P-1039

Letter of Intent for a Drell-Yan experiment with a polarized proton target

Co-Spokespersons: A. Klein, X. Jiang, Los Alamos National Laboratory

List of Collaborators:

D. Geesaman, P. Reimer
Argonne National Laboratory, Argonne, IL 60439
C. Brown , D. Christian
Fermi National Accelerator Laboratory, Batavia IL 60510
M. Diefenthaler, J.-C. Peng
University of Illinois, Urbana, IL 61081
W.-C. Chang, Y.-C. Chen
Institute of Physics, Academia Sinica, Taiwan
S. Sawada
KEK, Tsukuba, Ibaraki 305-0801, Japan
T.-H. Chang
Ling-Tung University, Taiwan
J. Huang, X. Jiang, M. Leitch, A. Klein, K. Liu, M. Liu, P. McGaughey
Los Alamos National Laboratory, Los Alamos, NM 87545
E. Beise, K. Nakahara
University of Maryland, College Park, MD 20742
C. Aidala, W. Lorenzon, R. Raymond
University of Michigan, Ann Arbor, MI 48109-1040
T. Badman, E. Long, K. Slifer, R. Zielinski
University of New Hampshire, Durham, NH 03824
R.-S. Guo
National Kaohsiung Normal University, Taiwan
Y. Goto
RIKEN, Wako, Saitama 351-01, Japan
L. El Fassi, K. Myers, R. Ransome, A. Tadepalli, B. Tice
Rutgers University, Rutgers NJ 08544
J.-P. Chen
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606
K. Nakano, T.-A. Shibata
Tokyo Institute of Technology, Tokyo 152-8551, Japan
D. Crabb, D. Day, D. Keller, O. Rondon
University of Virginia, Charlottesville, VA 22904

1. Physics motivation

It is well known that the proton is a spin-1/2 particle, but how the constituents (quarks and gluons) assemble to this quantized spin is still a mystery. There is a worldwide effort to map out the individual contributions to the proton spin [1,2]. It is established that the quark spins contribute around 30%, while the gluon intrinsic angular momentum is still under active investigation at the Relativistic Heavy Ion Collider [3]. Fully resolving the proton spin puzzle requires information on the orbital angular momentum (OAM) of both quarks and gluons. Recent studies have shown that the so-called transverse momentum dependent parton distribution functions (TMDs) can inform us about the OAM of the partons.

One of the most important TMDs, and the main focus of this LOI, is the so-called Sivers function [4]. It was introduced in 1990 to help explain the large transverse single-spin asymmetries observed in hadronic pion production at Fermilab [5]. The quark Sivers function represents the momentum distribution of unpolarized quarks inside a transversely polarized proton, through a correlation between the quark momentum transverse to the beam and the proton spin. On one hand, the Sivers function contains information on both the longitudinal and transverse motion of the partons and provides a unique way to perform 3-dimensional proton tomography in momentum space [1, 2]. On the other hand, it has been shown that there is a close connection between the Sivers function and quark OAM. Though the search for a rigorous, model-independent connection is still ongoing, it is clear that the existence of a non-zero Sivers function requires non-zero quark OAM [1]. From a detailed analysis of the azimuthal distribution of the produced particles from a transversely polarized nucleon, one can deduce properties of the nucleon structure.

This approach has been used in Semi-Inclusive Deep Inelastic Scattering (SIDIS) experiments, where non-zero values of the Sivers function from HERMES [6], COMPASS [7] and JLab [8] have indicated that the orbital angular momentum of the up quarks is positive ($L_u > 0$) but of the down quarks is negative ($L_d < 0$.) The anti-down versus anti-up quark excess in the proton observed in Drell-Yan (DY) measurements by E866 [Figure 1], when interpreted in the pion cloud model, provides a strong hint that the sea quarks contribute significantly to the orbital angular momentum [9], in the x range where significant valence quark Sivers asymmetries were observed in SIDIS. However, current SIDIS experiments have little sensitivity to the antiquark Sivers asymmetry in this kinematic range. Thus, a direct measurement of the Sivers function for the antiquarks has become crucial and can only be accessed cleanly via the Drell-Yan process. We propose to carry out the first measurement of the sea quark Sivers function, using Drell-Yan production from an unpolarized 120 GeV proton beam scattering off a transversely polarized proton target.

Besides helping to resolve the proton spin puzzle, this proposal helps address the recent NSAC milestone HP13 to "test unique QCD predictions for relations between single transverse spin phenomena in p-p scattering and those observed in deep inelastic lepton scattering." A fundamental prediction of QCD is that the Sivers function changes sign, when going from SIDIS to DY production [10]. This prediction is deeply rooted in the gauge structure of QCD as a field theory, and is based on the well-known QCD factorization formalism widely used in interpreting high-energy experimental data. Thus, its experimental verification or refutation is crucial. The existing SIDIS data from HERMES, COMPASS and JLab [6, 7, 8] have enabled us only to extract the Sivers function of valence quarks. This LOI proposes to make the first determination of the size and the sign of the sea quark Sivers function. Combined with higher luminosity SIDIS experiments planned at JLAB, which aim to measure the Sivers distribution for sea quarks, our results would allow a test of this fundamental prediction of QCD. Higher luminosity SIDIS experiments planned at JLAB should be able to measure the sea quark Sivers distribution for direct comparison with our results.

To summarize, we propose to make the first measurement of the Sivers function of sea quarks, which is expected to be non-zero if the sea quarks contribute orbital angular momentum to the proton spin, as expected from the pion cloud model which also partially explains the E866 results. Thus, we will be able to deduce whether or not sea quark orbital motion contributes significantly to the proton spin. Specifically, we will determine the contribution from the anti-up quarks, with Bjorken-x in the range of ~ 0.1 to 0.5. Drell-Yan production off a polarized proton target has never been measured and is complementary to the recently approved (stage-1) experiment E1027 at Fermilab [11], which will measure the Sivers function of the valence quarks using a polarized proton beam on an unpolarized proton target. If the measured sea quark Sivers function is non-zero, we will also determine its sign.

