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

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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.

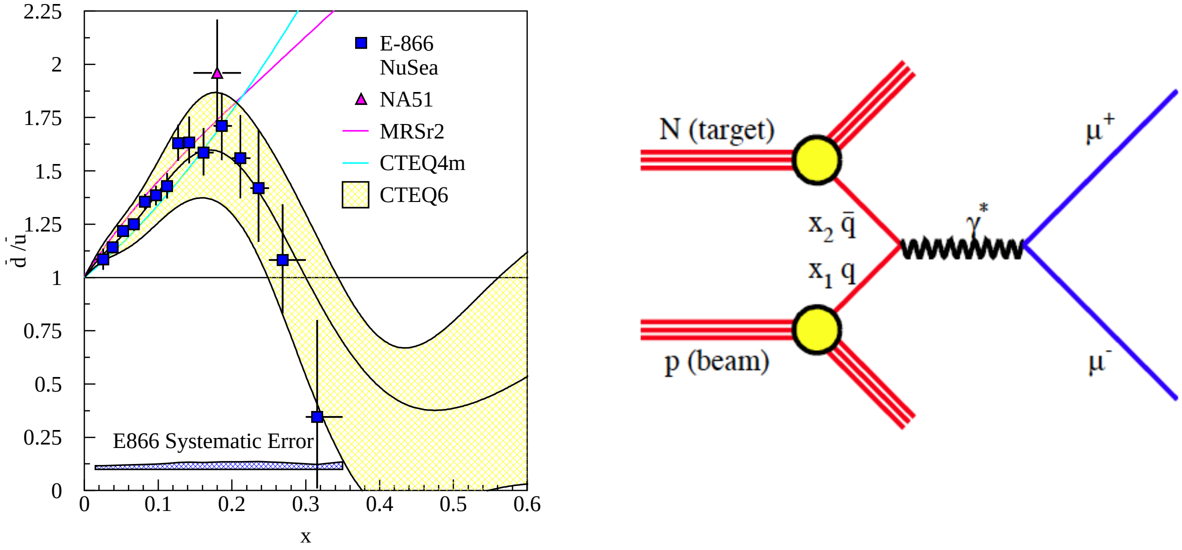


Figure 1. E866 DY result for anti-down versus anti-up quark content of the proton (left). If the excess of anti-down quarks is due to a pion cloud around the proton, then the pions (and sea quarks) contribute a significant amount of orbital angular momentum. On the right is a Feynman diagram for the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

