Memorandum of Understanding
between
Fermi National Accelerator Laboratory
and the
E-906 Drell-Yan Experiment

12 December 2008
Version 1.01

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1 Introduction

This is a memorandum of understanding between the Fermi National Accelerator Laboratory (Fermilab) and the E-906/Drell-Yan Collaboration to perform the E-906 Experiment at Fermilab using a 120 GeV proton beam extracted to the NM4 hall (also known as the KTeV experimental hall).

The E-906/Drell-Yan Experiment plans to use Drell-Yan scattering to measure the antiquark structure of both the nucleon and nucleus, to measure absolute Drell-Yan cross sections and to examine partonic energy loss. The physics goals of the experiment are presented in proposals to Fermilab[1,2,3] and summarized in Section 2. In order to accomplish these goals, the spectrometer used by earlier Drell-Yan experiments (E-866, E772, *etc.*) must be reconfigured on a new beam line (as the previously used beam line has been decommissioned) and upgraded to handle higher detector rates and lower beam energy.

This memorandum is intended solely for the purpose of providing a budget estimate and a work allocation for Fermilab, the funding agencies and the participating institutions. It reflects an arrangement that is currently satisfactory to the parties, however, it is recognized and anticipated that changing circumstances of the evolving research program may necessitate revisions. The parties agree to negotiate amendments to this memorandum which will reflect such required adjustments.

2 E-906/Drell-Yan Goals and Summary

The Fermilab E-906/Drell-Yan experiment aims to measure nucleon and nuclear structure at the parton level using Drell-Yan scattering. This experiment will use the 120 GeV/c proton beam extracted from the Fermilab Main Injector. It is anticipated that it will begin collecting data in 2010.

In the Drell-Yan process, a quark (antiquark) in the beam hadron annihilates with an antiquark (quark) in the target. In the limit of large *x*-Feynman, only the beam quark and target antiquark distributions are important, allowing Drell-Yan scattering to probe selectively the antiquark sea of the target hadron. It can also measure interactions of the initial state quark in the nuclear medium. Several previous Drell-Yan experiments have already exploited these properties but were limited by statistics to rather low values of parton fractional momentum, *x*. At fixed *x*, the Drell-Yan cross section scales as the inverse of the square of the center-of-mass energy (*i.e.* approximately as $1/E_{beam}$). Because of this, the Drell-Yan cross section is a factor of seven *higher* at the lower beam energy of the Fermilab Main Injector than in previous Fermilab Tevatron (800 GeV/c

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[1] P.E. Reimer (E906 Collaboration), *Drell-Yan Measurements of Nucleon and Nuclear Structure with the Fermilab Main Injector: E906*, 29 Sept 2006, unpublished.
[2] P906 Collaboration, *Proposal for Drell-Yan Measurements of Nucleon and Nuclear Structure with the FNAL Main Injector*, 9 April 1999, unpublished.
[3] P.E. Reimer (E906 Collaboration), *Addendum to Proposal for Drell-Yan Measurements of Nucleon and Nuclear Structure with the FNAL Main Injector*, 29 Oct 2001, unpublished.

beam momentum) Drell-Yan experiments. At the same time, most di-muon backgrounds (primarily J/ψ production) scale with the square of the center-of-mass energy. As such, they will be suppressed in a Main Injector experiment, allowing for an increase in instantaneous luminosity of a factor of seven. Thus, for the same running time, a factor of almost 50 times more Drell-Yan events may be recorded. The Fermilab E-906 collaboration plans to exploit this to make several important physics measurements at larger *x*-values than previously achievable. This allows for improved studies of several interesting topics, discussed below.

While perturbative Quantum Chromodynamics (QCD) provides a good description of the evolution of the proton's parton distributions, it provides no clues as to their origins. With the Drell-Yan process' sensitivity to the antiquark distributions, it can be used to measure the ratio of anti-down to anti-up quarks in the proton. As measured in previous Drell-Yan experiments, this ratio is far from unity for moderate values of *x*, indicating a significant non-perturbative component in the proton's sea. At larger values of *x*, the data show the strengths of the anti-down and anti-up distributions becoming more equal, possibly indicating that the perturbatively generated sea is becoming dominant. The proposed spectrometer will have the reach to study this region and determine the ratio of anti-down to anti-up from measurements on liquid hydrogen and deuterium targets.

As $x \rightarrow 1$, there is considerable uncertainty in the distributions of valence quarks. This is in part due to a lack of proton data, and in part due to uncertainties in nuclear corrections, which are significant as $x \rightarrow 1$, even in deuterium. In the kinematic region of this experiment, the absolute Drell-Yan cross section is sensitive to these high-*x* parton distributions in the *beam proton*. Data from the previous Drell-Yan experiment shows a discrepancy with next-to-leading order cross section calculations which could be attributed to the uncertainty in the ratio d/u as $x \rightarrow 1$. The proton-proton absolute cross section measurements which Fermilab E-906 plans to make will provide the data—free of nuclear corrections—needed to determine the behavior of $4u+d$ as $x \rightarrow 1$ with good statistical precision.

When the proton is contained in a nucleus, the proton's parton distributions appear to be modified. In addition to hydrogen and deuterium, E-906 plans to collect data on a variety of nuclear targets to study these changes. Pions in meson exchange models of nuclear binding should lead to an enhancement of the antiquark sea in nuclei when compared to deuterium. While this was not seen by previous Drell-Yan experiments, the large statistical uncertainty at high-*x* allowed considerable freedom for these models. Due to the increased cross section at higher *x*, Fermilab E-906 data should be able to significantly constrain these models. Absolute cross section measurements on deuterium provide a measurement of $\bar{d}(x)+\bar{u}(x)$, a quantity so far only accessible through neutrino deep inelastic scattering cross section measurements on heavy nuclear targets. At the same time, the absolute Drell-Yan nuclear target cross sections measure nuclear effects that influence the interpretation of the neutrino data.