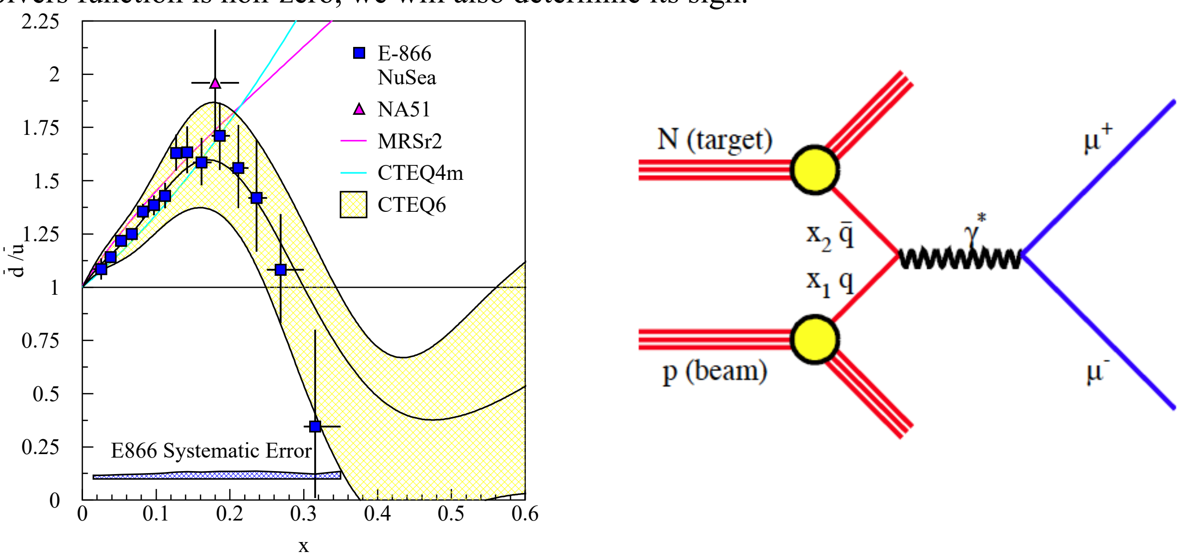


Figure 1. E866 DY result for anti-down versus anti-up quark content of the proton (left). If the excess of anti-down quarks is due to a pion cloud around the proton, then the pions (and sea quarks) contribute a significant amount of orbital angular momentum. On the right is a Feynman diagram for the Drell-Yan process.

On the theoretical side, Gupta, Kang, Vitev and collaborators are currently developing numerical simulation packages at LANL to provide accurate QCD predictions for the DY single-spin asymmetry in the kinematic region relevant to our experiment. Once our DY data become available, they will use a global fitting procedure to extract the sign and the shape of the Sivers function. To test the predicted sign change between SIDIS and DY, sea quark SIDIS data will also be required. In addition, they are performing a Lattice QCD calculation of the Sivers function to also pinpoint the sign in these two processes and to estimate the magnitude.

In order to perform the proposed measurement, a new LANL-designed high-luminosity polarized proton target system needs to be added to the existing E906 dimuon spectrometer at Fermilab (Figure 2). An essential component of this system is a superconducting magnet that produces a uniform field transverse to the beam direction. LANL, University of Virginia (UVa) and Oxford Instruments are refurbishing an existing 5 Tesla (T) superconducting magnet that will provide the necessary holding field for a polarized ammonia (NH_3) target. In addition, we need to build a new refrigerator and microwave system to populate the polarized spin states. The existing E906 cryogenic targets will be replaced with this polarized ammonia target. In section 4, we further discuss the required modifications to the E906 experiment.

We wish to emphasize that our proposed measurement is complementary to E1027. E1027 will measure the asymmetry and the crucial determination of the sign change for valence quarks. Our data will determine the sign and magnitude of the sea quark asymmetry. Furthermore, in semi-inclusive deep-inelastic scattering (SIDIS) measurements, there is, at leading twist, one structure function per TMD. In Drell-Yan measurements, there are at least two structure functions per TMD [12]. A Drell-Yan experiment with both a polarized beam and a polarized target would provide unique access to these structure functions. Therefore, it is imperative to perform both experiments. Similarily, our experiment is complementary to the COMPASS experiment at CERN [13], which concentrates on valence quarks.

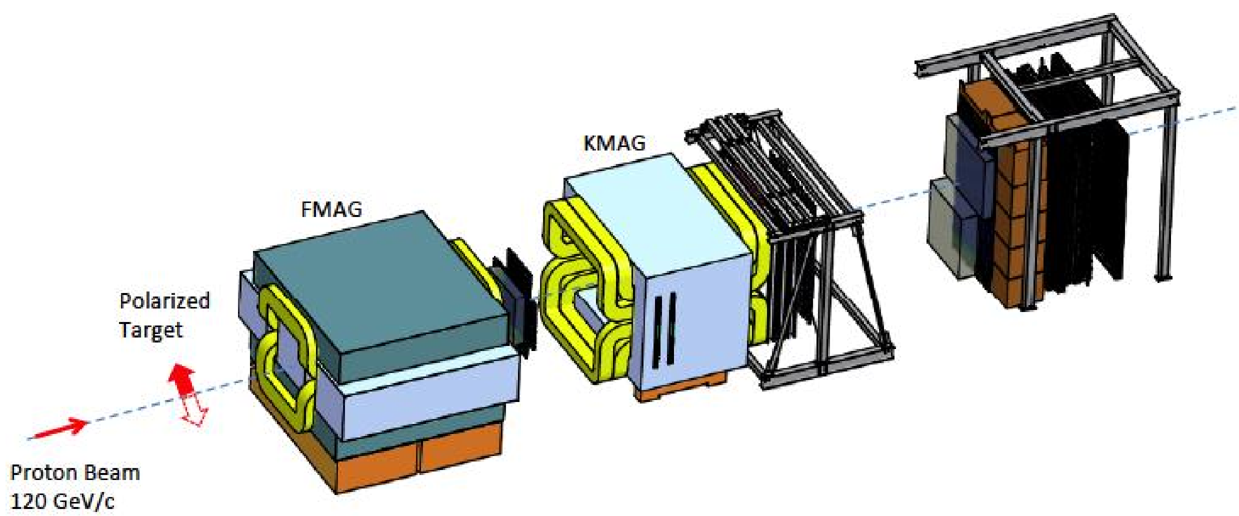


Figure 2. E906 spectrometer, showing the two dipole magnets, tracking stations and muon identifier. Shown on the left is the vertical direction of the polarization of the ammonia target. Further details of the target are shown in Figure 3.

2. Proposed measurement and experimental facility

The E906 spectrometer was designed to perform Drell-Yan measurements covering x_2 from 0.1 to 0.5. This is an excellent kinematic range for the proposed sea quark Sivers function measurement, covering the region of large anti-down quark excess observed by E866, where large pion-cloud effects may be expected. The contributions from target valence quarks at large x_2 can be made small by choosing $x_F > 0$. The existing 120 GeV Main Injector beam line and beam intensity of 10^{13} protons per 5 second spill, once a minute, are also appropriate. Some improvements to the final beam focus, beam position and halo monitoring may be required to minimize the size of the beam spot and avoid quenching the superconducting target magnet. Accurate relative beam luminosity measurements are also needed to minimize systematic uncertainties due to false asymmetries.

