Addendum to Proposal for Drell-Yan Measurements of Nucleon and Nuclear Structure with the FNAL Main Injector

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Abstract

We previously proposed measuring the fractional momentum (x) dependence of the ratio of the anti-down to anti-up quark distributions in the proton, $\bar{d}(x)/\bar{u}(x)$, using proton induced Drell-Yan reactions at 120 GeV. Since the submission of this proposal in April 2001, we have continued our work toward the realization of this experiment. In this addendum, we discuss details regarding the implementation of the experiment.

1   Introduction

In our proposal [1], we outlined an experimental program which will determine $\bar{d}_p(x)/\bar{u}_p(x)$ for $0.1 < x < 0.45$, where x is the fractional momentum carried by the struck quark. This is accomplished by measuring the ratio of proton-induced Drell-Yan cross sections on hydrogen
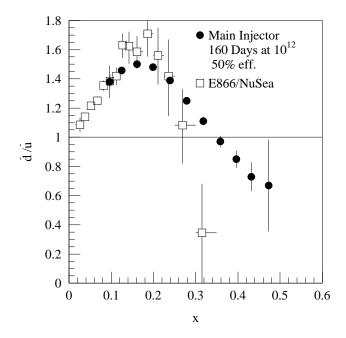
Figure 1: Projected results for the extraction of $\bar{d}/\bar{u}$ from a 160 day, 50% efficiency run with 10^{12} protons per pulse on 50 cm long liquid hydrogen and deuterium targets with the proposed apparatus. The shape of the distribution for the projected P906 results is based on the MRST [7] distribution of $\bar{d}/\bar{u}$. This, in turn, is primarily determined by a fit to the E866/NuSea Drell-Yan cross sections. Also shown are the E866/NuSea results. Note that the large statistical uncertainties in the high-x E866/NuSea data give considerable latitude to the MRST fit.

and deuterium. The deuterium data will also be directly sensitive to the strength of the antiquark sea, $\bar{d}_p(x) + \bar{u}_p(x)$, over this same range. At the same time, the experiment will measure proton-induced Drell-Yan cross sections on a number of nuclear targets.

In measuring $\bar{d}(x)/\bar{u}(x)$ the experiment is probing the origin of the partonic sea in the nucleon. The sea was originally believed to arise from gluonic splitting which would produce a flavor symmetric sea [2, 3]. This expectation was not born out in measurements done by the NMC [4] and NA51 [5] collaborations whose results showed $\int \bar{d}(x) - \bar{u}(x)dx = 0.148\pm0.039$ and $\left.\frac{\bar{u}}{\bar{d}}\right|_{x=0.18} = 0.51\pm0.04\pm0.05$ respectively. Using the Drell-Yan mechanism, Fermilab E866/NuSea measured the ratio of $\bar{d}/\bar{u}$ as a function of x over the range $0.015 \leq x \leq 0.35$ [6]. This data showed a significant excess of $\bar{d}$ quarks over $\bar{u}$ quarks at moderate x, but for $x > 0.25$, the light quark sea started to become symmetric. Unfortunately, this is also the region in which the measurement became statistically limited. P906 will extend these measurements to larger values of x. The FNAL E866/NuSea data are shown in Fig. 1 along with the statistical uncertainty which will be achieved by the proposed experiment. A more complete discussion of the data and its implications on the origins of the partonic sea may be found in our proposal [1].