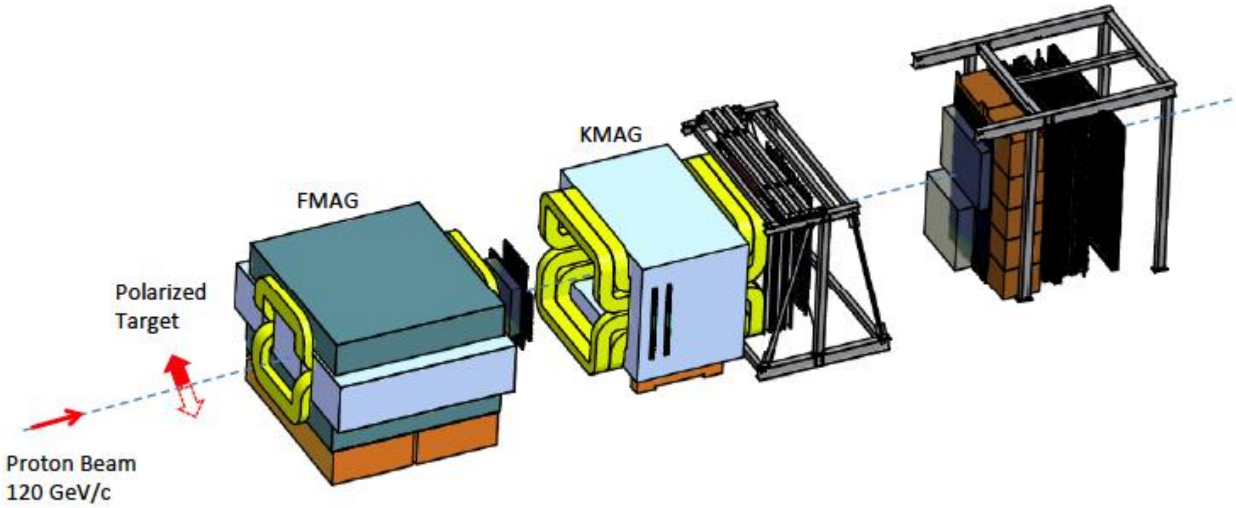


Figure 2. E906 spectrometer, showing the two dipole magnets, tracking stations and muon identifier. Shown on the left is the vertical direction of the polarization of the ammonia target. Further details of the target are shown in Figure 3.

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.

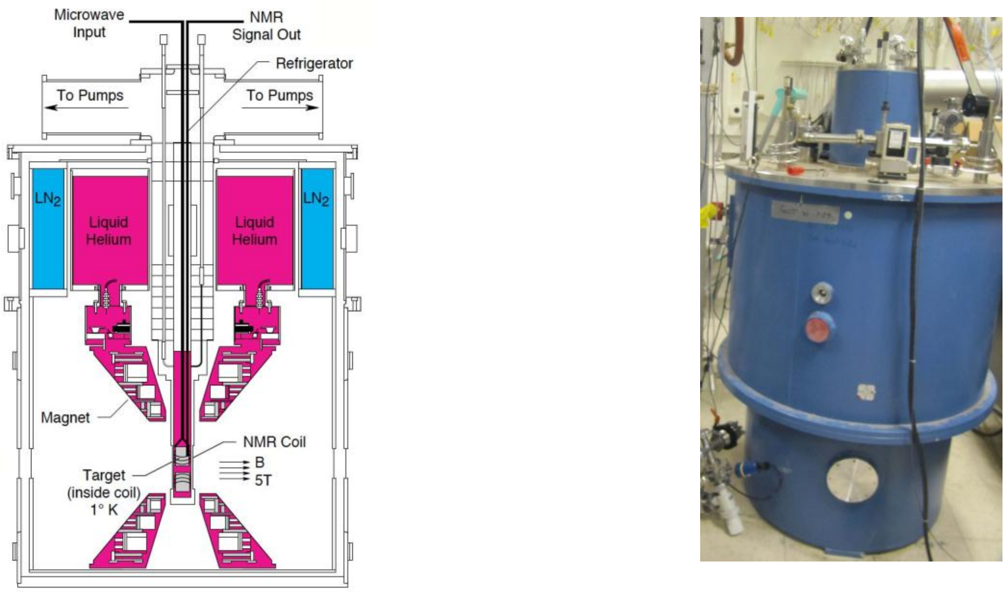


Figure 3. Schematic drawing of the polarized NH_3 target (left) and existing magnet (right).

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 2.7×10^{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].

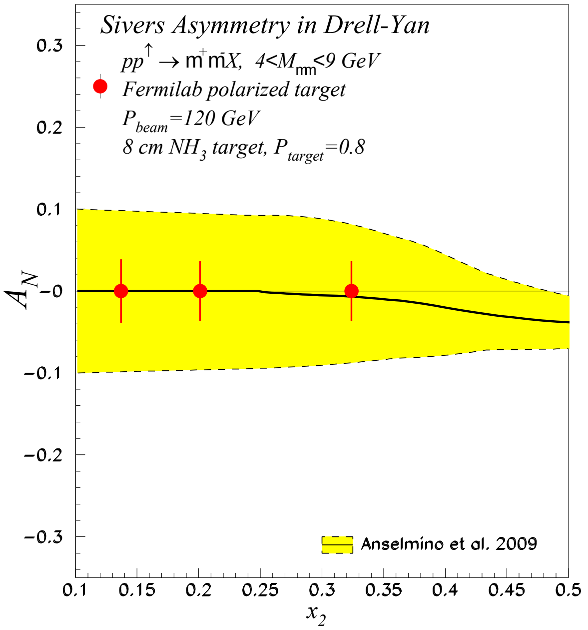


Figure 4. Estimated statistical precision for the DY Sivers asymmetry versus x_2. Also shown is the prediction from Anselmino [14] for the magnitude of the asymmetry. Note that we have extended the theoretical estimate below its valid minimum of x_2 of 0.2, in order to guide the eye. There is currently 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.