A 5 T superconducting magnet from LANL has recently been re-commissioned at full field at UVa during February, 2013. This target magnet was originally designed for longitudinal polarization (relative to the beam) while our experiment requires transverse polarization. Oxford Instruments of England will rotate the magnet coils to the transverse direction and reconnect the cryogenic supply lines. LANL and UVa will be jointly responsible for the polarized target. We will design and construct a target ladder insert, microwave and NMR systems. Furthermore, we will provide the necessary helium pumping system to reach 1 K, and irradiate the NH_3 beads at NIST. We emphasize that this is all proven technology and is almost identical to an existing polarized NH_3 target that has been successfully operated for years at SLAC and Jefferson Lab.

The target is polarized using Dynamic Nuclear Polarization (DNP) and is shown schematically in Figure 3. The beam direction is into the page, so that the target polarization is transverse to the beam direction. The existing superconducting magnet is also shown in the figure.

While the magnetic moment of the proton is too small to lead to a sizable polarization in a 5 T field through the Zeeman effect, electrons in that field at 1 K are better than 99% 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. The target spin direction will be reversed once every 8 hours by microwave frequency changes, while the magnet field is unchanged.

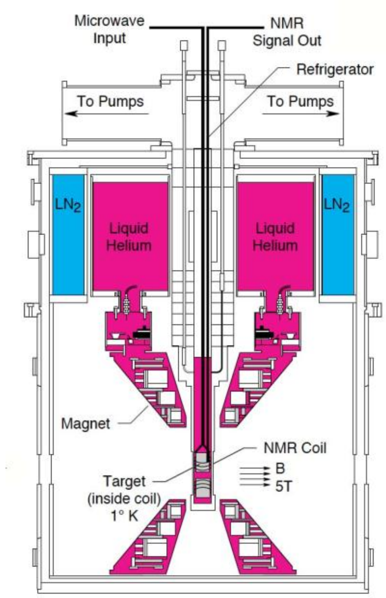


Figure 3. Schematic drawing of the polarized NH_3 target (left) and existing magnet (right).

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. Our collaborators at UVa have agreed to build a new cryogenic refrigerator, which works on the principle of liquid ^{4}He evaporation and can cool the bath down to ~1 K, by pumping ^{4}He vapor down to < 0.18 Torr. UVa scientists have built many polarized systems 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. The microwave system is used to induce the spin flip transition. NMR coils, placed inside the target, can determine the proton polarization to an accuracy of ~ +/- 4%. The maximum polarization achieved with such a target is better than 92% and the NH_3 bead packing fraction is about 60%. In our estimate for the statistical precision, we have assumed an average polarization of 80%. The polarization dilution factor, which is the ratio of free polarized protons to the total number of nucleons, is 3/17 for NH_3, due to the presence of nitrogen. The NH_3 beads need to be replaced approximately every 5 days, due to the beam induced radiation damage. This work will involve replacing the target stick with a new insert, cooling down the target and performing a thermal equilibrium measurement. From previous experience, we estimate that this will take about a shift to accomplish. Careful planning of these changes will reduce the impact on the beam time. Furthermore, we will be running with two active targets on one stick, thus reducing any additional loss of beam time.

3. Expected results

In Figure 4, we present the expected statistical precision of the single spin asymmetry that can be obtained in a one year run. We assume an integrated number of protons on target of 2.7 x 10^{18}. The assumptions on which these calculations are based are discussed in Appendix 1.

Approximately 110,000 reconstructed Drell-Yan pairs can be collected per year, after applying geometry cuts similar to that of E906. A strong sensitivity to the sign and magnitude of the Sivers asymmetry is demonstrated for non-zero values. The magnitude of the Sivers function can be determined to better than 4%. Also shown in Figure 4 is a theoretical estimation of the possible magnitude of the Drell-Yan Sivers asymmetry from a phenomenological fit by Anselmino et al [14] to the existing valence quark SIDIS data. We note that the error band on the sea quark Sivers function is not well constrained, since the fits are not very sensitive to the sea quark contribution. During this experiment, we expect to clearly answer the following questions:

- What is the sign of the Sivers asymmetry for sea quarks in DY?
- Does the sea quark orbital angular momentum contribute significantly to the proton spin?

The systematic uncertainties, not shown in Figure 4, are expected to be smaller than the statistical errors, for small measured asymmetries. The systematic errors are generally proportional to the size of the asymmetry. The absolute error will be ~ 1% and the relative error will be at the 4% level. Major sources of systematic error include uncertainties in the polarization, which contributes to the relative uncertainty, and the relative luminosity, which contributes to the absolute uncertainty.

In addition to these Drell-Yan events, we also expect to collect ~1 million J/ψ events. Since a substantial fraction of J/ψ production at this kinematics originates from quark-antiquark annihilation rather than gluon-gluon fusion, the single-spin asymmetry from J/ψ events is likely to be sensitive to the sea quark Sivers distribution [15].

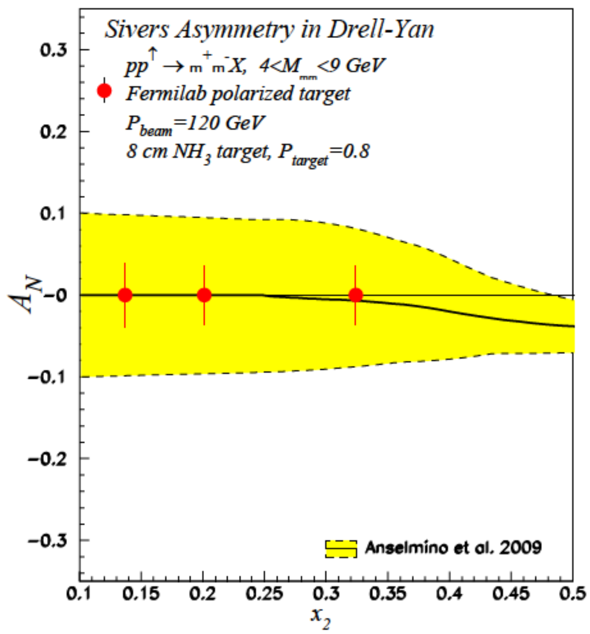


Figure 4. Estimated statistical precision for the DY Sivers asymmetry versus x_2. Also shown is the prediction from Anselmino [14] for the magnitude of the asymmetry. Note that we have extended the theoretical estimate below its valid minimum of x_2 of 0.2, in order to guide the eye. There is currently no theoretical prediction available for the asymmetry below that value.

After a successful measurement with polarized NH_3 is completed, a switch to polarized ND_3 would allow us to examine the Sivers effect in the neutron versus the proton. This would provide separate Sivers functions for anti-up and anti-down quarks in the proton, similar to how E866 and E906 are performed. However, the expected ND_3 polarization is only ~ 35%, which results in reduced statistical precision for the same integrated luminosity.