The experiment will also collect Drell-Yan data using nuclear targets. This data will be sensitive to modifications of the sea in nuclei, providing a comparison with νDIS measurements of the strength of the sea. In addition, this data will be a valuable cross check on possible nuclear modifications in the deuterium data which is used to extract $\bar{d}(x)/\bar{u}(x)$. A
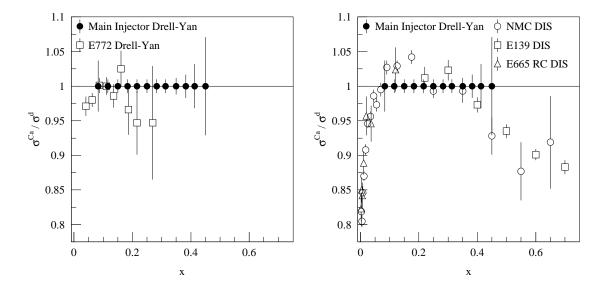
Figure 2: FNAL E772 Drell-Yan results (left) and a compilation of deep inelastic scattering (right) results on the ratio of cross sections of calcium to deuterium, compared with the statistical uncertainties of the proposed measurement (which are arbitrarily plotted at 1.0). The systematic error is expected to be less than 1%.

comparison of the expected statistical uncertainty achievable by the proposed experiment and existing Drell-Yan and DIS nuclear data is shown in Fig. 2. Also of importance is the information about partonic energy loss which can be extracted from this data. Within the context of different models, analyses of E866/NuSea and E772 nuclear Drell-Yan data show the energy loss of color-charged particles traveling through a colored media is consistent with no energy loss [8] or show significant energy loss [9]. The data collected by P906 will be able to clearly distinguish between these models. Again, a more complete discussion of the importance of the nuclear data is found in our proposal [1].

The experimental apparatus is based on the cumulative experience from E605, E772, E789 and E866 for the best technique to handle high luminosities in a fixed target Drell-Yan experiment. The apparatus uses relatively short liquid hydrogen, deuterium and solid nuclear targets. The muons produced in the target travel through two independent magnetic fields which focus the muons and measure their momentum. Within the first magnet a beam dump absorbs the uninteracted beam and a wall of hadronic absorber prevents hadrons from traversing the remaining detector. The detector is shown schematically in Figs. 3, 4 and 5. We are planning on housing this experiment in the Meson East experimental hall. This is primarily based on the crane capacity needed to assemble the "M1" magnet [10].

2 Experimental and Funding Time Line

Most of the equipment used in the 906 detector is being recycled from other experiments. The major new component of the detector is the focusing magnet, denoted "M1" in Fig. 3. A new magnet is necessary because of the very different energy of the muons produced with a 120 GeV beam. As described in our proposal, this magnet will be constructed using new coils which Argonne will have manufactured, and using the steel from the existing SM12 magnet. Approximately 1/3 the SM12 return yoke steel is necessary for this magnet
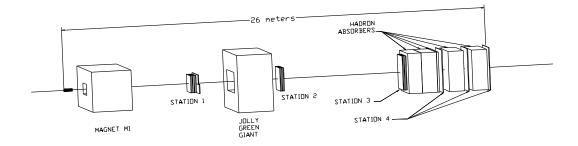
Figure 3: Schematic diagram of the proposed detector.

and must be reserved for this purpose. We estimate that construction of this magnet will take approximately two years (this includes contingency) from the time when construction funding is received. Naturally, DOE-NP is awaiting Fermilab's approval of the experiment to begin funding. With PAC approval in Nov. 2001, funding could begin in FY2003 (Oct. 2002) and the experiment will be ready to run in FY2005 (Oct. 2004). PAC approval in Apr. 2002 may delay this schedule by one fiscal year. Some time could be gained on this schedule by having the magnet coils fully designed and ready to be bid when funds become available.

The apparatus also makes use of a second magnet for momentum analysis. The proposal cited the Jolly Green Giant (JGG) as an excellent magnet for this purpose. P907 [11] also proposes using this magnet. If approved, P907 plans to take data starting in Nov. 2002. The P907 proposal calls for 3400 hours of beam time [11] which is easily achieved within a year (by Nov. 2003). Adding 5 months of contingency (Apr. 2004) would still allow for 6 months to move the magnet and to assemble the remaining detector around it. With the above time-scale, both experiments could successfully run sequentially using this magnet. Other magnet options are discussed in Sec. 3.