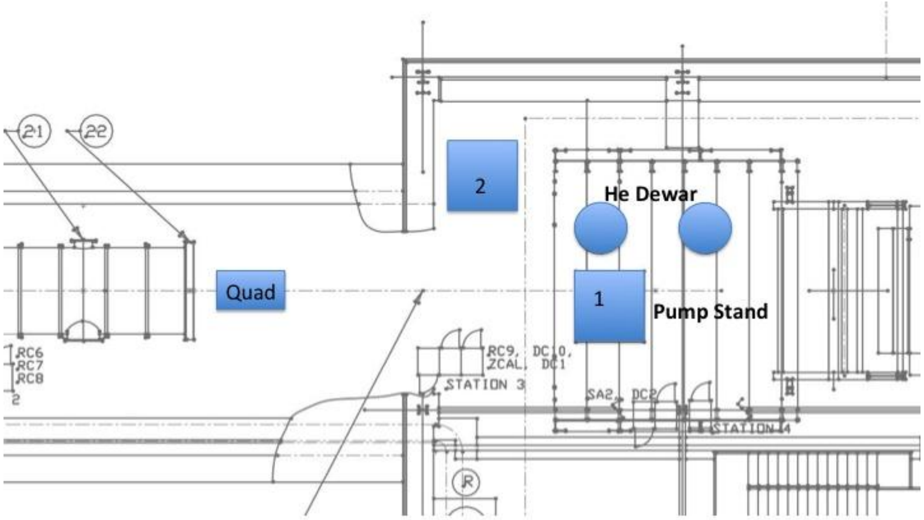


Figure 5. Top view of the E906 beam-line, target cave and proposed changes (in blue).

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.

