks and gluons within a nucleon, we will carry out the world's first measurement of the production of two simultaneous leptons (electrons or muons) from a polarized proton target bombarded by a high-energy proton beam. From a detailed analysis of the azimuthal distribution of such di-leptons, one can deduce properties of the polarized nucleon structure. In particular, we will measure both the sign and magnitude of the quark Sivers distribution [5], which is expected to be zero if the quarks have no orbital angular momentum. The Sivers function represents the distribution of unpolarized quarks inside a transversely polarized proton, through a correlation between the quark transverse momentum and the proton spin. One of the profound predictions of the theory of the strong interaction is that the Sivers function changes sign when going from Semi-Inclusive Deep Inelastic Scattering (SIDIS) to Drell-Yan (DY) production [6]. While the Sivers asymmetry has been measured in SIDIS [7], our polarized DY experiment will be the first definitive probe of the sign change, an extremely important test of the current theoretical formalism of strong interaction. In order to perform this measurement, a new LANL-designed high-luminosity polarized proton target will be added to the existing E906 di-muon spectrometer at Fermilab.

Interpreting the di-lepton measurement in terms of quark angular momentum requires a concomitant theoretical effort. Deducing the distribution of quarks inside the polarized proton demands knowledge of how this distribution translates into the experimentally observed SIDIS and DY Sivers asymmetries. The quark Sivers distribution is inherently non-perturbative and lattice QCD simulations, which we will perform, are necessary to constrain it from first principles. We will also carry out a program of precise perturbative QCD calculations to relate the quark Sivers distribution to polarized DY experimental observables. We will develop state-of-the-art analytical and computational tools using both perturbative and non-perturbative (lattice) QCD methods, with the goal of constructing a consistent and coherent formalism to describe the polarized DY process. At the end of this project, we will extract the quark Sivers distribution with ~20% theoretical uncertainty.

Background and Statement of Problem

Each atom that makes up everyday matter has a dense nucleus composed of nucleons (protons and neutrons). These nucleons are, in turn, composed of smaller particles called quarks and gluons. These facts are well established, but just how the quarks and gluons act together to give a nucleon its mass and spin is not understood. Spin plays a key role in the determination of the properties of fundamental particles and their interactions. Spin effects have often challenged our understanding of the underlying physics mechanisms of experimental phenomena. Only recently, however, has a strategy emerged of how to determine the individual contribution of quarks, gluons and their orbital angular momentum to the overall nucleon spin [8,9]. Implementing this strategy in a joint experimental and theoretical program will result in a new fundamental test of the theory of strong interactions, Quantum Chromodynamics, which will revolutionize our understanding of the structure of the proton [3,9]. The insight gained from these developments in theory and experiment is essential to construct, for the first time, an accurate 3-dimensional picture of the nucleon in momentum space [9].

Two of the best-known *unpolarized* reactions with nucleons are: (1) particle production from a proton target bombarded with energetic leptons (e, μ), known as Semi-Inclusive Deep Inelastic Scattering and (2) lepton pair production from a proton target bombarded with a pion or a proton beam, known as the Drell-Yan process. In recent years, important progress has been made in SIDIS measurements with *polarized* targets at SLAC, JLab, CERN and DESY [7,10]. These measurements indicate that the sum of the quark spins contributes only ~ 30% of the nucleon spin [10]. The spin program at the Relativistic Heavy Ion Collider (RHIC) has shown that the contribution of the gluon spins to the proton spin is consistent with zero (< 10%) [11]. A physics picture is now emerging, which suggests that the orbital motion of quarks contributes most of the proton spin. The correlation between the proton spin direction and the quark transverse momentum is described by the "quark Sivers distribution" $f^{\perp}_{1T}$ [5]. The Sivers distribution vanishes if the quarks have no orbital angular motion. One of the essential predictions of the theory of strong interactions is that the sign of the quark Sivers distribution must change when going from SIDIS to DY measurements with *polarized* targets: $f^{\perp}_{1T}(DY) = -f^{\perp}_{1T}(SIDIS)$ [6]. *No such DY experiment has ever been performed to test this prediction.*

Our proposed measurement of polarized Drell-Yan production will provide a definitive test of the sign change and determine the magnitude of the quark Sivers distribution. Together with our theoretical developments, which are vital to the interpretation of the experimental data, this work will constitute a significant breakthrough in the physics of strong interactions. A DY Sivers asymmetry with equal magnitude and opposite sign to the one established by SIDIS measurements would be a major triumph of QCD in *polarized* proton reactions. A confirmation of the sign change, but a difference in magnitude, would point to significant unknown corrections to the leading order prediction. A lack of sign change in the measured Sivers asymmetry between the SIDIS and DY polarized target reactions would reveal a fundamental flaw in the current theoretical interpretation of spin phenomena. The outcome of this DR project will thus determine research priorities and directions in the field of spin physics for the coming years.

What sets the quest to understand the origin of the nucleon spin apart from other exciting questions in nuclear and particle physics is that experimental discoveries in this area are expected in the next five years, due to worldwide interest and intense competition [3]. *Now is the opportune time to lead in these discoveries.* Due to the current funding situation, the AnDY experiment [2] at RHIC has been cancelled without a production run, which makes this proposal the only dedicated experimental effort to measure the Drell-Yan Sivers asymmetry in the U.S.