Finally, the Drell-Yan process can be used to study the interactions of fast, colored partons traversing cold nuclei. Since the final state muons only interact electromagnetically and not strongly, only the initial state strong interactions of the incident quarks are apparent. This makes Drell-Yan an ideal laboratory to study the energy loss of partons in nuclei—a subject of considerable interest to the Relativistic Heavy Ion community. Several models have been proposed to describe the energy loss process. By comparing different nuclei, previous Drell-Yan experiments have placed limits on parton energy loss within the context of these models. Because the lower beam energy provides both higher statistics and increased sensitivity to energy loss, this experiment plans to measure this energy loss and quantitatively distinguish between competing models.

Fermilab E-906 is a straight forward extension of the earlier Drell-Yan experiments at Fermilab. The apparatus to be constructed will be very similar to that used by previous high-rate Drell-Yan experiments at Fermilab. In fact it will reuse many of the detector components and much of the electronics from these and other Fermilab experiments. The proposed apparatus will consist of two large dipole magnets and a number of tracking/triggering stations. The liquid hydrogen, liquid deuterium and solid targets will be positioned upstream of the first magnet. The first magnet, which focuses the muons produced in the target, will contain the beam dump and a thick wall of absorber material, designed to allow only muons to traverse the active detector elements. The second magnet will provide the primary momentum measurement of the muons. A total of four tracking and triggering stations will be constructed between the two magnets and after the second magnet. Because of the lower beam energy, relative to previous Drell-Yan experiments, the entire layout of the experiment must be contracted along the beam axis. This necessitates the construction of a new muon focusing magnet.

3 Personnel and Institutions

3.1 Collaboration Leadership

The organization of the collaboration is described elsewhere[4]. The primary management responsibilities are those of the Spokespersons, Upgrade Manager, Safety Manager and Fermilab Liaison. The persons currently holding these positions are listed in Table 1.

Table 1 This table lists the management positions and the persons currently holding those positions in the E-906 Collaboration.

Position	Person	Affiliation
Spokespersons	Paul E. Reimer Don Geesaman	Argonne Argonne
Upgrade Manager	Paul E. Reimer	Argonne
Safety Manager	Chuck Brown	Fermilab
Fermilab Liaison	Chuck Brown	Fermilab

[4] P.E. Reimer (E906 Collaboration), Fermilab *E906/Drell-Yan Management Plan*, Version 0.2, April 16, 2007

3.2 Current Collaboration

The current membership of the E-906/Drell-Yan Collaboration by institution, along with positions and other research commitments is given in Table 2.

Table 2 Current members of the E-906 collaboration by institution.

Person	Position	Other Research Commitments
Abilene Christian University		
L.D. Isenhower	Professor	PHENIX, NIFFTE
M.E. Sadler	Professor	NIFFTE, MIPP, EPECUR
R.S. Towell	Professor	PHENIX, NIFFTE
S. Watson	Physicist	
Academia Sinica		
W.-C. Chang	Physicist	Spring-8
Y.-C. Chen	Physicist	CDF
D.-S. Su	Engineer	
Argonne National Laboratory		
J. Arrington	Physicist	JLab
D.F. Geesaman	Senior Physicist	
K. Hafidi	Physicist	JLab
R.J. Holt	Senior Physicist	JLab, EDM
H.E. Jackson	Senior Physicist	HERMES
P.E. Reimer	Physicist	
D. Potterveld		
P. Solvignon	Post Doc	JLab
University of Colorado		
E. Kinney	Professor	HERMES
Fermi National Accelerator Laboratory		
C.N. Brown		
University of Illinois		
N.C.R. Makins	Professor	HERMES
J.-C. Peng	Professor	
KEK		
S. Sawada		J-PARC
Kyoto University		
K. Imai	Professor	Spring-8, J-PARC
T. Nagae	Professor	Spring-8, J-PARC
Ling-Tung University		
T.-H. Chang	Professor	
Los Alamos National Laboratory		
G.T. Garvey		MiniBoone
M.J. Leitch		PHENIX
M.X. Liu		PHENIX
X. Jiang		
P.L. McGaughey		PHENIX

J.M. Moss		PHENIX
University of Maryland		
E. Beise	Professor	neutron physics
University of Michigan		
W. Lorenzon	Professor	HERMES, Radon-EDM
R. Raymond	Physicist	
RIKEN		
Y. Goto		PHENIX
A. Taketani		
Y. Fukao		
M. Togawa		
Rutgers University		
L. El Fassi	Post Doc	JLab
R. Gilman	Professor	JLab
R. Ransome	Professor	MINERvA
E. Schulte		MINERvA
Texas A&M University		
C.A Gagliardi	Professor	STAR
R.E. Tribble	Professor	Texas A&M Cyclotron Facility
Thomas Jefferson National Accelerator Facility		
D. Gaskell	Physicist	JLab
Tokyo Institute of Technology		
T.-A. Shibata	Professor	HERMES, PHENIX
Y. Miyachi	Professor	HERMES

4 Experimental Area and Beams

4.1 Experimental Area

The experiment will take place in the NM4 Hall (also known as the KTeV Hall). Fermilab will be responsible for removing old equipment not needed for this experiment from the hall; will be responsible for providing necessary utilities for the experiment in this hall; and will be responsible for other necessary modifications to the hall that are needed to fulfill Fermilab's responsibilities as outlined in Sec. 6.

4.2 Proton Beam Structure and Intensity

The experiment will use a primary proton beam with a momentum of 120 GeV extracted from the Main Injector. The experiment requires a slow spill with a maximum rate of 2×10^{12} protons/s with a macroscopic duty factor greater than 8% (one 5 s spill per minute) for a total of 7×10^{18} protons in a period of two years from the beginning of the experiment. (This number includes a factor of 1.3 to account for experimental efficiency and downtime, but not accelerator efficiency and downtime.) The experiment requires frequent target changes to control systematic effects. It is requested that the time between spills be sufficient to interchange targets. (In E-866, this was accomplished in less than 40 sec) If this is not possible, additional calendar time will be required to meet the physics goals.