3   Focusing Magnet

A momentum measurement of the muons is made with the second magnet. We proposed using the Jolly Green Giant (JGG) for this magnet. We still feel that this is the best existing magnet for our experiment. P907, however, has also proposed using this magnet. While the experimental time-lines are different enough that both experiments could be completed using this magnet (see Sec. 2), we have undertaken a study of other possible large aperture magnets so that Fermilab can maximize physics output and minimize any potential equipment conflicts. The field integral of the second magnet and the amount of hadron absorber between the target and tracking stations determine the momentum resolution of the spectrometer. Different values of total field integral have been simulated with the P906 Monte Carlo code. For field integrals above 1.16 T-m (350 MeV p_T kick), the resolution was dominated by multiple scattering and energy loss of the muons in the hadron absorber located between the target and the first tracking station. For smaller field integrals, the resolution began to degrade with unacceptable resolution for fields at or below 0.33 T-m (100 MeV p_T kick). The aperture of the magnet defines the acceptance. In general, the bend plane aperture defined the low x_F (x-Feynman) reach and hence the high x_2 acceptance, as is seen in Fig. 4. The field aperture translates into an overall reduction in acceptance at all x_2; although there is some correlation between large horizontal aperture
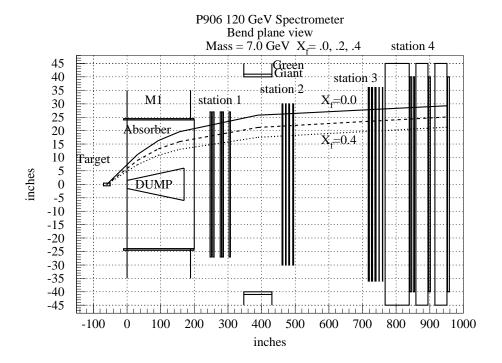
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Figure 4: Bend plane view of the trajectories of one of the two muons resulting from the muon decay of a 7 GeV virtual photon (which has x_F of 0.0, 0.2 or 0.4) in an 8 T-m spectrometer. Since low x_F corresponds to high x_2 it is clear that an aperture less than 54 inches in the bend plane will significantly reduce the high-x_2 acceptance.
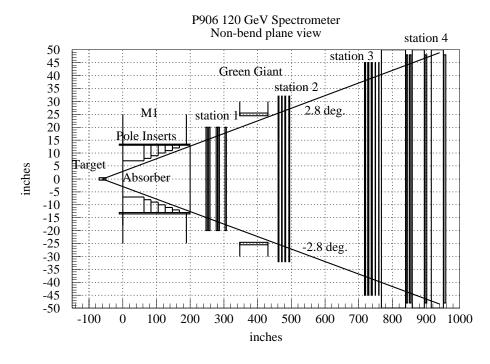

Figure 5: Non-bend plane view in an 8 T-m spectrometer. Only muons which pass around the beam dump in the bend plane contribute to the acceptance and so the beam dump is not shown.

and large x_2. In particular, the experimental acceptance is limited by the magnet aperture[1] if it less than 55×54 inches. For larger apertures, the dimensions of the already existing tracking chambers and the "M1" design start to affect the acceptance.

A survey of existing magnets encompassing several DOE facilities [12] shows that there are several which might produce acceptable resolution and acceptance, all located here at Fermilab. Listed below are, first, complete magnets and second, magnets and coils which would need additional iron to increase the gap, but whose coils could provide the necessary field integral, with the increased gap.

JGG: The Jolly Green Giant is still the preferred magnet. Its field (1.65 T-m) and aperture (80×50 inches) are the most closely suited to our apparatus. Assuming the time line outlined in Sec. 2, proposal 907 could easily be completed before this experiment needs the magnet.

KTeV: The KTeV magnet is also a good choice for use as an analysis magnet. It has an aperture of roughly 2×2 m and its field could provide a p_T kick of 600 MeV. The CKM experiment is currently planning on using this magnet, but on a time scale which may make it possible for P906 to run, followed by CKM. It would require that the magnet be moved to the Meson area for P906 and then to CKM's experimental area. We have started to explore these possibilities with CKM [13].