Preliminary studies

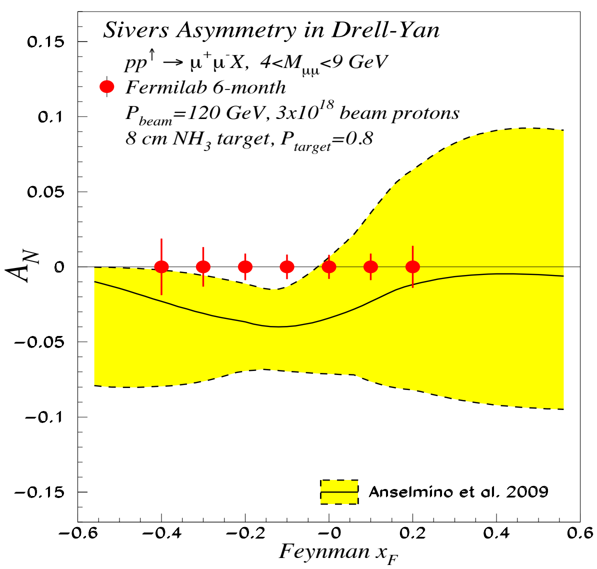


Figure 1. Expected statistical precision of our Sivers asymmetry A_N measurement versus the current huge theoretical uncertainty [12].

The HERMES and COMPASS experiments in Europe and experiments at JLab in the U.S. have measured the asymmetry in polarized SIDIS [7], from which information on the quark Sivers distribution was extracted. Because of the limited experimental kinematic coverage and limited statistics, this distribution remains poorly constrained. By reversing its sign, we can predict the asymmetry for polarized DY production, defined as $A_N = (\sigma^{\uparrow}-\sigma^{\downarrow})/(\sigma^{\uparrow}+\sigma^{\downarrow})$. Here, $\sigma^{\uparrow}$and $\sigma^{\downarrow}$ represent cross section measurements with opposite target polarization. The current theoretical expectation for Fermilab's E906 planned kinematic coverage is given by the yellow band in Figure 1. The uncertainty in these predictions is huge, especially at large Feynman x_F (defined as the ratio of the di-lepton pair longitudinal momentum to the center-of-mass energy). The red error bars are a simulation of the expected statistical precision of our experimental A_N measurement at the end of this DR project: a 6-month run at Fermilab will deliver $3\text{x}10^{18}$ protons on a 8 cm long solid NH_3 target, with an average polarization of 80%. Approximately 1.5 x 10^6 total Drell-Yan events will be recorded, which results in a ~1% error in A_N for the central x_F bins, as shown in Figure 1.

In summary, our preliminary studies indicate that we can determine the quark Sivers distribution with much better accuracy than previous SIDIS experiments. Our proposed polarized DY measurement, due to its high integrated luminosity and ideal kinematic coverage, will pinpoint the sign and magnitude of the Sivers asymmetry. In the intermediate x_F region we will definitively test the sign change paradigm between SIDIS and DY.

Proposed Innovation and Significance

Technical impact

In recent years, transverse spin experiments have become a focal point in high-energy nuclear physics. Transverse single-spin Sivers asymmetry measurements are currently planned for SIDIS experiments at Jefferson Lab [13] and for Drell-Yan experiments at BNL [14] and at CERN [15]. The JLab experiments will take data from 2015 through 2020 and will only be able to determine the valence quark Sivers distributions, due to the low 12 GeV electron beam energy. At RHIC, polarized Drell-Yan measurements from proton-proton collision at 510 GeV are an ultimate goal for both the STAR and PHENIX experiments. However, the collider's beam luminosity of ~6×10^{31} cm^{-2} s^{-1} will severely limit their precision. Also, the earliest possible transversely polarized Drell-Yan data from RHIC will only be available after 2016. *Thus, for the near future, our DR project would be the only viable polarized Drell-Yan measurement in the U.S.*

The main competitor of our project is the pion-induced polarized Drell-Yan di-muon experiment planned by the COMPASS II Collaboration at CERN [15]. Their measurement will be dominated by the valence quark Sivers distribution in the proton, but benefits from the valence anti-quark in the pion beam. However, their π^- flux can only reach 6×10^7 per second, thus limiting the ultimate precision. COMPASS II will collect data from 2014 to 2016. Our proposed DY measurement has better statistics and larger kinematical coverage, allowing the separation of valence and sea quark contributions to the Sivers distribution. This DR project will allow us to collect ~ 1.5×10^6 total DY events, or roughly 5 times that of COMPASS II in the region of 4 < mass < 9 GeV/c^2.

Besides breaking new physics ground, our project will advance the state-of-the-art in high luminosity polarized proton targets. Working together with experts from the University of Virginia, we will design and construct the world's highest luminosity target using polarized frozen ammonia (NH_3). This target would also be very useful for future experiments at Jefferson Lab and J-PARC. A reconfigured target with longitudinal polarization would be the cornerstone for double spin asymmetry measurements at FNAL, if the Main Injector beam is polarized, as has been proposed. Since our target will also be able to polarize ND_3, one could extend the spin physics program to include polarized neutrons. *We expect LANL to become one of the leaders in polarized target physics and technology in the U.S.*

Our effort to successfully interpret the experimental data in terms of the quark Sivers distributions in the proton will stimulate, and indeed require, a number of concurrent theoretical advances. The most striking existing prediction for the polarized SIDIS and DY experiments lies in the opposite sign of the Sivers function extracted from each of the two processes [6]. This means that $f^{\perp}_{1T}(DY) = -f^{\perp}_{1T}(SIDIS)$ for each individual quark flavor, *if compared at the same energy scale*. The two results that need to be established by the experimental data are (1) the sign change and (2) the equality of the magnitude. Our theoretical efforts will be focused on making these determinations possible, since the current SIDIS experiments typically were performed at relatively low energy (Q^2~2-3 GeV^2), while the expected DY experiments will cover the high-energy region (Q^2~16–81 GeV^2). In order to compare the Sivers function at the same energy scale, we will develop the relevant energy evolution equations.

To derive the evolution equations with the required accuracy, we will apply both the traditional perturbative QCD (pQCD) and effective field theory (EFT) approaches. In the pQCD framework, initial efforts have already produced results to leading-logarithmic (LL) accuracy [16,17]. On the other hand, applications of EFT methods to high-energy cross sections in QCD have led to impressive improvements in theoretical precision, in some cases achieving next-to-next-to-next-to-leading-logarithmic (N^3LL) accuracy (typically an order of magnitude greater precision than LL). However, EFT has not yet been applied to spin phenomena. We will develop, for the first time, this framework. We will also incorporate the results of our lattice QCD simulation effort in the theoretical analysis to enhance the precision with which we will extract the quark Sivers distribution. This combined effort will pioneer the use of EFT and lattice QCD for a wide variety of spin physics phenomena.