The microscopic spill structure to the Fermilab beam is such that the protons are delivered in "buckets" that occur every 19 ns. The microscopic duty factor (which will be referred to as just duty factor) represents how evenly the protons are distributed over these buckets. An average duty factor of 67% for the High-Mass and 71% for the Low-Mass spectrometer configurations was achieved in E-866/NuSea. The average proton rate for E-906 has been greatly increased from E-866/NuSea. Backgrounds and rate effects from this increase have been studied, *assuming that there is no significant change in the duty factor* from E-866/NuSea and the E-906 collaboration believes that it can handle the associated rate effects. Therefore, E-906 requires that the extracted beam has essentially the same duty factor as was achieved for E-866/NuSea. **Specifically, E-906 requires an average duty factor of greater than 60% for the run. Spills with a duty factor of less than 25% (a cut used in E-866) are not counted as protons delivered to the experiment. E-906 recognizes that this may be difficult to achieve as high-intensity, slow-spill fixed-target beam has not been extracted from the Main Injector yet.**

5 Collaboration's Responsibilities

The general responsibilities of the collaboration institutes as well as the specific responsibilities of the individual institutions in terms of decommissioning and upgrading the spectrometer, data collection, analysis and decommissioning are outlined below. When providing experimental equipment, these responsibilities include appropriate support structures and alignment fixtures, unless otherwise specified. For the major tasks, these responsibilities are summarized in Table 3.

5.1 General Responsibilities of All Institutions

5.1.1 All institutions will support the normal research operating expenses (such as physicists' salaries, project managers' salaries, travel expenses, miscellaneous supplies and administrative support) of their respective groups working on this experiment.

5.2 Abilene Christian University

5.2.1 Abilene has primary responsibility for the fabrication, installation, operation and maintenance of the Station 3 and 4 hodoscope arrays. RIKEN will also participate in this task.

5.2.2 Abilene will also participate in the installation of the Station 1 and 2 hodoscope arrays.

5.2.3 Abilene will participate in the development and maintenance of the Monte Carlo code.

5.2.4 Abilene will participate in the data collection and analysis.

5.2.5 Abilene is responsible for the decommissioning of the Station 3 and 4 hodoscope arrays as outlined in Sec. 8.2.

5.3 Academia Sinica

5.3.1 Academia Sinica has primary responsibility for the development, operation and maintenance of the electronics and readout system for the Station 1 MWPC and the hodoscope arrays. Ling Tung University will also participate in this task.
5.3.2 Academia Sinica will participate in the development, implementation, programming and operation of the trigger system.
5.3.3 Academia Sinica will participate in the data collection and analysis.
5.3.4 Academia Sinica will participate in the development and implementation of the DAQ system.
5.3.5 Academia Sinica is responsible for the decommissioning of the electronics and readout for the Station 1 MWPC and hodoscope arrays as outlined in Sec. 8.2.

5.4 Argonne National Laboratory

5.4.1 Argonne will provide the Upgrade Manager to coordinate with the FNAL Liaison all aspects of Experiment installation.
5.4.2 Argonne will coordinate the transfer of up to a total of $1.2M from DOE-NP to Fermilab over the time frame of FY08-FY10, for partial support of experiment, magnet and beam line installation. This is outlined more fully in Sec. 7.

5.4.3 Argonne is responsible for the mapping of the field in the KTEV spectrometer magnet and for the field calculations of FMAG.
5.4.4 Argonne will participate in the development and maintenance of the Monte Carlo code.
5.4.5 Argonne will participate in the development and maintenance of the analysis code.
5.4.6 Argonne will participate in the data collection and analysis.
5.4.7 Argonne will participate in the implementation of the DAQ system.
4.5.7 Argonne will provide two Linux-based work stations and disk storage for DAQ.

5.5 University of Colorado

5.5.1 Colorado is responsible for the fabrication, installation, operation and maintenance of the Station 1 MWPC.
5.5.2 Colorado will participate in the data collection and analysis.
5.5.3 Colorado is responsible for the decommissioning of the Station 1 MWPC as outlined in Sec. 8.2.

5.6 University of Illinois

5.6.1 Illinois has primary responsibility for the fabrication, installation, operation and maintenance of the Station 1 and 2 hodoscope arrays. Abilene will also participate in this.

5.6.2 Illinois is responsible for the provision, installation, operation and maintenance of the MWPC, drift and prop. tube gas systems. It is assumed that these systems will use pieces recovered from other Fermilab systems and the HERMES experiment. Illinois will provide technical support to design, install and document the flammable gas distribution systems. E-906 will use two gas systems: Station 1 MWPC's will use CF_4:isobutane (80:20) and Stations 2, 3 and 4 will use Ar:ethane (50:50). Illinois is responsible for both systems. Safety documentation shall follow relevant FESHM chapters including:

- Flammable Gas Safety http://www-esh.fnal.gov/FESHM/6000/6020.3.html
- Pressure Vessels http://www-esh.fnal.gov/FESHM/5000/5031.htm
- Pressure Piping http://www-esh.fnal.gov/FESHM/5000/5031_1.htm

This item **specifically does not include** the flammable gas alarm systems (see Sec. 6.2.7) or the acquisition of the chamber gas itself.

5.6.3 Illinois is responsible for the development and maintenance of the analysis code.
5.6.4 Illinois will participate in the data collection and analysis.
5.6.5 Illinois is responsible for the decommissioning of the Station 1 and 2 hodoscope arrays as outlined in Sec. 8.2.

5.6.6 Illinois is responsible for the decommissioning of the MWPC and drift chamber gas systems as outlined in Sec. 8.2.

5.7 KEK

5.7.1 KEK will participate in the fabrication and operation of the Station 3 tracking chamber, subject to successful budget approval from a Japanese agency. RIKEN has primary responsibility for the Station 3 tracking chamber.
5.7.2 KEK will participate in the data collection and analysis.
5.7.3 KEK will participate in the decommissioning of the Station 3 tracking chamber arrays as outlined in Sec. 8.2.