SM3: This magnet was used by the previous Drell-Yan experiments, is already located in Meson East and would be an excellent choice for the experiment. It has a field integral of 3.0 T-m and an aperture of roughly 60×60 inches. Before the end of Run II, this magnet will be moved to the C0 hall for installation into BTeV. It is unlikely that the P906 measurements could be completed before it is moved.

The following magnets and/or coils could provide sufficient acceptance if their gap was increased to 55 inches. This would require that Fermilab locate additional iron and reconfigure the magnet. All of the coils, when regapped, should still have sufficient field integral for the experiment.

MW9AN: Only coils exist for MW9AN and are stored in Meson East. The aperture of these copper coils is 50×36) inches. If sufficient iron is available, the coils could be configured with a large enough gap for the experiment. The coils are 20 turns/pancake $\times$ 12 pancakes $\times$ 2 sides, which gives 480,000 A-turns at 2000 A. After being regapped to 55 inches, a field integral of approximately 1.45 T-m could be achieved.

FOCUS magnet: The Focus experiment used two magnets. Each had an aperture of 50×30 inches with a maximum p_T kick of 1 GeV. From a preliminary look at these magnets, regapping to 55 inches would require a substantial amount of additional iron. Without increasing the gap, the impact on the 906 acceptance is unacceptable.

Rosie: Rosie was last used in the Donut experiment. The magnet has an aperture of 73×36 inches with a transverse momentum (p_T) kick of 821 MeV (2.7 T-m) [14]. The small aperture in the field direction would cost a factor of 3 in acceptance for the $0.35 \leq x_2 \leq 0.45$ bin (compared with the JGG). With sufficient iron, the magnet could be regapped to 50 inches, and still have sufficient field integral. However, P907

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[1]Throughout this discussion, magnet dimension will be given in terms of *width (bend plane) $\times$ gap (field plane)*

is now also planning on using this magnet, instead of TPL-B ($82 \times 23 \times 208$ cm) magnet listed in their proposal [11]. The JGG is preferred over this magnet.

Finally, there is enough additional steel after the construction of "M1" remaining from SM12 to provide for the return yoke for a new magnet. Argonne could design coils for this magnet at the same time as the "M1" coils, provided that Fermilab was willing to pay for their fabrication and the assembly of the magnet. Cost estimates say that these coils would cost approximately half that of the M1 coils[2], or roughly $600,000.

In conclusion, the JGG is still our preferred magnet. If it is not available, we have begun to explore other possibilities. The most promising would be for Fermilab to provide the iron for the MW9AN coils to configure it with a 50×55 inch gap.

4   Beam Requirements

Our basic beam requirement of 5.2×10^{18} slow-spill protons has not changed. To deliver these protons to the fixed target area, a new scheme for operating the Main Injector, known as the "Double Slow Spill" has recently been proposed [15]. This scheme would allow protons to be delivered to the antiproton target at 90% of the nominal intensity, as well as sending a modest number of protons to a fixed target program. Without delving into the details of the "Double Slow Spill", as proposed, it could provide 0.5×10^{12} protons per spill, extracted over approximately 1.15 s with a total cycle period of 3.1 s. To reach our requested 5.2×10^{18} protons on target, assuming 66% accelerator and experimental efficiency, the experiment could be run in roughly 1.5 years, or approximately double that of our original proposal. While doubling the run time for the experiment, the lower intensity will significantly lower our background from random coincidences, which is proportional to the square of the intensity. Since running with "Double Slow Spill" scheme only increases the time to complete the experiment to 1.5 years it could easily be run with this method. Of course, our original request of 10^{12} protons per pulse is also acceptable.