Mission impact

The proposed work is central to the FY13 LDRD Strategic Investment Plan of the Beyond the Standard Model category. Building upon our existing strategic partnership with Fermilab (E906, MiniBoone and LBNE), this project will strengthen our fundamental science capabilities, bring new high-luminosity polarized target technology to LANL and provide a “major physics thrust to follow current commitments to RHIC”. This project will maintain LANL’s leadership position in the field of spin physics and produce the world’s most accurate polarized Drell-Yan measurement in proton-proton reactions. Our proposal is a timely and direct response to the DOE Milestone (HP13) to “test unique QCD predictions for relations between single-spin phenomena in p-p scattering and those observed in deep-inelastic scattering” [3]. We anticipate that this LDRD project will result in DOE Office of Science funding for a LANL-led spin physics program at Fermilab. Our integrated experimental and theoretical program will allow us to lead in a major advance in understanding the polarized nucleon structure through the only U.S.-based dedicated polarized DY experiment. Providing a polarized target to FNAL will greatly enhance Fermilab’s capabilities and provide a much needed user facility for spin physics. Our target will also be able to polarize ND_3, thus enabling one to extend the spin physics to polarized neutrons. Furthermore, developing and testing particle detector technology at high luminosity will directly benefit MaRIE, a LANL institutional priority.

R&D Methods and Anticipated Results

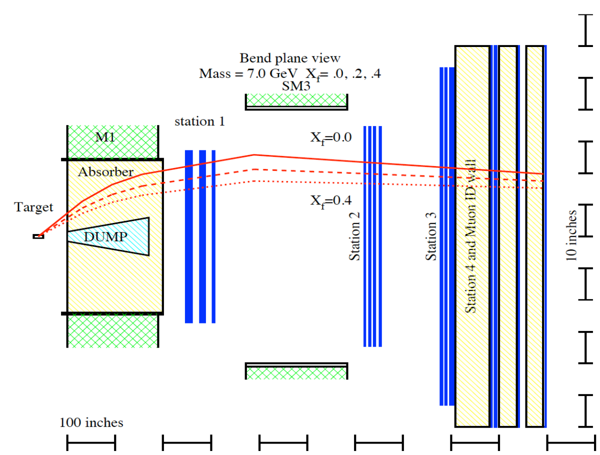


Figure 2. A top view of the E906 setup, showing one muon (red) from a Drell-Yan pair, the target, beam dump, absorber, two analyzing dipole magnets (green), and four tracking stations. A polarized NH_3 target will replace the existing E906 targets.

Methods

Experiment: Our team will design the proposed experiment based upon the existing E906 spectrometer at Fermilab. We plan to replace the unpolarized E906 targets with a LANL-built transversely polarized proton target (NH_3) and carry out the first fixed-target polarized Drell-Yan measurement in the U.S. Figure 2 shows the E906 experimental setup, which had its test run in early 2012 and will continue to take data during 2013-2014 on ^1H and ^2D targets. Once our team has built and installed the polarized target at FNAL, we expect to take data in 2015.

The hardware effort supported by this DR includes the design, manufacture and installation of a new polarized target, which can handle the expected beam flux of 10^{13} protons in a 5 sec spill, once per minute, from FNAL’s Main Injector. This target will use Dynamic Nuclear Polarization (DNP) [18] and is shown schematically in Figure 3. While the magnetic moment of the proton is too small to lead to a sizable polarization in a 5 Tesla (T) magnetic field through the Zeeman effect, electrons in that field at 1°K are better than 92% polarized. By doping a suitable solid target material with paramagnetic radicals to provide unpaired electron spins, one can make use of the highly polarized state of the electrons. The dipole-dipole interaction between the nucleon and the electron leads to hyperfine splitting, providing the coupling between the two spin species. By applying a suitable microwave signal, one can populate the desired spin states. We will use frozen ammonia (NH_3) as the target material and create the paramagnetic radicals (roughly 10^{19} spins/ml) through irradiation with a high intensity electron beam at NIST.

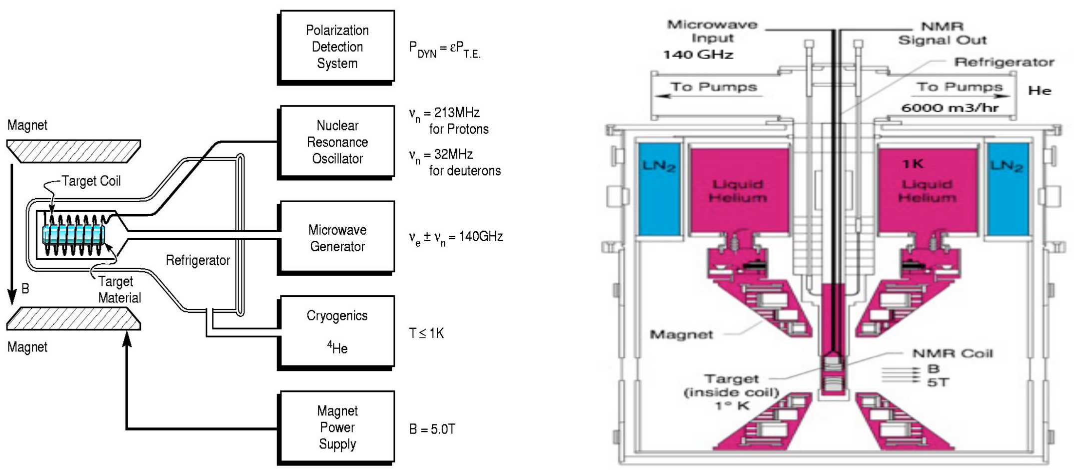


Figure 3. Left panel: schematic of the polarized target system and supporting infrastructure. Right panel: detailed view of the experiment with beam direction into the page.