5.8 Kyoto University

5.8.1 Kyoto will participate in the fabrication and operation of the Station 3 tracking chamber, subject to successful budget approval from a Japanese agency. RIKEN has primary responsibility for the Station 3 tracking chamber.
5.8.2 Kyoto will participate in the data collection and analysis.
5.8.3 Kyoto will participate in the decommissioning of the Station 3 tracking chamber arrays as outlined in Sec. 8.2.

5.9 Ling-Tung University

5.9.1 Ling-Tung will participate in the development, operation and maintenance of the electronics and readout system for the Station 1 MWPC and the hodoscope arrays. Academia Sinica has primary responsibility for this readout.

5.9.2 Ling-Tung will participate in the development, implementation, programming and operation of the trigger system.
5.9.3 Ling-Tung will participate in the data collection and analysis.
5.9.4 Ling-Tung will participate in the development and implementation of the DAQ system.
5.9.5 Ling-Tung is responsible for the decommissioning of the electronics and readout for the Station 1 MWPC and hodoscope arrays as outlined in Sec. 8.2.

5.10 Los Alamos National Laboratory

5.10.1 Los Alamos has primary responsibility for the reconditioning, installation, operation and maintenance of the Station 4 prop. tubes. Rutgers will assist with the Station 4 prop. tubes.
5.10.2 Los Alamos will participate in the development and maintenance of the Monte Carlo codes.
5.10.3 Los Alamos will participate in the development and maintenance of the analysis codes.
5.10.4 Los Alamos will participate in the data collection and analysis.
5.10.5 Los Alamos is responsible for the decommissioning of the Station 4 prop. tubes as outlined in Sec. 8.2.

5.11 University of Maryland

5.11.1 Maryland will participate in the development and maintenance of the DAQ system.
5.11.2 Maryland will work with the Fermilab's cryogenic target experts to develop the cryotarget control systems and participate in the integration of target assemblies and target controls.
5.11.3 Maryland will participate in the data collection and analysis.
5.11.4 Maryland is responsible for the decommissioning of the DAQ and cryotarget control systems as outlined in Sec. 8.2.

5.12 University of Michigan

5.12.1 Michigan, working with Fermilab, will lead the design, fabrication, installation and maintenance of the cryogenic target system.
5.12.2 Michigan is responsible for providing and testing new cryocoolers (including cold heads and compressors) modifying the E-866 targets for use with the new cryocoolers, participating in the integration of target assemblies and target controls, and for refurbishing the target table assembly. (It is expected to use the present rails, lead screws and encoders.)
5.12.3 Michigan will participate in the data collection and analysis.

5.12.4 Michigan is responsible for the decommissioning of the target system as outlined in Sec. 8.2, with the exception of the storage and disposal of the activated elements of the target system.

5.13 RIKEN

5.13.1 RIKEN will have primary responsibility for the fabrication, installation, operation and maintenance of the Station 3 tracking chamber, subject to successful budget approval from a Japanese agency. KEK, Kyoto and Tokyo Tech will also participate in this.
5.13.2 RIKEN will participate in the fabrication, installation, operation and maintenance of the Station 3 and Station 4 hodoscopes. Abilene has primary responsibility for these hodoscopes.
5.13.3 RIKEN will participate in the data collection and analysis.
5.13.4 RIKEN is responsible for the decommissioning of the Station 3 tracking chamber arrays as outlined in Sec. 8.2.

5.14 Rutgers University

5.14.1 Rutgers is responsible, in conjunction with Academia Sinica and Ling-Tung University, for the development, fabrication, installation and maintenance of the trigger.
5.14.2 Rutgers is responsible for the reconditioning, installation, operation and maintenance of the Station 2 drift chambers.
5.14.3 Rutgers will assist with the installation and maintenance of the Station 4 prop. tubes. Los Alamos has primary responsibility for this.
5.14.4 Rutgers will participate in the data collection and analysis.
5.14.5 Rutgers is responsible for the decommissioning of the Station 2 drift chambers as outlined in Sec. 8.2.

5.15 Texas A&M University

5.15.1 Texas A&M will participate in the data collection and analysis.
5.15.2 Texas A&M will assist with the trigger development. Rutgers has primary responsibility for this.

5.16 Thomas Jefferson National Accelerator Facility (JLab)

5.16.1 JLab will participate in the data collection and analysis.

5.17 Tokyo Institute of Technology

5.17.1 Tokyo Tech will participate in the fabrication and operation of the Station 3 tracking chamber, subject to successful budget approval from a Japanese agency. RIKEN will have primary responsibility for the Station 3 tracking chamber.
5.17.2 Tokyo Tech will participate in the data collection and analysis.

5.17.3 Tokyo Tech will participate in the decommissioning of the Station 3 tracking chamber arrays as outlined in Sec. 8.2.

Table 3 This table summarizes, for each significant task in the spectrometer upgrade where the E906/Drell-Yan collaboration has the lead, the institution(s) with primary and secondary responsibility. Fermilab's responsibilities are discussed in Sec. 6.

Task	Primary Institute	Secondary Institute
Spectrometer		
Design	Argonne	Fermilab, Texas A&M
Upgrade Management	Argonne	
Target		
Hardware	Michigan	Fermilab
Controls	Maryland	Fermilab
FMag Field Simulation & Map	Argonne	
Station 1		
Hodoscope	Illinois	Abilene Christian
Hodoscope Readout	Academia Sinica	Ling-Tung, Illinois, Abilene Christian
MWPC	Colorado	
MWPC Readout	Academia Sinica	Ling-Tung
KMag Field Map	Argonne	
Station 2		
Hodoscope	Illinois	Abilene Christian
Hodoscope Readout	Academia Sinica	Ling-Tung, Illinois, Abilene Christian
Drift Chamber	Rutgers	
Drift Chamber Readout	Rutgers	
Station 3		
Hodoscope	Abilene Christian	RIKEN
Hodoscope Readout	Academia Sinica	Ling-Tung, Abilene Christian
Drift Chamber	RIKEN	KEK, Kyoto, Tokyo Tech
Drift Chamber Readout	RIKEN	KEK, Kyoto, Tokyo Tech, Rutgers
Station 4		
Hodoscope	Abilene Christian	RIKEN
Hodoscope Readout	Academia Sinica	Ling-Tung, Abilene Christian
Prop. Tubes	Los Alamos	Rutgers
Prop. Tube Readout	Los Alamos	Rutgers
DAQ	Maryland	Academia Sinica, Argonne, Ling-Tung, Rutgers
Trigger	Rutgers	Academia Sinica, Ling-Tung, Argonne
Gas System	Illinois	Fermilab
Analysis and Monte Carlo Software	Illinois	Abilene Christian, Academia Sinica, Argonne, Los Alamos, Maryland