Once a polarized proton beam is available for E1027, our polarized target will become a crucial component for performing double spin asymmetry measurements. This would allow us to develop a full spin physics program at Fermilab using the Drell-Yan process, since all of the required infrastructure will be available. For example, the Drell-Yan beam-target transverse double-spin asymmetry will provide direct access to the product of the valence and sea quark transverse spin distributions, without introducing the T-Odd spin-dependent quark fragmentation functions contained in the SIDIS measurements.

4. Collaborators and required resources

For this LOI, the initial collaboration includes groups that have been heavily involved in previous Fermilab Drell-Yan measurements, as well as groups that successfully built and operated polarized NH_3 targets. Many of the E906 collaborators will join this new experiment and continue to support and maintain the E906 spectrometer. LANL and UVa will develop and support the polarized target and existing superconducting magnet. In order to achieve transverse polarization, the superconducting coils of the magnet have to be rotated. Oxford Instruments, the original manufacturer, will do this. To reach 1 K temperature in the refrigerator, large Roots pumps, provided by LANL, will pump on the refrigerator's He bath. Once the system is at 1 K, with the microwaves and beam as the only heat-loads (only ~ 1/4 watt for beam), the system will evaporate roughly 100 liters of liquid He per day. This will necessitate a buffer receptacle for the exhaust helium. Liquid He will most likely be supplied from Dewars. We are studying the possibility of adding a He liquefier system. While such a system could be cost prohibitive for a two year run period, it would be preferable if this target would become part of the regular infrastructure of FNAL. In order to design and run such a liquefier plant, we would need support from FNAL. LANL will also provide the microwave system consisting of the klystron, power supply and frequency meter, as well as the NMR system needed to determine the polarization in the target. The frozen ammonia beads will be irradiated by UVa and LANL personnel at NIST. They must be replaced after every 5 days of proton beam, requiring about one shift of access to the target.

The experiment may require beam-line improvements and new safety infrastructure from Fermilab, possibly including a pinhole collimator, final focusing quadrupole magnet set and an additional beam position monitor. These will reduce the probability of quenching the superconducting magnet. Preliminary discussions with the E906 beamline physicist (Mike Geelhoed) indicate that the existing upstream quadrupole may be adequate. A method for the safe venting of helium gas during a quench is required. A partial redesign of the target cave is required to accommodate the large Roots pumps, two He Dewars and liquid nitrogen supply. The FMAG and KMAG magnet fields will require occasional reversals to minimize systematic errors. A convenient way to switch their polarities is necessary.

In Figure 5, we have assumed that liquid He would be supplied from two 1000 liter Dewars. We are currently studying two options for placing the Roots pumps, which are labeled as 1 and 2. In case 1, we would place the pump stand outside of the beam area on top of the shielding. For case 2, the stand would be in the cave. Shielding issues as well as pumping power will govern the final choice. Also drawn is the additional quadrupole for beam focusing. In addition, the overhead space will need to be increased, in order to allow for replacement of the target's NH_3 beads every 5 days, due to the radiation damage. Depending on the location of the big Roots pumps, additional cave modifications may be needed in order to accommodate the pump's vacuum line to the magnet. Finally, the current crane in the cave has to be replaced with one with a higher lift capacity (2 ton) and lift rails installed that extend further upstream. This is necessary to perform any needed repairs to the magnet.

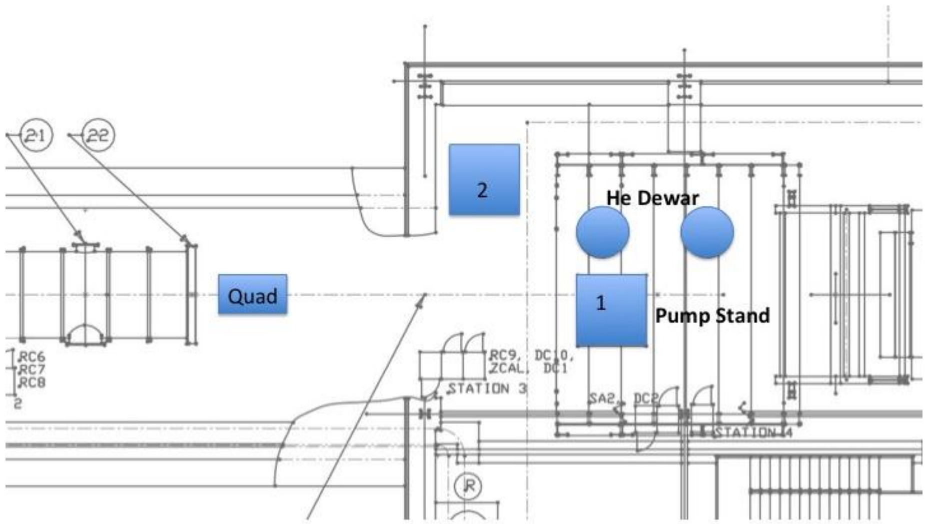


Figure 5. Top view of the E906 beam-line, target cave and proposed changes (in blue).

In Figure 6, we show a drawing of the target cave and shielding for E906, as viewed along the beam-line. The dashed blue line is the current cave ceiling, while the blue box represents the space needed for the polarized target. A minimum of 140" of vertical space is required above the floor, in order to accommodate the extraction of the target ladder. This would require raising the roof of the cave by roughly 32", through a partial restacking of the target cave shielding. This may, in turn, necessitate new MARS shielding calculations.

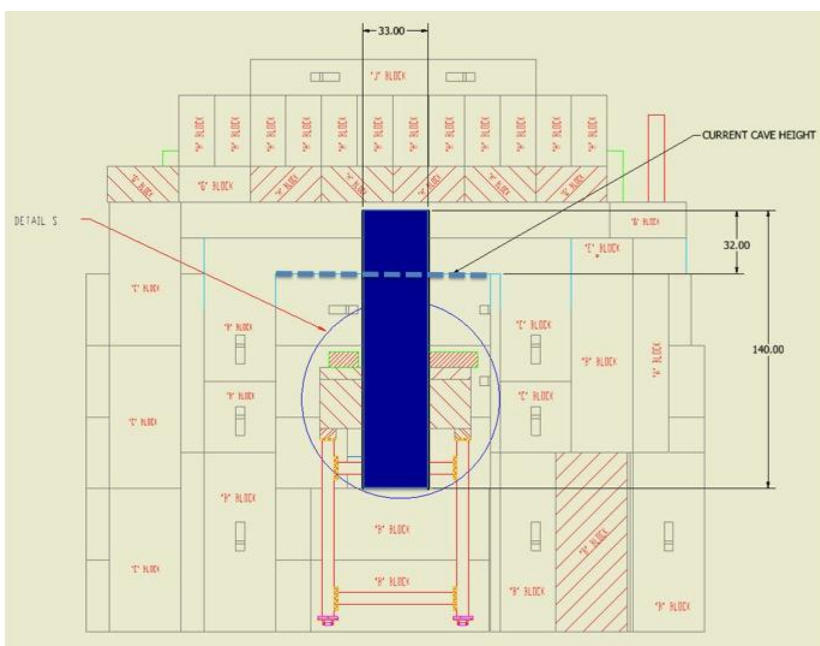


Figure 6. Beam's eye view of the E906 target cave, looking downstream toward the polarized target. The blue rectangle represents the height and vertical clearance required for the polarized target. The dashed line is the current (insufficient) cave height.