The most expensive component in any polarized target system is the superconducting magnet. Fortunately, we have identified an existing 5 T magnet, built by Oxford Instruments U.K., which was used in a previous experiment at LANL. This magnet was designed for longitudinal polarization (relative to the beam) and our experiment requires transverse polarization. Oxford will rotate the coils to the transverse direction and re-mount them. They will also check the integrity of all the coils and repair any possible problems resulting from many years of disuse.

Two of us (A. Klein, X. Jiang) have previously built cryogenic ^{3}He targets, which operated using the same principles as our proposed new target. Our collaborators at UVa have agreed to rebuild an existing cryogenic refrigerator, which works on the principle of liquid ^{4}He evaporation and can cool the bath down to 1°K through pumping on the ^{4}He vapor. UVa scientists have built many polarized targets over the last two decades and are world experts on such DNP targets.

In parallel, our team will design and build the new target cell, microwave system and Nuclear Magnetic Resonance (NMR) system used to measure the polarization, as shown Fig. 3. The microwave system is used to induce the spin flip transition. The NMR coils, placed inside the microwave cavity, can determine the proton polarization to an accuracy of ~ +/- 2%. The polarization achieved with such a target is better than 92% [19]. Once we have received the refrigerator from UVa and the magnet back from Oxford, we will integrate the target cell into the cryostat and start testing the system at LANL. When we have demonstrated that the required polarization is achieved, we will ship the target to FNAL to be installed in the E906 experiment.

Theory: The theory needed to interpret the experimental data relies on calculating the matrix elements of operators that describe interactions with a quark inside a proton. In this DR, we are specifically interested in quarks with non-zero momentum transverse to the direction of motion of the proton. The building blocks of the non-perturbative analysis leading to the determination of the Sivers function are lattice QCD calculations, such as the ones already being done by Gupta to evaluate the scalar and tensor charges of the proton [20]. The characteristics of the Sivers function, however, require new developments. First, the new matrix elements have to probe distributions in momentum space, while lattice calculations are done in position space. A straightforward Fourier transform is insufficient and has to be supplemented by taking suitable moments. Second, the composite quark, anti-quark and gluon operator is non-local. Such operators are poorly understood in existing theoretical and numerical work. Third, the existing calculations have neglected contributions arising from spontaneous quark-antiquark pair creation, which is a result of quantum fluctuations of the proton state. Lastly, while one can ascertain the change in sign of the Sivers function between SIDIS and DY from these matrix elements, the amount that the orbital angular momentum contributes to the proton spin has not been analyzed. In the proposed work, we will address these issues in collaboration with M. Engelhardt at NMSU, who has done the first preliminary calculation [21]. Obtaining moments of the quark Sivers distribution to 50% accuracy via realistic lattice QCD simulations that include vacuum fluctuations will be a major step forward in this field.

The perturbative QCD formalism for evaluating polarized SIDIS and DY cross sections is now at the level of leading-logarithmic accuracy [16,17]. We will use both traditional perturbative QCD techniques and effective field theory to achieve an accuracy of at least next-to-leading logarithmic (NLL) level for the Sivers asymmetry in both polarized SIDIS and DY production. The pQCD and EFT approaches are complementary and will serve as cross-checks of each other. We will use them together to make the most precise predictions for the Sivers spin physics observables.

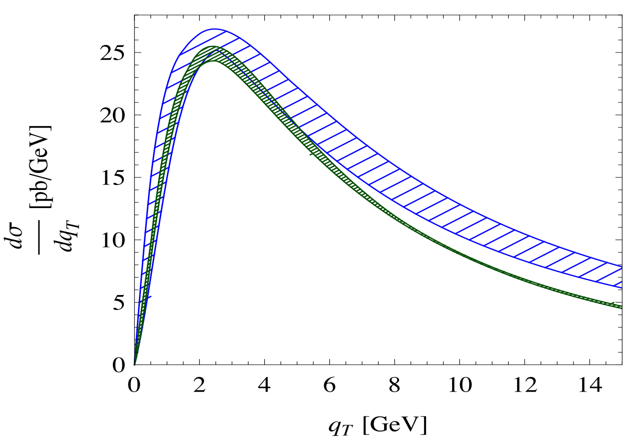


Figure 4: Resummed predictions for unpolarized Drell-Yan cross sections using SCET [23]. The distribution of the lepton pairs created in proton-antiproton collisions at the Tevatron versus transverse momentum q_T, at NLL (wide blue band) and NNLL (narrow green band) accuracy are shown.

In recent years, the modern tools of effective field theory have made possible vast improvements in the precision and reliability of predictions for many QCD cross sections. Soft Collinear Effective Theory (SCET) [22] organizes the effects of multiple quark and gluon emissions from the incoming proton beams or the energetic outgoing particles in high-energy reactions in a systematic power expansion. This radiation makes large contributions to the cross section that must be resumed. SCET provides elegant tools for this resummation and yields precise predictions for physics observables. SCET techniques are especially relevant when large ratios of energy scales appear, such as in Drell-Yan production, where the transverse momentum of the lepton pair q_T is much smaller than the collision energy. A convincing example is shown in Figure 4, where for the *unpolarized*

DY cross sections the theoretical uncertainties have been reduced from the 20-30% level (NLL, shown by the blue band) down to the 5-10% level at next-to-next-to-leading logarithmic (NNLL, shown by the green band) accuracy [23].