6 Fermilab's Responsibilities

In order to successfully complete the proposed measurement, Fermilab is directly responsible for the tasks and equipment described in this section. For convenience they are listed by the Fermilab Division or Section most likely to be responsible for these tasks, but this is not a strict division. Fermilab has estimated its cost to mount E-906 to be approximately \$1.0M in materials and supplies and approximately \$1.4M in labor[5,6], both including contingency and indirect costs. These costs are summarized in Table 4.

6.1 Accelerator Division

6.1.1 Provide primary proton beam as outlined in Sec. 4.2

6.1.2 Provide beam line and appropriate instrumentation, cabling and electronics. This includes reactivating existing SWICs and BLMs in the beam line to NM4 and adding a target SWIC and SEM just upstream of the E906 cryotargets.

6.1.3 Provide appropriate radiation shielding, radiation safety interlocks and handle all aspects of radiation safety monitoring for the beam intensity delivered. As part of this, provide lead or other shielding curtain which can be lowered between targets and beam dump to allow access to the targets for servicing and repair. This MOU calls for 2×10^{12} 120 GeV proton/s for 5s/min (a total of 1×10^{13}/min) being dumped in the first 2 feet of FMAG.

6.1.4 Renovate existing radioactive water system (RAW) to cool the beam dump.

6.2 Particle Physics Division

6.2.1 Prepare NM4 area (KTeV Hall) to house E-906/Drell-Yan.

6.2.2 Provide, install and maintain utilities (power supplies and cooling water) for both spectrometer magnets.

6.2.3 Design FMAG magnet using SM3 coils and magnet steel from SM12; fabricate new parts and modify reused parts as required; provide and install a small water-cooled beam dump in FMAG and provide necessary water cooling; install the new magnet in NM4. Note that the current crane in the NM4 area can only support 25t while the steel blocks are 30t. Fermilab is responsible for either reinforcing the crane, cutting the blocks into smaller pieces so that they can be moved, or finding alternative means of moving these blocks.

6.2.4 Move the KTeV magnet to the appropriate location, approximately 10 ft downstream of the present location, for the Drell-Yan spectrometer.

6.2.5 Provide "Ziptrack" magnetic field mapping apparatus. Argonne is responsible for mapping the KTeV magnet field with "Ziptrack".

6.2.6 Move and install muon ID absorber walls consisting of approximately 36" of steel or comparable material and 36" of concrete. If constructed from the material previously used in MW, these materials can be moved with the existing 25t crane.

6.2.7 Provide some support for the cryogenic targets. This includes:

- Provide existing E-866 cryogenic targets and target table assembly.

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[5] David Christian, *et al.*, Estimated Cost to Mount E906, 4 December 2006, EPP-doc-296-v15.

[6] EPP-doc-431-v2.

- Provide technical and safety support for the hydrogen and deuterium targets. Engineering and technical work will be done in cooperation with Michigan.

- Provide hydrogen tent, vent system and hydrogen gas alarm system for targets.
- Examine the existing targets and measure their present activation. It is expected that the present flasks can be reused. If not, Fermilab is expected to provide and test new flask assemblies.

- Provide the vacuum pumps and pump carts for the cryotargets.
- Fermilab will commission the targets, but will not provide operators on shift.
- Provide the solid targets and target supports.

6.2.8 Provide high purity (99.9%) hydrogen and (99.99%) deuterium gas for use in cryogenic targets. If Fermilab wants to recover this gas, Fermilab will provide a recovery system and be responsible for the recovery.

6.2.9 Provide flammable gas alarm system and provide technical and safety review of design and installation of chamber gas distribution system.

6.2.10 Conduct flammable gas safety review of tracking chambers.

6.2.11 Provide rigging for installation of spectrometer elements and for removal of spectrometer elements at the conclusion of the experiment.

6.2.12 Provide facilities for the collaboration to use for hodoscope (scintillator and light guide) fabrication.

6.2.13 Provide wire winding facilities for the collaboration to use for fabrication of the Station 1 MWPC, and possibly Station 3 drift chambers.

6.2.14 Review designs of Station 1 MWPC and possibly Station 3 drift chambers before fabrication at Fermilab

6.2.15 Provide counting house and electronics areas with appropriate utilities installed.

6.2.16 Provide 12 electronic equipment racks[7].

6.2.17 Provide equipment staging areas as needed for assembly of the spectrometer and for the removal of the spectrometer at the conclusion of the experiment.

6.2.18 Provide office space and furniture, using a combination of Wilson Hall and near the experimental area, for approximately 10 persons for the duration of the experiment and analysis.

6.2.19 Provide an alignment survey of the spectrometer once installed. The experimenters will supply alignment marks on the detector elements in consultation with Fermilab.

6.3 Computing Division

6.3.1 Provide appropriate networking at KTeV hall including WiFi in both the counting area and detector hall for commissioning, data transfers to mass storage, network access for user's laptops, etc. Provide firewalls/bridges which Fermilab deems necessary to isolate the experiment's network from the general Fermilab network.

[7] Available from Fermilab surplus; Scott Borton, e-mail.