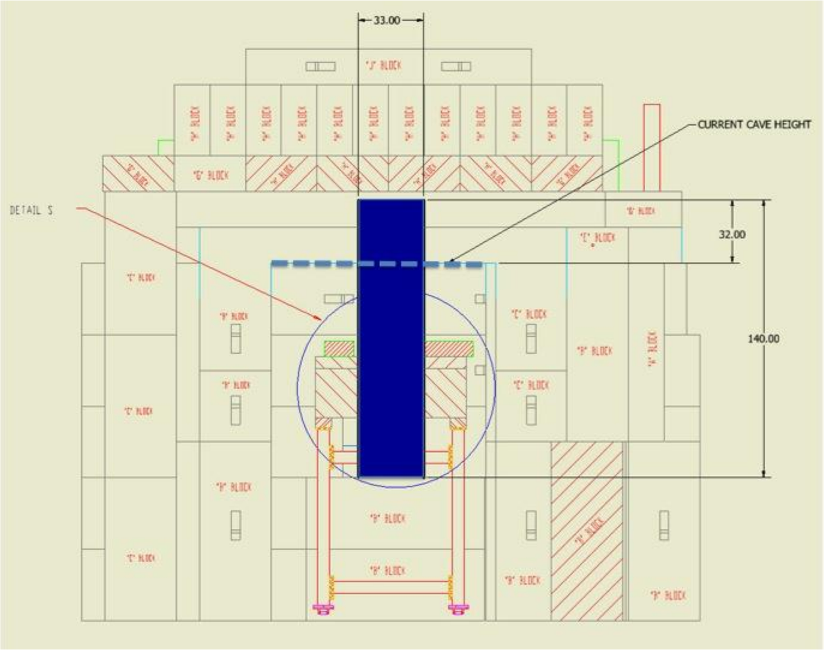


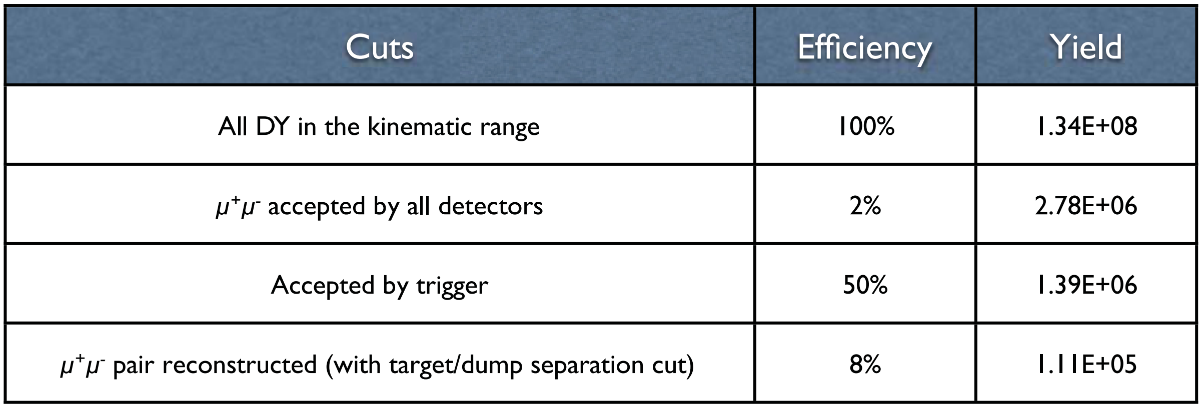
Figure 6. Beam's eye view of the E906 target cave, looking downstream toward the polarized target. The blue rectangle represents the height and vertical clearance required for the polarized target. The dashed line is the current (insufficient) cave height.

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 2.7×10^{18} effective protons on target (one year), as shown in Table 1. This corresponds to 1.0×10^{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 6.5×10^{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.

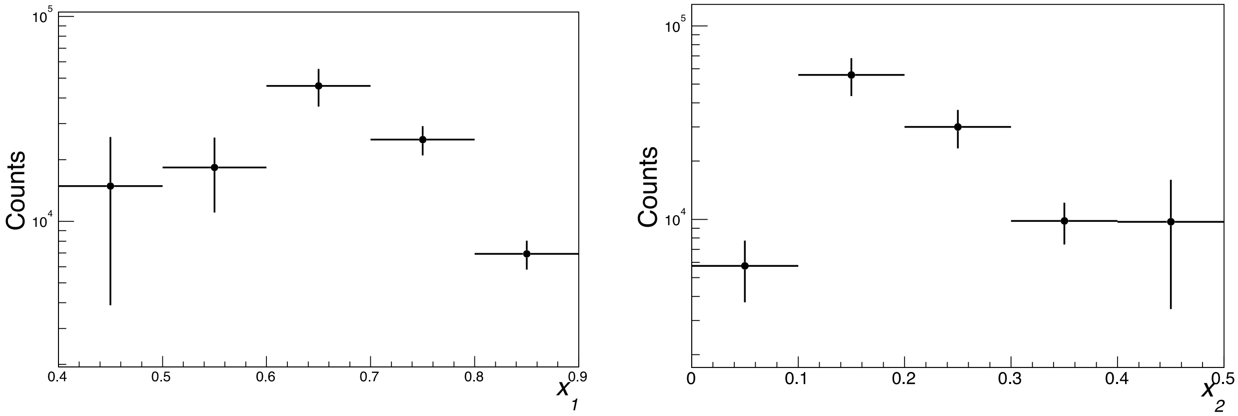


Figure 7. Expected distribution of Drell-Yan events, in terms of Bjorken-x_1 (beam) and x_2 (polarized target). The vertical axis is number of events and error bars are statistical.

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