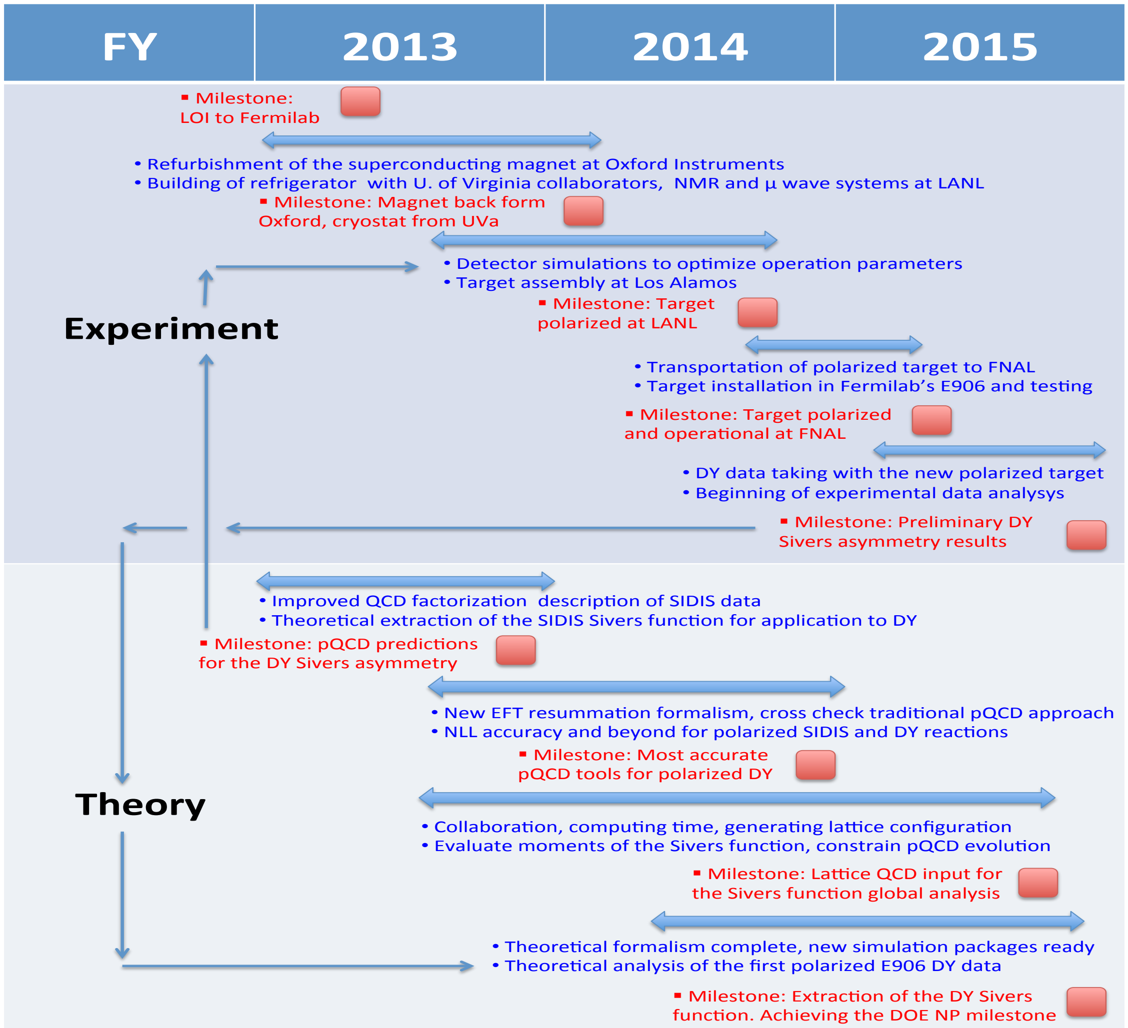
An important theoretical goal of our project is to develop equations that describe the evolution of the quark Sivers distribution between different energy scales. Recently, a definition of transverse momentum-dependent parton distributions has been provided by SCET [24], which leads to simple and elegant energy evolution equations. This definition appears to be most convenient for achieving higher-order resummation accuracy in calculations that involve the transverse momentum-dependent distributions. We will apply this new technology to the Sivers function (which is one particular transverse momentum-dependent distribution) and develop a consistent theoretical framework for the evaluation of the *polarized* SIDIS and DY cross sections. We expect that we will be able to reduce the theoretical uncertainties in our predictions in similar relative steps, as illustrated in Figure 4.

Expected results

Experiment: We will build a new polarized proton target, which will be able to handle the highest luminosity in the world. While this system will use an existing superconducting magnet, our experiment requires a different field geometry, an improvement of the cryostat and construction of new NMR and microwave systems. Due to the versatile nature of this target, we will also be able to provide a polarized ^{2}D target for the development of a neutron spin program. The expected statistical precision of our measurement of the Sivers asymmetry is shown in Figure 1. The yellow band represents the current huge theoretical uncertainty [12]. Our measurement will definitively determine the sign and magnitude of A_N in a 6-month run, with better precision than the COMPASS II experiment [15] over a wider kinematic range. Our experimental data, with statistical errors of ~1%, will provide the first information on the dependence of Sivers asymmetry on the momentum of the di-lepton pair. Specifically, we expect to be able to extract both the valence quark and sea quark Sivers distributions. With an anticipated additional beam time of ~12 months, supported by DOE NP, we could achieve statistical errors approaching 0.5% and expand the Feynman x_F coverage, further constraining the theoretical models.

Theory: To interpret the experimental data, we will first derive a consistent and coherent QCD formalism for evaluating the polarized SIDIS and DY reactions to sufficient theoretical precision (5%-10% level). Then, we will use these new theoretical tools to interpret the existing polarized SIDIS data, validate our approach and accurately extract the Sivers function at the energy scale where the SIDIS experiments were performed. We will evolve the Sivers function to the relevant energy scale for our proposed DY experiment and make a precise prediction for the DY Sivers asymmetry. This will guide our experiment toward the correct kinematic region for observing the largest initial asymmetry, in order to establish the sign change as quickly as possible. To confirm the sign change, theoretical uncertainties at the ~50% level will be more than sufficient. Finally, combining perturbative QCD techniques with input from lattice QCD, we will examine the new DY data to verify or refute the cornerstone prediction of the theory of strong interactions for the sign and magnitude of the Sivers function: $f^{\perp}_{1T}(DY) = -f^{\perp}_{1T}(SIDIS)$. With our high luminosity fixed-target DY experiment at Fermilab, we expect to establish the equality of the magnitude of the Sivers function to ~20% or better, which is the present accuracy of the unpolarized parton distribution functions [25]. Accomplishing this goal would complete an important DOE Nuclear Physics milestone (HP13) [3], with which our project is well aligned.