6.3.2 Provide "General Computing" accounts for collaborators (see Sec. 3.2). Primary analysis and Monte Carlo computing will be done on LINUX-based PC's provided by the collaboration.
6.3.3 Provide storage for 5Tb of raw data. The collaboration also plans to keep a second copy of the raw data on disk.
6.3.4 Provide the following electronics (and have spares available) from PREP:

- 12 VME crates;
- 18 LeCroy 4416 Discriminators;
- 6 CAMAC crates with 350 W or larger power supply;
- 56 LeCroy 3377 multi-hit TDC (LRS3377);
- 10 NIM crates;
- 22 LM-E5 +5V power supplies or equivalent;
- 22 LeCroy 429A ;
- 24 PS710 discriminators (alternatives are LeCroy 623 or 621);
- 12 LeCroy 624 Mean Timers;
- 6 LeCroy 4616 NIM-to-ECL level translators;
- HV power supplies for approximately 416 channels for photomultiplier tubes (LeCroy 1440 HV systems would work for this);
- 10 LeCroy 4434 scalers; and
- 3 oscilloscopes.

6.4 Environment, Safety and Health

6.4.1 Assistance with safety reviews, training, and personal dosimetry**.**
6.4.2 Reinstall the necessary MUX stations in the beam line.

6.5 Facilities Engineering Services

6.5.1 Participate in identification of building system requirements to include HVAC, and work with PPD to identify the most efficient way to satisfy the necessary requirements. Provide building system maintenance in accordance with current FESS core functions and responsibilities. Assess the ability to provide standard utilities and services to support the experiment, specifically electrical power and industrial cooling water (ICW).

Table 4 This table summarizes Fermilab's estimate of the Materials and Services costs to mount E-906/Drell-Yan in NM4. Indirect costs are based on 2008 rates[8]. "Base" is rounded to the nearest $1k. The "Total" and "W/cont." columns use unrounded "Base" and then round to the nearest $1k.

Description	MOU Ref.	Base	Contin-gency	W/cont.	Indirect Rate	Total
Accelerator Division						
Proton Beam	6.1.1					
Beam Line	6.1.2	$338k	1.25	$422k	1.16	$490k

[8] Indirect rates for 2008 provided by Jeff Appel, e-mail 24-Sept-2008.

Radiation Shielding[9]	6.1.3	$30k	1.30	$39k	1.16	$45k
RAW system[10]	6.1.4	$4k	1.25	$5k	1.16	$6k
Total Accelerator		*$372k*		*$466k*		*$541k*
Particle Physics Division						
NM4 Area Prep	6.2.1	$40k	1.25	$50k	1.16	$58k
Spect. Mag. Utilities[11]	6.2.2	$27k	1.50	$40k	1.16	$47k
Assemble M1	6.2.3	$10k	2.00	$20k	1.85	$36k
Move KTeV Magnet[9]	6.2.4	$12k	1.50	$18k	1.16	$21k
Mag. Map (zip track)[11]	6.2.5	Available for use				
Muon ID wall[9]	6.2.6	$10k	1.50	$15k	1.16	$17k
Cryotarget Support[9]	6.2.7	$24k	1.50	$35k	1.16	$41k
Gas system support	6.2.8	$30k	1.50	$45k	1.16	$52k
Target Gas	6.2.9	Available at Fermilab				
Flammable Gas Safety Review	6.2.10	$0k	1.50	$0k	1.16	$0k
Rigging for installation[9]	6.2.11	$5k	1.50	$8k	1.16	$9k
Scintillator Shop	6.2.12	$0k	1.50	$0k	1.16	$0k
Chamber Winding Facilities[11]	6.2.13	$10k	1.50	$15k	1.16	$17k
Chamber Design Review	6.2.14	$0k	1.50	$0k	1.16	$0k
Near Detector Utilities[11]	6.2.15	$20k	1.50	$30k	1.16	$35k
Electronic Equip. Racks[7]	6.2.16	Available from surplus at Fermilab				
Staging areas	6.2.17	Space Available in NM4				
Office Space	6.2.18	No M&S cost				
Alignment	6.2.19	Labor only, no M&S				
Total PPD		*$187k*		*$276k*		*$333k*
Computing Division						
Network Connections	6.3.1	$0k	1.00	$0k	1.16	$0k
Data Storage	6.3.3	$0k	1.00	$0k	1.16	$0k
PREP	6.3.4	$20k	1.00	$20k	1.16	$23k
Total CD		*$20k*		*$20k*		*$23k*
Environment, Safety and Health						
Assistance	6.4.1	$0k		$0k		$0k
MUX	6.4.2	$0k		$0k		$0k
Total ES&H		*$0k*		*$0k*		*$0k*
Facilities Engineering Services						
NM4 Utilities/HVAC	6.5.1	$0k	1.25	$0k	1.16	$0k
Total FES		*$0k*		*$0k*		*$0k*
Grand Total		**$579k**		**$762k**		**$897k**

[9] Rates provided by Chuck Brown, e-mail, 22-Sept-2008.
[10] Cost from Chuck Brown, e-mail, 21-Oct-2008.
[11] Cost from Dave Christian, e-mail, 03-Oct-2008.

Table 5 This table summarizes Fermilab's estimate of the labor costs to mount E-906/Drell-Yan in NM4. Indirect costs are based on 2008 rates[8]. "Base" is rounded to the nearest $1k. The "Total" and "W/cont." columns used unrounded "Base" and then round to the nearest $1k.