Appendix 1. Rate estimates and expected precision

The Drell-Yan yields were calculated in a similar fashion to those for the E906 experiment, using the E906 GEANT 4 based Monte Carlo calculation for the acceptance. The Drell-Yan cross section was taken from PYTHIA using the CTEQ5M parton distribution functions and verified against a modern NLO DY calculation from Vitev, et.al. The polarized target and a simplified holding magnetic field were added at the E906 target location. Effects due to fringe fields from the FMAG have not yet been included, but will be carefully studied. A field clamp plate will be added to the FMAG, to eliminate the ~ 15 Gauss residual field measured in the target region that could degrade the polarization. We assume a target polarization of 80%, packing fraction (from the NH_3 beads) of 60%, dilution factor of 3/17 and target length of 8 cm. The NH_3 beads plus the surrounding He bath correspond to a total target areal density of ~ 5 g/cm^2.

Approximately 110,000 DY events are expected for 2.7 x 10^{18} effective protons on target (one year), as shown in Table 1. This corresponds to 1.0 x 10^{13} protons per spill. The distribution of sampled parton momentum fraction, in terms of x_1 and x_2, is shown in Figure 7. Good coverage for sea quarks in the target is obtained. Valence quarks are dominant in the beam. The integrated proton–nucleon luminosity, including 50% beam availability and 80% experimental livetime, is estimated to be 6.5 x 10^{42} per cm^2. The kinematic coverage is given in the table below. Since the spectrometer will be operating at very high rates, a good beam duty factor is essential to prevent high trigger rates and chamber occupancies. Poor duty factor hampered the first run of E906. Whatever solution is found for E906 should be adequate for our purpose.

- Kinematic range: *$4 < M < 8$ GeV, $-0.2 < x_F < 0.8$*

Cuts	Efficiency	Yield
All DY in the kinematic range	100%	1.34E+08
$\mu^+\mu^-$ accepted by all detectors	2%	2.78E+06
Accepted by trigger	50%	1.39E+06
$\mu^+\mu^-$ pair reconstructed (with target/dump separation cut)	8%	1.11E+05

Table 1. Drell-Yan yield estimates for a one-year long run.

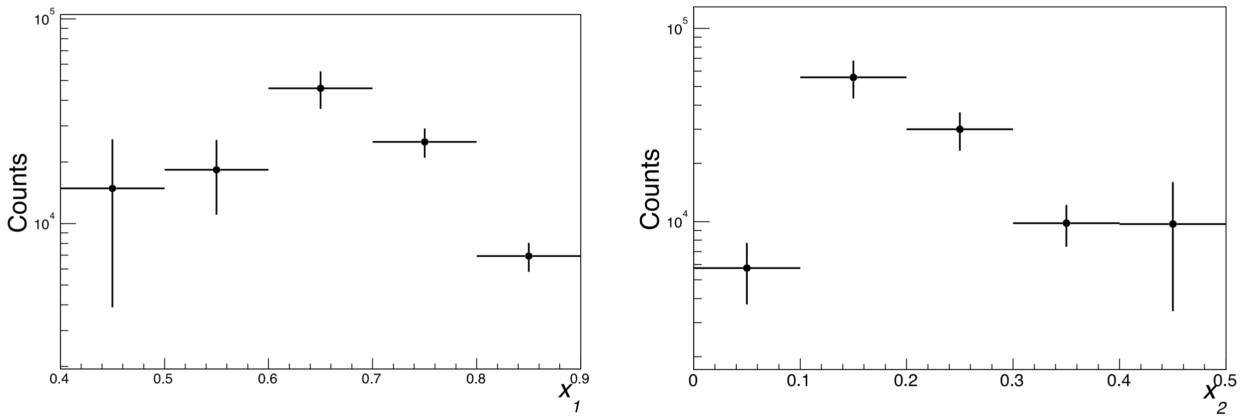


Figure 7. Expected distribution of Drell-Yan events, in terms of Bjorken-x_1 (beam) and x_2 (polarized target). The vertical axis is number of events and error bars are statistical.

References

1. D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang, D. Kaplan, H. Montgomery and S. Vigdor et al., "Gluons and the quark sea at high energies: Distributions, polarization, tomography", arXiv:1108.1713 [nucl-th].
2. A. Accardi, J. L. Albacete, M. Anselmino, N. Armesto, E. C. Aschenauer, A. Bacchetta, D. Boer and W. Brooks et al., "Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all", arXiv:1212.1701 [nucl-ex].
3. E. Aschenauer, A. Bazilevsky, K. Boyle, K. Eyser, R. Fatemi, C. Gagliardi, M. Grosse-Perdekamp, J. Lajoie and Z. B. Kang et al., "The RHIC Spin Program: Achievements and Future Opportunities", arXiv:1304.0079 [nucl-ex].
4. D. Sivers, Phys. Rev. D41 (1990) 83.
5. D. L. Adams et al. [FNAL-E704 Collaboration], Phys. Lett. B 264, 462 (1991).
6. A. Airapetian et al. [HERMES Collaboration], Phys. Rev. Lett. 103, 152002 (2009).
7. M. Alekseev et al. [COMPASS Collaboration], Phys. Lett. B 673, 127 (2009).
8. X. Qian et al. [JLab Hall A Collaboration], Phys.Rev.Lett.107:072003, 2011.
9. G. Garvey, Phys. Rev. C81 (2010) 055212 and E866 collaboration, Phys. Rev. Lett. 80 (1998) 3715-3718.
10. J. C. Collins, Phys. Lett. B536, 43–48 (2002).
11. Fermilab E1027 proposal, 2012.
12. S. Arnold, A. Metz, M. Schlegel, Phys.Rev. D79 (2009) 034005.
13. COMPASS-II collaboration, http://wwwcompass.cern.ch/compass/proposal/compass-II_proposal/
14. M. Anselmino, private communication, based on M. Anselmino et al. Eur. Phys. J. A39, 89–100 (2009).
15. M. Anselmino et al, Phys. Lett. B594 (2004) 97.

Update for Experiment E1039
December 2014

Joint E906/E1039 statement

The collaboration has agreed on the following plan as the best path forward in terms of physics and timeliness. While the beam intensity for E906 is lower than requested, we feel that E906 will, by summer 2016, accumulate enough statistics to substantially achieve its physics goals. At this point, we propose to start the changeover to the E1039 configuration by installing the polarized target. We estimate that this installation will take roughly 6 month at which time the commissioning of E1039 will start. After this period, we are planning to run for two years with a polarized proton target.