Project plan



Data management plan

This project will produce a significant amount of both simulated and real data. Currently, at E906 we are collecting events at 1 KHz from all subsystems, producing 3~5 TB of raw data on disk during one year of operation. For a polarized DY run, we expect a similar data volume. The raw data and the processed physics events will be archived at the Fermilab Computing Facility and distributed to users at LANL for final data analysis. A similar amount of simulation data (~ 5 TB) will be generated and stored together with the real physics events at LANL. Our lattice QCD data will be stored at National Computing Centers and made available to the community.

Transition plan

A successful DR project will bring new world-class capabilities to the LANL Nuclear Physics program: (1) the world's highest-luminosity polarized target, (2) a program for polarized DY measurements of unsurpassed precision to probe the nucleon spin structure and (3) state-of-the-art theoretical tools for data interpretation. We expect to continue recording polarized DY data at Fermilab for a few additional years with DOE funding, in order to cover an even larger kinematic range with improved accuracy. We also plan to extend our spin program to include polarized neutrons. Our model for transition to DOE funding is based upon the E906 experiment at FNAL and the FVTX detector at BNL, both of which began as LANL LDRD projects and evolved into major national efforts funded by the DOE NP program.

During this DR project we will work closely with Fermilab, LANL and DOE NP program managers to develop a long-term national polarized DY spin physics program, using our polarized proton target and possibly a new polarized proton beam from Fermilab's Main Injector. Corresponding theoretical efforts will also continue through support from DOE's NP program office. This program will allow us to identify and attract exceptional young staff to LANL and to expand our effort in this key area of nuclear science.

Budget Request

Our requested budget is: FY13 $1.975M, FY14 $1.775M, FY15 $1.675M. The PI I. Vitev and Co-PI A. Klein will commit 40% of their time to this project (0.4FTE). Co-investigators will be supported at the following fractions: R. Gupta (0.3FTE), X. Jiang (0.4FTE), C. Lee (0.25FTE), M. Liu (0.2FTE), P. McGaughey (0.2FTE). We will need a technician's assistance, R. Mortensen (0.5FTE). We plan to have a theoretical postdoc (Z. Kang, G. Ovanesyan) and an experimental (M. Durham) postdoc (up to 1 PD each). LDRD DR participants will lead important parts of this project that overlap with their primary area of expertise (see Appendix).

Special FY13 budget justification: Due to the complexity of the experimental apparatus, we need to procure components of the polarized target system in FY13. This will allow us to assemble and test the new polarized target in FY14 and have a polarized DY run in FY15. We request additional $175K in FY13 above the $1.8M limit as part of the $750K capital equipment funds. We make up for this additional request by having no significant equipment costs in FY15.

Subsection on financial justification

We request $750K in FY13 for capital equipment. This will be used to acquire the main components of the polarized target. Oxford Instruments will modify the LANL superconducting magnet for transverse geometry ($100K). In addition, we will need to buy a large pumping system capable of pumping 6000 m^3/hr of He at a cost of $150K. The components for the NMR system (120K$) will also be purchased in FY13. We will need vacuum pumps, a magnet power supply, compressor and vacuum supplies at a total cost of 150K$. Our collaborators at UVa will provide the microwave tube necessary to induce the electron and proton spin-flip ($170K). We are asking for $90K of M&S in the first year. Most of this amount is necessary to pay for beam time at NIST to irradiate the ammonia, where the cost for the beam time alone is $60K. We will also need funds to cover travel to NIST, as well as travel to UVa and to Oxford, UK. This M&S will also pay for the shipping of the magnet to the manufacturer. In FY14 we will need $380K of M&S to pay for the refurbished refrigerator from UVa ($150K) and related equipment ($30K). We plan for five complete cool downs and system tests of the system in that year, requiring 5 dewars of liquid Helium at a total cost of $40K. We will also have to pay for shipment of the system to Fermilab. Finally, we will complete the production of the ammonia target cell. For FY15 we request $200K of M&S. This will cover data storage, travel costs to Fermilab and additional Helium for the system tests at FNAL. We expect to have a postdoc and at least one staff member from Los Alamos at Fermilab at any given time. We have built a 10% contingency into all of our capital equipment and M&S cost estimates.

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20) T. Bhattacharya et al., Phys. Rev. D85 054512 (2012)
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23) I. Stewart *et al.*, Phys. Rev. Lett. 106, 032001 (2011); T. Becher *et al.*, JHEP 1202, 124 (2012)
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BIOGRAPHICAL SKETCH Dr. Ivan Vitev, PI

Group T-2, MS B283, T-Division *Phone:* 5-8066; *E-mail:* ivitev@lanl.gov

Education and Training

- B.S. M.S. in Th. Particle and Nuclear Physics, Sofia U., Sofia, Bulgaria, 1990-1995
- Ph.D. in Theoretical Nuclear Physics, Columbia University, New York, NY, 2000-2002
- Post Doctoral Fellow, Theoretical Nuclear Physics, ISU, Ames, IA, 2002-2004

Professional Experience

- J. Robert Oppenheimer Fellow (tenure track), Theoretical and Physics Divisions - Group T-16 and Group P-25, LANL, 2004-2007
- Staff Scientist, Theoretical Division, Group T-2, LANL, 2007-present