5   Competing Measurements

After our first presentation in 1999, the PAC asked, "How well would your results compare with competing measurements?" Even though several years have intervened, we still see no significant competing measurement. The primary measurement of the light quark sea come from neutrino and antineutrino deep inelastic scattering (νDIS). These measurements have allowed a precise determination of $\bar{d} + \bar{u}$ but on an isoscaler target have little sensitivity to the asymmetry of the sea, $\bar{d} - \bar{u}$. There are also uncertainties from nuclear effects in heavy targets which affect extraction of $\bar{d} + \bar{u}$ from the νDIS data. In this respect, our data will be complimentary to this data, since we will obtain both light and heavy target data in a kinematic range which overlaps the νDIS data. The situation is largely unchanged with respect to semi-inclusive deep inelastic scattering and pp collider experiments. These techniques have some reach at moderate x, but fixed target Drell-Yan still represents the best technique to measure $\bar{d}/\bar{u}$ at higher x.

One significant development is the funding of the High Intensity Proton Accelerator Facility (formerly known as the Japanese Hadron Facility). This facility is scheduled for completion in 2007. Recently announced , planned funding cuts for basic research in Japan

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[2]As we expect to use an existing magnet, no detailed cost estimate has been done.
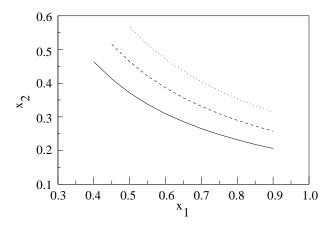
Figure 6: The correlation between x_2 and x_1 for Drell-Yan dimuon pairs with effective masses of 4.25 GeV (solid), 4.75 GeV (dashed), and 5.25 GeV (dotted) in the proposed experiment at JHF [16]. The curves are drawn for (x_1,x_2) values that satisfy $x_F > -0.06$.

may introduce further delays. When completed, it could provide a 50 GeV slow-spill proton beam. After this time, a Drell-Yan experiment could be mounted there and an Expression of Interest has already been written for this type of experiment [16].

The lower proton beam energy at JHF implies that an experiment there would be sensitive to a higher range of x_2 values (0.2–0.6) than covered by P906 (0.1–0.45), but this additional reach in x_2 has costs associated with it. The 50 GeV proton beam energy may also be marginal for use with a W target, at least for some of the x_1 range, according to the minimum beam momentum condition of Bodwin, Brodsky and Lepage [17]. The x_2 range with good statistics would provide very little overlap with either FNAL E772 or E866, making consistency checks difficult, whereas it will be straightforward to cross-check P906 results with those of E772 and E866. From an experimental point of view at 50 GeV, the background from pions decaying before the absorber will increase because of the lower boost. Decreasing the target-absorber separation can partly over come this difficulty. At the same time, however, the lower energy muons will have greater multiple scattering and energy loss while traveling through the hadron absorber, making target-dump separation more difficult.

In P906 we propose to investigate incident-parton energy loss using only events for which $0.1 < x_2 < 0.2$. This x_2 region has already been investigated with moderate statistics by FNAL E772 and found to demonstrate little or no nuclear target dependence. Thus, P906 will be able unambiguously to attribute any observed effects to energy loss. Then, after determining the nuclear modifications associated with incident-parton effects, P906 will be able to measure the antiquark density in the nuclear targets at larger x_2, where several models that attempt to explain the EMC effect predict there should be similar reductions in the antiquark distributions.

Such a separation will be difficult to achieve at JHF. Reference [16] proposes to investigate energy loss by observing the x_1 dependence of the Drell-Yan cross section as a function of A, while integrating over all x_2, and to investigate target parton distribution modifications by observing the x_2 dependence of the Drell-Yan cross section, while integrating over all x_1. However, given the need to impose an effective mass cut of at least 4 GeV on Drell-Yan dimuon pairs to eliminate ψ' contamination, the 50 GeV proton beam energy will

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introduce important correlations between x_1 and x_2, as shown in Fig. 6. Note that a JHF experiment will cover no kinematic region where either nuclear target or energy loss effects are already known to be small. Thus, the x_1-x_2 correlations at JHF will likely introduce systematic effects when separating any nuclear dependence which is observed into individual contributions from nuclear target parton-density modifications and incident-parton energy loss. Finally, if significant nuclear dependences are observed at JHF, that could lead to ambiguities in the interpretation of $\bar{d}/\bar{u}$ results with a 50 GeV proton beam as well.