Optimizing the Experiment and new Estimates based on E906

Since the presentation to the PAC in July 2013, three significant improvements to the experiments performance have been achieved:

- *The spectrometer acceptance for low Bjorken x has been improved by a factor of 2.*
- *The event reconstruction efficiency has been improved by a factor of 6.*
- *The accelerator has achieved a 50% increase in the number of "useful" protons.*
- *In spite of a reduced integrated luminosity these improvements result in an increase of 3.3 in statistics..*

The combination of these improvements results in a dramatic increase in the statistic.

We have modified the original E906 Monte Carlo and included a realistic simulation of the 5T target magnet. Because of the requirement that the field homogeneity of the target magnet is better than $dB/B < 10^{-4}$,we checked the fringe field of FMAG at the current target position. The field variation turned out to be of the order of 25G , which can be easily handled by field clamps. However, in the analysis of E906 it turned out that because of the limited vertex resolution along the beam axis, a cut to the data had to be applied, in order to clearly separate events from the dump from the ones from the target. This cut reduced the reconstruction efficiency by ~25 **%.**In order to eliminate this data loss we studied moving the target upstream by 220 cm to -350cm from the front of FMAG. Our calculations show that this leads to a significant increase in the x_T acceptance of the spectrometer as shown in figure 1.

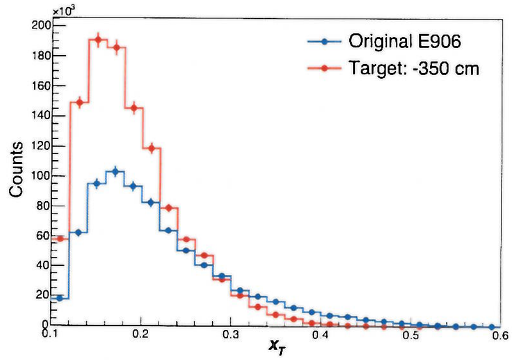


Figure 1: Accepted events for polarized target in the E906 target position (blue) and the new position (red).

At the lowest two xbins, this leads to an increase of roughly a factor of two. While such a repositioning of the target increases the background at the edges of the spectrometer, only a small increase occurs in the region of high mass DY pairs. Our study of the trigger efficiency has shown that we can run the experiment the E906 trigger rate, but with higher efficiency, because the background roads in the trigger matrix are more localized at the edge of the acceptance.

In addition to the optimizing studies, the reconstruction team of E906 has also made tremendous progress, improving the reconstruction efficiency for di-muon events. Compared to our original LOI this reconstruction efficiency has improved by factor of 6.

For our original calculations we used the beam intensity assumption of the original E906 proposal which assumed a 60% duty factor, since at this time this was still considered a realistic assumption. the experience over the last year have shown that this number was too high and the accelerator was only able to provide up to 30% DF, limiting the number of protons collected and also leading to higher DAQ dead time. However, in the 3rd week of December a dramatic increase of the duty factor has been achieved as shown in figure

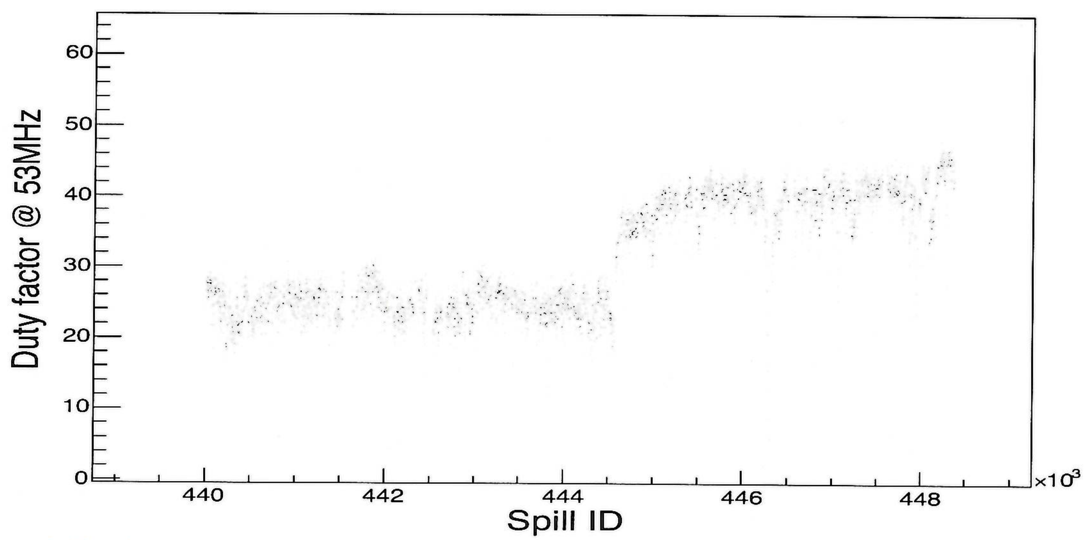
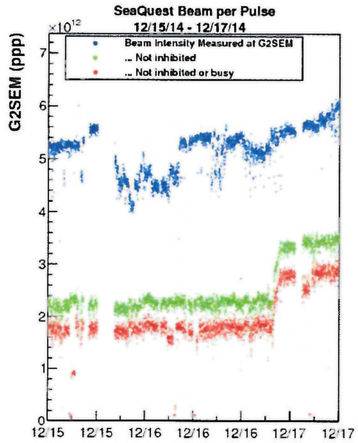


Figure 2: The change in duty factor as seen on Dec 16. The x-axis displays the spill number, which corresponds to time.



The duty factor increased from slightly below 30% to 40% and is still showing an increasing trend. This immediately translates in an overall increase of the useful protons of 50% as can be seen in figure. The red curve represents the "good" protons, where neither an inhibit due to poor beam quality was nor was the DAQ busy.

Figure 3 A strip chart of the proton intensity.

In the following table we show the projected statistical errors for the four data bins. These improvements will allow us to bin the data in four bins instead of the original three. One can clearly see the improvement in the error by moving the target backwards from the current E906 target position.

x_T Bin	Mean x_T	N: E906	N: -350 cm	ΔA: E906	ΔA: -350 cm
0.10 - 0.14	0.126	18735	68390	5.2	2.7
0.14 – 0.17	0.155	34811	93806	3.8	2.3
0.17 – 0.21	0.188	43819	100403	3.4	2.2
0.21 – 0.50	0.259	78121	106423	2.5	2.2

Target System Status

Since the presentation of the LOI to the PAC in July 2013, tremendous progress has been achieved with the polarized target.