Awards and Service

- Awards: Presidential Early Career Award for Scientists and Engineers (PECASE) 2009, J. Robert Oppenheimer Fellowship 2004-2009, Eureka Foundation Fellowship 1997, Sofia University Fellowship,1990-1995
- Grant review: DOE NT2006 – present, NSF 2009 – present; Reviewer for 10 journals

Primary Areas of Expertise

- Perturbative QCD calculations of hard processes (leading hadrons, heavy flavor, electromagnetic probes, and jets); Drell-Yan and next-to-leading order calculations; many-body nuclear dynamics at collider energies; fixed target, RHIC and LHC physics
- 3,800+ citations; 70+ papers; twenty (20) letters 130+ invited talks, seminars, colloquia

BIOGRAPHICAL SKETCH Dr. Andreas Klein, Co-PI

Group P-23, MS H803, P-Division *Phone:* 7-8990; *E-mail:* aklein@lanl.gov

Education and Training

- Diploma in Experimental Physics, University of Basel, Switzerland ,1986
- Ph.D. in Experimental Nuclear Physics, University of Basel, Switzerland ,1986

Professional Experience

- Director's Postdoctoral Appointment, LANL, 1986-1988
- Post Doctoral Fellow, NMSU 1988-1990
- Professor of Physics, Old Dominion University 1990-2004
- Staff Member P-23 2002 - present

Awards and Service

- Reviewer for NSF and DOE Nuclear Physics
- Spokesperson for polarized target experiments at LAMPF and PSI
- Spokesperson for Experiments at JLAB
- Co-author of 230+ publications
- Author of Book on Computational Physics
- Designed and built Hall C SOS Hodoscopes, Hall B region 2 Drift chambers

Research History:

- Pion scattering and absorption on polarized targets, electron scattering on polarized and unpolarized targets, detector development.

BIOGRAPHICAL SKETCH **Dr. Rajan Gupta**

Phone: 505-667-7664; Email: rajan@lanl.gov Theoretical Division, T-2, MS B285, LANL

Education

- University of Delhi, Delhi, India Physics M.Sc. 1975
- California Institute of Technology Theoretical Physics Ph.D. 1982

Employment:

2006 – Present Laboratory Fellow, Los Alamos National Laboratory
1988 – 2006: Staff Scientist, Theoretical Division, Los Alamos National Laboratory
1985 – 1988: J. Robert Oppenheimer Fellow, Los Alamos National Laboratory
1983 – 1986 Honorary Postdoctoral Fellowship, Harvard University

Selected Awards and Honors

2006 Elected Fellow of LANL; 1999 Distinguished Performance Award, LANL;
1994 Elected APS Fellow; 1970-75 National Science Talent Scholarship, India

Publications

Author or coauthor of more than 125 research papers in high energy physics, lattice QCD, statistical mechanics, computational biology, parallel computing, education, and public health. Thirteen TOPCITE with 100+ publications, H index 36; contributed review articles in 7 books.

Scientific Leadership:

Leader of LANL lattice QCD effort since 1985; Co-leader of HotQCD; Division associate editor for PRL; PI for DOE Grand Challenges Computer allocations 1988-2001; HPC at Los Alamos.

BIOGRAPHICAL SKETCH **Dr. Xiaodong Jiang**

Phone (505) 606-0437, Email: xjiang@lanl.gov Physics Division, P-25, MS H846, LANL

Education:

- B.S. in physics. University of Science and Technology of China (1988).
- Ph.D. Experimental Nuclear Physics, University of Massachusetts at Amherst (1998).

Employment:

- Staff Member, LANL Physics Division, P-25 group, 2007-present.
- Research Scientist, Rutgers University, and at TJNAF, 1999-2007.
- Postdoc Research Associate, Rutgers University, 1998-1999.

Award:

Peter Demos award of best Ph.D. thesis. MIT Bates Linear Accelerator Center (1998).

Scientific and Project Roles:

Expert in nucleon spin experiments using polarized targets. Co-spokesperson of the most recent polarized target DIS experiment in US (JLab E06-010), which made the first Sivers asymmetry measurement on a polarized neutron target (^{3}He). Co-spokesperson of nine nuclear physics experiments at JLab, including polarized target experiments: E06-010 (“Neutron Transversity”), E06-014 (“Neutron d_{2n}”), E07-013 (“DIS-SSA”), E05-015 (“Quasi-elastic A_y”), E07-011 (“Deuteron g_{1d}”) and E10-006 (“SoLID-Transversity”).

Recent publications on nucleon spin physics:

X. Jiang, Nuovo Cimento, 333, 35(2012); J. Huang, … X. Jiang … et al., Phys. Rev. Lett. 108, 052001 (2012); X. Qian … X. Jiang … et al., Phys. Rev. Lett. 107:072003, 2011.

BIOGRAPHICAL SKETCH **Dr. Zhongbo Kang**

Phone (505) 664-0580, Email: zkang@lanl.gov Theoretical Division, T-2, MS B283, LANL

Education:

- B.S., Physics, Central China Normal University, Wuhan, China 2001
- M.S., Theoretical Physics, Central China Normal University, Wuhan, China 2003
- Ph.D., Theoretical Nuclear Physics, Iowa State University, 2009

Employment:

- Director's Postdoctoral Fellow, Los Alamos National Laboratory, 2012-present
- Research Associate, Brookhaven National Laboratory, 2009-2012

Awards and Service:

Director's Postdoctoral Fellowship, Los Alamos National Laboratory, 2012-present

Named one of the most valued reviewers, Nuclear Physics A, 2012

G. W. Fox Memorial Award for excellence in research, Iowa State University, 2009

Peer Reviewer for Physics Review Letters, Physical Review C, Physical Review D, Nuclear Physics A, Journal of Physics G, New Journal of Physics

Research History:

Perturbative QCD calculations of hard processes, Spin physics, Polarized Drell-Yan and Resummation, Sivers effect, QCD evolution equations and global analysis

525+ citations; 35+ papers, 5 Physics Review Letters, 50+ invited talks at workshops and conferences, seminars, and colloquia.