Description	MOU Ref.	Base	Contin-gency	W/cont.	Indirect	Total
Accelerator Division						
Proton Beam	6.1.1	$0k	0.00	$0k	1.80	$0k
Beam Line	6.1.2	$246k	1.25	$307k	1.80	$553k
Radiation Shielding[9]	6.1.3	$0k	1.00	$0k	1.80	$0k
RAW system[10]	6.1.4	$6k	1.25	$8k	1.80	$14k
Total AD		*$252k*		*$315k*		*$566k*
Particle Physics Division						
NM4 Area Prep	6.2.1	$82k	1.50	$123k	1.61	$198k
Spect. Mag. Utilities[11]	6.2.2	$52k	1.50	$78k	1.61	$126k
Assemble M1	6.2.3	$46k	1.50	$69k	1.61	$111k
Move KTeV Magnet[9]	6.2.4	$3k	1.50	$5k	1.61	$7k
Mag. Map (zip track)[11]	6.2.5	$4k	1.50	$6k	1.61	$10k
Muon ID wall[9]	6.2.6	$0k	1.50	$0k	1.61	$0k
Cryotarget Support[9]	6.2.7	$76k	1.50	$114k	1.61	$184k
Target Gas	6.2.8	$0k	1.50	$0k	1.61	$0k
Gas system support	6.2.9	$1k	1.50	$2k	1.61	$2k
Flammable Gas Safety Review	6.2.10	$1k	1.50	$2k	1.61	$2k
Rigging for installation[9]	6.2.11	$2k	1.50	$3k	1.61	$4k
Scintillator Shop	6.2.12	$0k	1.50	$0k	1.61	$0k
Chamber Winding Facilities[11]	6.2.13	$5k	1.50	$8k	1.61	$12k
Chamber Design Review	6.2.14	$0k	1.50	$0k	1.61	$0k
Near Detector Utilities[11]	6.2.15	$15k	1.50	$23k	1.61	$36k
Electronic Equip. Racks[7]	6.2.16	$0k	1.50	$0k	1.61	$0k
Staging areas	6.2.17	$0k	1.50	$0k	1.61	$0k
Office Space	6.2.18	$0k	1.50	$0k	1.61	$0k
Alignment	6.2.19	$0k	1.50	$0k	1.61	$0k
Total PPD		*$287k*		*$430k*		*$693k*
Computing Division						
Network Connections	6.3.1	$0k	1.00	$0k	1.68	$0k
Data Storage	6.3.3	$0k	1.00	$0k	1.68	$0k
PREP	6.3.4	$20k	1.00	$20k	1.68	$34k
Total CD		*$20k*		*$20k*		*$34k*
Environment, Safety and Health						
Assistance	6.4.1	$0k		$0k		$0k
MUX	6.4.2	$0k		$0k		$0k
Total ES&H		*$0k*		*$0k*		*$0k*
Facilities Engineering Services						
NM4 Utilities/HVAC	6.5.1	$0k	1.25	$0k	1.38	$0k
Total FES		*$0k*		*$0k*		*$0k*

Grand Total		**$559k**		**$765k**		**$1,293k**

7 Schedule and Budget

The reconfiguration of the spectrometer will begin in fall, 2008 and will be completed by summer, 2010. The experiment will start collecting data in summer, 2010. This schedule is subject to the final budget and funding timeline.

The budgets and sources of funding for the E-906/Drell-Yan spectrometer reconfiguration are listed in Table 6.

Table 6 This table shows the expected funding by source, institution, and fiscal year for the E-906/Drell-Yan spectrometer upgrade.

		US Fiscal Year				
Funding Source	Institution	2007	2008	2009	2010	Total
US DOE Office of Nuclear Physics						
	Abilene			$130k	$ 12k	$142k
	Argonne	$100k				$100k
	Argonne to Fermilab	$275k[a]	$292k[a]	$150k	$291k	$1,008k
	Colorado			$90k	$ 98k	$188k
	DOE/ONP Total	$375k	$292k	$370k	$401k	$1,438k
US NSF						
	Illinois			$20k	$20k	$40k
	Maryland				$50k	$50k
	Michigan				$117k	$117k
	Rutgers			$15k		
Japan						
	RIKEN		$20k[b,c]	$300k[b,c]	$15k[b,c]	$335k[b,c]
Taiwan						
	Academia Sinica, Ling-Tung		$30k	$200k	$100k	$330k

[a] This money is already available at Argonne. DOE/Office of Nuclear Physics will "take back" this money and transfer it to Fermilab.
[b] Here, the year refers to the Japanese Fiscal Year which starts in April.
[c] Subject to successful budget approval from a Japanese agency.

7.1 Funding for Fermilab activities related to installation of E-906/Drell-Yan

To offset the M&S expense to Fermilab of mounting the experiment, the collaboration and Fermilab expect that DOE/Office of Nuclear Physics will provide up to a maximum of $1,008k. These M&S expenses are outlined in Table 4 and Section 6. In addition, this money may be used for the labor expense of assembling the FMag. Specifically, Argonne is coordinating the transfer of $1,008k from DOE/Office of Nuclear Physics to Fermilab over three fiscal years. The expected funding scenario is given in Table 7.

Table 7 This table lists the expected funding profile from DOE/Office of Nuclear Physics to Fermilab for the installation of E-906/Drell-Yan.

Fiscal Year				
2007	2008	2009	2010	Total
$275k	$292k	$115k	$291k	$1,008k

7.2 Timeline

The experiment will be ready to take test data in spring 2010 and production data in summer 2010. In order to maintain this tight schedule, the FMag assembly, KMag movement, and the downstream end of the beam line and "heavy" crane work must be completed in NM4 by May, 2009, allowing the collaboration access to the hall with no interference from these activities.

8 Special Considerations

8.1 During Construction, Installation, and Operation of the Experiment

8.1.1 The responsibilities of the Spokespersons and procedures to be followed by experimenters are found in the Fermilab publication "Procedures for Experimenters" (PFX)[12]. The Spokespersons agree to those responsibilities and to follow the described procedures.

8.1.2 To carry out the experiment, a number of Environment, Safety and Health (ES&H) reviews are necessary. The procedures to carry out these various reviews are found in the Fermilab publication "Review Procedures for Experiments" (RPX)[12]. The Spokespersons undertake to follow those procedures in a timely manner.

8.1.3 A Hazard Identification Checklist for the E-906/Drell-Yan experiment is shown in Appendix A.

8.1.4 For the purpose of estimating budgets, specific products and vendors may be mentioned within this memorandum. At the time of purchasing, the policies of the procuring institution shall apply. This may result in the purchase of different products and/or from different vendors.