6   Conclusion

The physics addressed by P906 is still relevant and interesting. It addresses a fundamental question of nonperturbative QCD: What are the origins of the nucleon's quark sea? These measurements are still best done here at Fermilab using the 120 GeV Main Injector Proton beam and the Drell-Yan mechanism to probe the antiquark structure of the proton. The additional measurements on nuclear targets can be compared directly with the ν-DIS determination of $\bar{d} + \bar{u}$ to determine the influence of nuclear effects on the $\bar{d} + \bar{u}$ extraction. In addition, the nuclear target data will provide precise measurements of the energy loss of strongly interacting particles traveling through the nucleus.

The experiment could be ready to collect data in late 2004. This date would allow time for the funding and construction of a new focusing magnet for the experiment. By Fall 2004, P907's proposed program of 3400 hours of beam time should be completed and the JGG magnet could be transfered to P906. If the JGG is not available, several other magnet possibilities have been discussed. The experiment can easily run under the "Double Slow Spill" extraction scheme; although the lower intensity requires that the beam time be increased, to achieve the same number of protons on target and statistical precision.

References

[1] L.D. Isenhower *et al.* (P906 Collaboration) *Proposal for Drell-Yan Measurements of Nucleon and Nuclear Structure with the FNAL Main Injector*, April 2001, unpublished.

[2] D.A. Ross and C.T. Sachrajda, Nucl. Phys. B **149**, 497 (1979).

[3] F.M. Steffens and A.W. Thomas, Phys. Rev. C **55**, 900 (1997).

[4] P. Amaudruz *et al.*(NMC) Phys. Rev. Lett. **66**, 2712 (1991); M. Arneodo *et al.* (NMC) Phys. Rev. D **55**, R1 (1994).

[5] A. Baldit *et al.* (NA51) Phys. Lett. B **332**, 244 (1994).

[6] E. A. Hawker *et al.* (FNAL E866/NuSea) Phys. Rev. Lett, **80** 3715 (1998); J.-C. Peng *et al.* (FNAL E866/NuSea) Phys. Rev. D **58**, 092004 (1998); R. S. Towell *et al.* (FNAL E866/NuSea), Phys. Rev. D **64**, 052002 (2001).

[7] A.D. Martin, R.G. Roberts, W.J. Sterling and R.S. Thorne, Eur. Phys. J. **C4**, 463 (1998).

[8] M.A. Vasiliev *et al.* (FNAL E866/NuSea) Phys. Rev. Lett. **83**, 2304 (1999).

[9] M.B. Johnson *et al.* (FNAL E772) Phys. Rev. Lett. **86** 4483 (2001).

[10] C.N. Brown, Fermilab, private communication.

[11] Y. Fisyka *et al.* (P907 Collaboration) *P-907: Proposal to Measure Particle Production in the Meson Area Using Main Injector Primary and Secondary Beams*, May 2000, unpublished.

[12] L. Keller, SLAC, private communication; A.F. Pendzick, BNL, private communication.

[13] P. Cooper, private communication.

[14] T. Alexopoulos *et al.* (FNAL E771) Nucl. Instrum. Meth. **A376** 375 (1996).

[15] C.S. Mishra T. Murphy, and R. Raja, *A scheme to extract a low intensity slow spill Main Injector beam to the Meson Area without compromising antiproton production rate.* October 2000, unpublished, FNAL-TM-213.

[16] M. Asakawa *et al.*, *Expression of interest for Nuclear/Hadron physics Experiments at the 50-GeV Proton Synchrotron*, unpublished (see http://jkj.tokai.jaeri.go.jp/NuclPart/Science.html); J.C. Peng, G.T. Garvey, J.M. Moss, S. Sawada, and J. Chiba, hep-ph/0007341.

[17] G.T. Bodwin, S.J. Brodsky, and G.P. Lepage, Phys. Rev. D **39**, 3287 (1989).