BIOGRAPHICAL SKETCH **Dr. Christopher Lee**

Phone (505) 665-0965, Email: clee@lanl.gov Theoretical Division, T-2, MS B283, LANL

Education:

- B.A., Mathematics-Physics, Reed College, Portland, OR, 2000, Barry M. Goldwater Scholarship in Science and Engineering, 1998-2000 Phi Beta Kappa, 2000
- Ph.D., Physics, California Institute of Technology, Pasadena, CA, 2005, NSF Graduate Fellowship, 2000-01, NDSE Graduate Fellowship, 2001-04

Employment:

Postdoctoral Research Associate, INT, University of Washington, Seattle, WA, 2005-2007

Postdoctoral Scholar in Theoretical Physics, UC, Berkeley, and LBNL, 2007-2010

Senior Postdoctoral Associate, Center for Theoretical Physics, MIT, Cambridge, MA, 2010-2012

Staff Scientist, Theoretical Division, T-2, Los Alamos National Laboratory, 2012-present

Awards and Service:

Organizer, Boston Jet Physics Workshop, Harvard University, 2011

Peer Reviewer for Physical Review D, Physics Letters B, JHEP, 2008-present

Leroy Apker Award, Finalist, American Physical Society, 2000

Founding President, Reed College Chapter of Society of Physics Students; SPS Leadership Scholarship, 1999

Research History:

Effective Field Theories for Quantum Chromodynamics, Resummed Perturbative Predictions for Hadronic Jet Cross Sections in High-Energy Collisions

15 refereed publications, 400 citations, 55+ invited talks at workshops and conferences, seminars, and colloquia.

BIOGRAPHICAL SKETCH **Dr. Ming Xiong Liu**

Phone (505) 667-7125, Email: mliu@lanl.gov P-25, MS H846, Physics Division, LANL

Education:

- Ph.D, High Energy Physics, Yale University, *1997*

Awards:

- Norman R. M. Blatherwick Fellowship: *1995*;
- J. Sloan Fellowship: *1997*

Research History and Area of Expertise

- Experimental study of QCD and electroweak physics, spin physics with polarized high-energy beams, nucleon and nucleus structure physics.
- 15+ years experience in design, construction and operation of large experiments, including the PHENIX muon trackers and silicon vertex detectors at BNL, muon identification detectors for E906 experiment at Fermilab. Lead several major high energy nuclear physics experimental projects at SLAC, BNL and FNAL.
- Collider physics phenomenology and simulations.
- DOE Nuclear Physics grants reviewer; over 250 publications, 50+ in Phys. Rev. Lett.

Selected recent publications relevant to this proposal

Les Bland, Stanley J. Brodsky, Gerry Bunce, **Ming Liu**, Matthias Grosse-Perdekamp, Akio Ogawa, Werner Vogelsang, Feng Yuan, RHIC-SPIN 2007 whitepaper; **M. X. Liu**, X. Jiang, D. G. Crabb, J.P. Chen, M. Bai, arXiv:1012.2051.H. Gao, **M.X. Liu** … *et al,*”, Eur.Phys.J.Plus 126:2,2011.

BIOGRAPHICAL SKETCH **Dr. Patrick L. McGaughey**

Phone (505) 667-1594, Email: plm@lanl.gov Physics Division, P-25, MS H846, LANL

Education:

B.A. (Magna Cum Laude), Physics + Chemistry Majors, Augsburg College 1977

Undergraduate scholarships from State of MN and Augsburg College 1973-77

Ph.D., Nuclear Chemistry/Physics, University of California, Berkeley CA, 1982

Graduate Student of Glenn T. Seaborg - Nobel Prize Winner

Employment:

Director's Postdoctoral Appointment, LANL, 1982-1984

Staff Member in Physics Division, 1984-present

Awards / Achievements:

Floor Manager for E772 Experiment at Fermilab, 1987-88

Co-designer of PHENIX Experiment, 1991-94 and PHENIX FVTX Detector, 2001-2011

Spokesman for E866 Experiment at Fermilab, 1995-1998

Fellow of American Physical Society, 1998

Principal Investigator for LANL LDRD ER and DR Grants, 2001-2007

Co-author of 250+ publications, with 15,000+ citations and 82 highly-cited papers

Research History:

Anti-proton annihilations in Nuclei, Relativistic Heavy Ion Reactions, Drell-Yan Reactions in Nuclei, Heavy Quark Production in Nuclei, Cosmic-ray Muon Tomography

BIOGRAPHICAL SKETCH **Dr. Grigory Ovanesyan**

Group T-2, MS B283, T-Division *Phone:* 7-0174; *E-mail:* ovanesyan@lanl.gov

Education and Training

- B.S. and M.S., Moscow Institute of Phys. and Tech., Moscow region, Russia, 1999-2005
- Ph.D. in Theoretical Particle Physics, UC Berkeley, Berkeley, CA, 2005-2010

Professional Experience

- Postdoctoral Research Associate, Group T-2, Los Alamos, NM, 2010-present

Awards and Service

- II International Competition in Mathematics, Gold Medal, Konya, Turkey, 1998
- XXX International Physics Olympiad (IPHO), Silver Medal, Padova, Italy, 1999
- Presidential award of Republic of Georgia, Tbilisi, Georgia, 1997, 1998 and 2000
- Stipend from Dynasty Foundation: ”We-the future of Russian Fundamental Science”, Moscow, Russia, 2003-2005
- Stipend from Landau Institute for Theoretical Physics, Moscow, Russia, 2003
- Telegdi award, Moscow, Russia, 2004
- Peer review: Referee for Physical Review D

Primary Areas of Expertise

- Effective field theories for jets in lepton and hadron colliders. Soft collinear effective theory. Effective theories for jets in medium.
- 99 citations; 13 papers; four (4) letters (Phys. Lett. B), 20+ invited talks, seminars