- *The Superconducting magnet has been reconfigured for transverse polarization.*
- *Designed and purchased the pumping package necessary to reach 1K operation.*
- *We purchased a new 140GHz microwave system.*
- *Designed, built and tested completely new NMR system to measure the polarization.*

Originally, the superconducting magnet was configured for longitudinal polarization, requiring a field parallel with the beam axis. In order to measure the Sivers asymmetry, a transvers nucleon polarization is required, necessitating reorienting the magnet's split coils by a rotation of 90 degrees. After having successfully tested the magnet at the University of Virginia, we shipped the system to Oxford Instruments (OI, the original manufacturer) in the UK for the necessary changes. Once the magnet had arrived, a path forward was laid out for

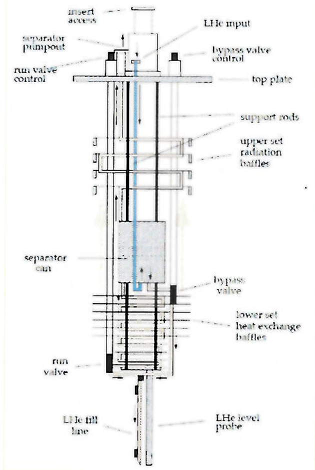
changing the coil assembly, refurbishing the cryogenic plumbing and electronics lines, and a redesign of the lower target part together with a new tail piece for the refrigerator. Because of the transport failure, we also decided to redesign the coil mounting and came up with a design where the coils could be separated from the tanks for shipping.
In Spring of 2014, OI started with the refurbishing and reorienting work, which they finished at the end of November 2014. Subsequently, the magnet system has been completely assembled and undergone leak checking at 70K. We will travel to Oxford in the last week of January for two weeks of acceptance testing and shipping preparation of the system. We anticipate to have the magnet fully operational in the US in spring 2015. (120K$)

During this time, we have designed a pump package necessary to cool the target system to the low operating temperature necessary. As described above, the polarized target operates at 1K and a field of 5T. This temperature is reached by lowering the vapor pressure of the liquid Helium bath to .117 Torr . This pumping package will pump roughly 12,000 m^3/hr of Helium gas at STP. We have received the whole system in November 2014, and are in the process of testing it. (190K$)

In order to polarize NH_3, the NH3 material has to be irradiated by 140 GHz microwave. A specialized high power microwave tube, manufactured by CPII, achieves this. While Los Alamos had an old tube, subsequent tests showed that only 50% of the necessary power could be achieved. Sending the tube back to the manufacturer confirmed our initial measurements, and reconditioning efforts at the factory were not successful. We have ordered a new tube in FY14, which was delivered to LANL in the fall. (120 K$)

In order to drive such a tube, a special power supply has to be used, which is built on order. We have purchased such a power supply, and the manufacturer is currently building it. The power supply will be specially tuned at the factory to the tube and then be shipped to Los Alamos in June 2015. (98 K$)

Over the last 30 years the way to measure the polarization was through NMR with the so called Liverpool Q meter. This system was designed in the 70's and relied on now obsolete analog electronic circuitry. In addition, to reach the necessary temperature stability, which is crucial for the Thermal Equilibrium (TE) measurements, the system had to be cooled, leading to a somewhat complicated and cumbersome system. In the case of the typical polarized target of this kind, this was not a problem since one target cell had just one NMR circuit. However, due to the extended size of our target cell (8cm long) we will need to have three circuits for every cell, and each target insert will have two active cells. This requires 6 circuits per target stick, making the Liverpool system unsuitable. We therefor designed a new system with new, state of the art analog and digital components. The first prototype was tested at the UVa polarized target Lab in Spring of 2014, and performed excellently. We showed that the system was extremely low noise and temperature stable. This low noise system will greatly reduce the time needed to measure the TE , the crucial baseline measurement and therefore increase the time we can take beam.
Currently we are modifying the system such that we will have a VME form factor allowing us to have the 6 measurement systems in one VME crate. The boards have already be designed and we plan to test the first prototypes in spring of 2015. (50 K$)



The central part of the whole system are the so called refrigerator and the target insert. The original refrigerator is currently being refurbished by UVa under a contract to the University. While most of the system can be reused, some leaks have been found, which are being worked on. We estimate that the refrigerator work will be finished in summer 15.

Figure 4: A schematic of the refrigerator

We have also started on the design for the target insert for the system. In the current conceptual design, the polarized target cells will have an elliptical face of H:18mm x V:27mm by 80mm long. This is necessitated by the requirements that the geometry of the existing system does not allow for a more extended or circular target. This limited horizontal extension also will require additional optics in the beam line to reduce the size horizontally. Shown is a typical target configuration as used at JLAB. The microwave horns can be easily seen. Because of our extended target (the ones shown are only 2o mm thick) we need different microwave horns. We have already accomplished a new design for the horns and received quotes. Most of the target work is being performed by UVa. In addition, the target stick will have an empty cell and a hole. The system is designed such that we could also load ND_3 thus allowing us to measure DY on a polarized neutron. This would be especially interesting if FNAL would eventually provide polarized beam. The overall size of the UVa contract is 230K$.

Figure 5 A typical target assembly as used at Jefferson Lab. The microwave horns are clearly visible.

In the following we list a table of the purchases made by LANL and the planned costs with the year of purchase.

Purchases	Costs	Delivery
ROOT pumps	$180,000	**FY14**
Microwave tube	$120,000	**FY14**
Microwave power supply	$98,000	FY14/15
NMR system (Prototype)	$15,000	**FY14**
NMR system VME	$20,000	FY15
Chiller, Separator pumps	$70,000	**FY14**
UVa contract part 1	$50,000	**FY14**
UVa contract part 2	$180,000	FY15-16
NIST irradiation	$62,000	FY15-16
Microwave electronics	$50,000	**FY14**
NIST irradiation	$60,000	FY15-16
Travel	$90,000	FY14-16
M&S	$90,000	FY14-16
Contribution to FNAL Infrastructure	$200,000	FY16
TOTAL LANL	**$1,285,000**	**FY14-16**

Estimates of Installation and Infrastructure Needs.