8.1.5 The Spokespersons will undertake to ensure that no PREP and computing equipment be transferred from the experiment to another use except with the approval of and through the mechanism provided by the Computing Division management. The Spokespersons also undertake to ensure that no modifications of PREP equipment take place without the knowledge and consent of the Computing Division management.

8.1.6 Each institution will be responsible for maintaining and repairing both the electronics and the computing hardware supplied by them for the experiment,

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[12] *Procedures for Experimenters* (Fermi National Accelerator Laboratory, 1999) http://www.fnal.gov/directorate/documents/pfx.pdf)

unless otherwise specified in this memorandum. All items for which the experiment requests that Fermilab perform maintenance and repair appear explicitly in this memorandum.

8.1.7 The experiment will consult with the Computing Division on issues involving on-line data acquisition and/or data communications equipment brought to Fermilab to be integrated with Fermilab owned equipment.

8.2 At the Completion of the Experiment:

8.2.1 The Spokespersons are responsible for the return of all PREP equipment, computing equipment and non-PREP data acquisition electronics. If the return is not completed after a period of one year after the end of running, the Spokespersons will be required to furnish, in writing, an explanation for any non-return.

8.2.2 The experimenters agree to remove the non-Fermilab experimental equipment as the Laboratory requests them to. They agree to remove it expeditiously and in compliance with all ES&H requirements, including those related to transportation. All the expenses and personnel for the removal will be borne by the experimenters, except that rigging and staging areas will be provided by Fermilab as specified in 6.2.11 and 6.2.17. Fermilab will also remain responsible for the removal and storage cryogenic and solid targets which likely will be radioactive and for FMag.

8.2.3 The experimenters will assist the Fermilab Divisions and Sections with the disposition of any articles left in the offices they occupied, including computer printout, disks, magnetic tapes, etc. Disposition of magnetic tapes will be in compliance with Fermilab's tape retirement policies. Costs for shipment of printout and/or tapes will be borne by the receiving institution.

8.3 Publications and Reviews

8.3.1 Electronic versions of all theses, where available, will be submitted to the Fermilab Information Resources Department. Submission instructions are available at http://fnalpubs.fnal.gov/techpubs/thesesinstruct.html.

8.3.2 Electronics versions of all preprints, where available, will be submitted to the Fermilab Information Resources Department. Submission instructions are available at http://fnalpubs.fnal.gov/techpubs/guidelines.html.

8.3.3 Experimenters agree to participate in reviews of their programs as requested.

SIGNATURES

P. Reimer – E-906 Co-spokesperson Date 12 Dec 08

D. Geesaman – E-906 Co-spokesperson Date 12 Dec 08

R. Dixon – Accelerator Division Head Date 12-16-08

G. Bock – Acting Particle Physics Division Head Date 12/16/08

V. White – Computing Division Head Date 12/16/08

R. Ortgiesen – FESS Head Date 12-16-08

N. Grossman – ES&H Director Date 15-Dec-08

S. Holmes – Associate Director for Accelerators Date 12/16/08

Y-K. Kim – Deputy Director Date 12/16/08

P. Oddone – Director Date 12/16/08

SIGNATURES

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P. Reimer – E-906 Co-spokesperson Date

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V. White – Computing Division Head Date

R. Ortgiesen – FESS Head Date

N. Grossman – ES&H Director Date

S. Holmes – Associate Director for Accelerators Date

Y-K. Kim – Deputy Director Date

P. Oddone – Director Date

Appendix A. Hazard Analysis Checklist

The hazard analysis checklist is given in Table 8.

Table 8 Hazard analysis checklist for E906/Drell-Yan.

Cryogenics		**Electrical Equipment**		**Hazardous/Toxic Materials**	
	Beam line magnets		Cryo/Electrical devices		List hazardous/toxic materials
	Analysis magnets		capacitor banks		planned for use in a beam line or experimental enclosure:
1	Target (lH_2 and ld_2)	2	high voltage	5	Lead shielding curtain
	Bubble chamber		exposed equipment over 50 V		
Pressure Vessels		**Flammable Gases or Liquids**			
	inside diameter	Type:	ethane (with Ar) isobutene (with CF_4)		
	operating pressure	Flow rate:	15 l/min ethane 1 l/min isobutane		
	window material	Capacity:	4200 l ethane 200 l isobutane		
	window thickness	**Radioactive Sources**			
Vacuum Vessels			permanent installation	**Target Materials**	
	inside diameter	3	temporary use		Beryllium (Be)
	operating pressure	Type:	^{55}Fe (sealed), and ^{90}Sr (sealed)		Lithium (Li)
	window material	Strength:	≈ 5 μCi (both)		Mercury (Hg)
	window thickness	**Hazardous Chemicals**			Lead (Pb)
Lasers			Cyanide plating materials	6	Tungsten (W)
	Permanent installation		Scintillation Oil		Uranium (U)
	Temporary installation		PCBs		Other
	Calibration		Methane	**Mechanical Structures**	
	Alignment		TMAE		Lifting devices
type:			TEA	7	Motion controllers
Wattage:			photographic developers	8	scaffolding/elevated platforms
class:		4	Other: Activated Water?		Others

Notes:

1. Liquid hydrogen and liquid deuterium targets will contain approximately 2.2 l of liquid each.
2. High voltage will be used to power wire chambers and photomultiplier tubes at each tracking station.
3. We do not anticipate bringing sources from off site. We hope to be able to check out appropriate sources for testing from Fermilab and keep these sources in NM4, with appropriate security, for the duration of the installation and testing work on the spectrometer.
4. Cooling water for beam dump will require a closed-loop radioactive water system.
5. There will be a removable lead shielding curtain between the target and beam dump to allow for service work to take place on the target.
6. We require a solid tungsten (W) target which will receive approximately 10% of the experiment's integrated proton beam.
7. The liquid hydrogen, liquid deuterium, empty and solid targets will be mounted on a remotely movable platform, which will allow the experiment to change targets between beam spills and hence minimize systematic effects.
8. The downstream detector stations are of such size that temporary ladders and platforms may be necessary for installation.