In the following paragraph we will discuss the changes and additions to the base E906 configuration needed, in order to field the polarized target. We have identified four major areas, where substantial work is needed:

- *Cryogenics for liquid Helium and Nitrogen distribution and exhaust*
- *Mechanical layout and modification of the target area*
- *Beamline improvments for a tighter final focus*
- *Shielding modification required for new target location and servces*

Cryogenics:

The major cryogenic issues with a polarized ^{4}He target are the liquid He consumption and the collection of the exhaust gas. Keeping the target at 1K will lead to a overall consumption of roughly 100 liters of liquid He per day. This is a sizable amount of a nonrenewable resource, as well as a large cost. Furthermore, such a system will need a special plumbing and recovery infrastructure consisting of Helium and Nitrogen transferlines, pumping lines from the target to the ROOTS pumps as well as a special quenchline, which would handle the Helium exhaust gas in case of a magnet quench. Together with the FNAL cryogenic group we have developed three different scenarios for the liquid Helium and obtained quotes and cost estimates for each of them:

1. A closed loop system
2. A system where we buy liquid helium and collect the exhaust gas.
3. Buy liquid He and exhaust it into the atmosphere

1. *Closed Loop System*

While this would be the preferred way to go in terms of independence from price fluctuation as well as He supply shortages, it turned out to be economically not viable. The total cost of such a system would be close to 2.5M$. The costs of running such a system during the experiment would be relatively small requiring about 10% of a tech FTE

2. *Collecting the exhaust gas.*

Due to space constraints, such a system would have to be in the upper part of the experimental area, requiring extensive cryo-engineering design work, storage facilties for the gas and a compressor, which could transfer the gas from the atmospheric storage area to the helium trailers. The total estimate for this system would be 880K$. A further disadvantage of this solution would be the need for sizable manpower to operate the compressor and transfer the He on a regular basis from one of the storage containers to the He trailers. The estimate for this manpower would be 160K$ a year. In this scenario we need to buy Helium and we have estimated the costs of 1 lt at 10$ (current price is $6.5). Assuming that we would need to run the target at 1K for 250 days of beam, we estimate the yearly total costs of running the polarized target to be 406K$.

3. *Venting the Helium into the atmosphere*

While this solution still requires the same transferlines as the other two proposals, we would not need additional storage space or a compressor. Our cost estimate for this approach comes out to 613K$ and the yearly costs would be the costs of the liquid Helium, which would be 250K$

While venting the Helium is certainly an undesirable approach, it seems to be the only financially viable solution without additional significant investment from either DOE or FNAL.

Mechanical Issues

As we have outlined in the section describing the progress in optimizing the experiment, we will need to move the target 220 cm upstream from it's current position as indicated in the displayed figure. However this configuration poses not only challenges in terms of routing all the necessary cryogenics and pump lines but also in terms of mechanical and new shielding issues. This position will require some restacking of the shielding immediately above the magnet in order to have enough vertical space to change the target , which we will need to do roughly every 10 days, in order to exchange the radiation damage material. In addition we will need a target platform which will allow us to work around the target at a height of 8 feet

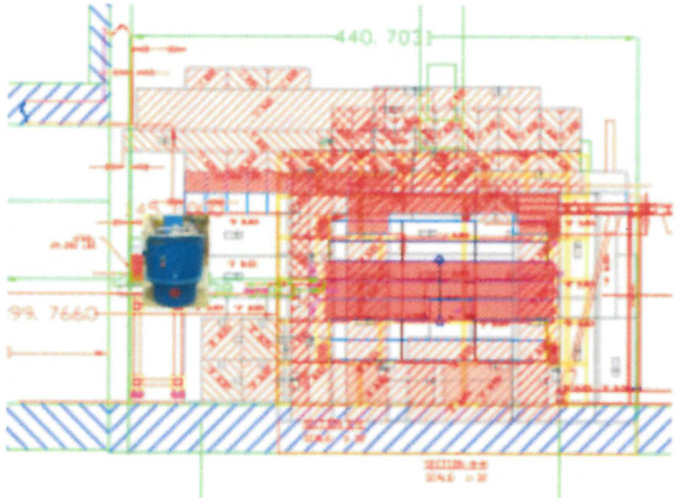


Figure 6 Current Shielding configuration with the polarized target shown in its anticipated position.

(beam height above the ground). A further complication arises from the limited reach of the overhead crane. While we can lower the target into the area on the side, the crane will not be able to access the position of the target itself. Therefore we will need to mount a hoist to the overhead shielding. All these mechanical changes to accommodate the target are estimated to be 180K$.

Beamline

Due to the small size of the target and the requirements on the relative luminosities, we will need a beam size of σ_H =2mm and σ_V =3.3mm, which is much smaller than the current E906 beam, which is σ_H =4mm and σ_V =3mm. This will require additional quadrupole magnets. We will also need a collimator upstream of the target, which will prevent possibility of the beam hitting the polarized target coils and quenching it due to miss-steering. At the time of this update writing, the estimates were still being done.

Overall Table of costs as currently known with the three different cryogenics options.

Installation			
	Closed Loop	Balloon Storage	exhaust
	$2,455,308	$892,280	$613,280
-LANL contribution	- $240,000	- $240,000	- $240,000
Cryo Installation	**$2,215,308**	**$652,280**	**$373,280**
Target Mechanical	$180,000	$180,000	$180,000
Electrical	$54,000	$54,000	$54000
Beamline			
Shielding			
Total as of 12/21/14	**2,449,308**	**$886280**	**$607,280**
Yearly running costs:			
Cryo	$156,000	$406,000	$250,000
E906 (70% contingency)	$61,200	$61,200	$61,200
TOTAL yearly	**$217,200**	**$467,200**	**$311,200**

The mechanical and electrical calculations have an overall contingency of **50%** and the cryogenic estimate one of **60%**.

Shielding Calculations and modifications.

At the current time this cost is the largest uncertainty due to the complexity of the MARS calculations. In order to get an estimate of any additional shielding needed as well as mechanical load calculations and possible civil engineering needed, FNAL has to perform a detailed MARS calculation. We would like to ask FNAL management to provide the necessary resources to the Accelerator division to perform these calculations as soon as possible, such that we could obtain a final cost estimate by the summer of this year.

Collaboration and Contributions from Members

In summer 2014 we had the first collaboration meeting with a session specially dedicated to the E906 extension with a polarized target. At this time, UVa and New Hampshire joined the existing E906 collaboration. In the second week of February we will have our next combined collaboration meeting, where we will discuss possible contributions to the experiment from our collaborators.
The three most critical components of the polarized target are the ROOTS pump system, the microwave tube and its power supply. While the pumps are known to be very stable and run for many years without problems, the tube and power supply are known to fail and in need of repair. It is therefore crucial to run such an experiment with spares for either component on hand. We are glad to report that the University of Michigan will contribute its microwave tube to the experiment, while the University of Virginia has agreed to provide us with a spare power supply. UVa has also assumed the responsibility for the new target inserts and the repair of the refrigerator.

Conclusions

During the last one and a half year we have made large progress in our preparation for a polarized Drell Yan experiment. We have successfully optimized the experimental setup and improved the data reconstruction. Together with an improved duty factor for the beam, these changes lead to an overall improvement of the statistics of 3.3 .
Furthermore, the construction of the polarized target is well under way, most of the major purchases have been done, and the project completion date is still ahead of the E906 end, which will allow us to seamlessly transition from the Seaquest liquid targets to the polarized target. A smooth continuous running of Seaquest will accelerate this process.

We have identified the challenges to the changeover and gotten budget estimates for all but the shielding and beam line modifications. In order to complete these estimates, we are asking for the support from the PAC and FNAL.