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FNAL PROPOSAL

MEASUREMENT OF $\overline{d}(x)/\overline{u}(x)$ IN THE PROTON

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Introduction

While it is usually assumed that the light quark (u, d) sea of the nucleon is flavor symmetric, this symmetry is not intrinsic to QCD. Indeed, there is strong circumstantial evidence that $\overline{d}^p(x) \neq \overline{u}^p(x)$ in the proton. The evidence is the observed violation of the so-called Gottfried Sum Rule[1] (GSR). The GSR is most simply written as the integral over all x of the difference between the $F_2(x)^*$ structure function of the proton (p) and neutron (n).

$$\begin{aligned}\int_0^1 \frac{F_2^p(x) - F_2^n(x)}{x} dx =& \frac{1}{3} \int_0^1 \left[u_v^p(x) - d_v^p(x)\right] dx \\ &+ \frac{2}{3} \int_0^1 \left[\overline{u}^p(x) - \overline{d}^p(x)\right] dx \qquad \text{(1a)} \\ =& \frac{1}{3} - \frac{2}{3} \int_0^1 \left[\overline{d}^p(x) - \overline{u}^p(x)\right] dx \quad . \qquad \text{(1b)}\end{aligned}$$

where

$$u_v^p(x) \equiv u^p(x) - \overline{u}^p(x) \quad \text{etc.}$$

To derive Eq. (1a), isospin symmetry must be assumed, i.e., $u_v^p(x) = d_v^n(x)$, $\overline{u}^p(x) = \overline{d}^n(x)$, etc.

A recent experiment[2] has obtained

$$\int_{0.004}^{0.8} \frac{F_2^p(x) - F_2^n(x)}{x} dx = 0.227 \pm 0.007 \pm 0.014 \quad , \qquad (2)$$

and on using extrapolation to extend the integration over the unmeasured interval find

$$\int_0^1 \frac{F_2^p(x) - F_2^n(x)}{x} dx = 0.240 \pm 0.016 \quad , \qquad (3)$$

which is 5.6σ away from the GSR value of one-third, assuming $\overline{d}^p(x) = \overline{u}^p(x)$.

The large difference from one-third reported in Ref. 2 has resulted in a great deal of attention being focused on the nucleon sea. The various approaches that have been taken can be distinguished as follows:

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* The Q^2 dependence in all expressions will be suppressed.

1. Reparameterizing the $\overline{u}^p(x)$, $\overline{d}^p(x)$ distributions so that the measured value of the GSR is obtained.[3-6]
2. Explicit calculation of the contribution of virtual mesons to $\overline{u}^p(x)$, $\overline{d}^p(x)$.[5,7-11]
3. Retaining $\overline{u}^p(x) = \overline{d}^p(x)$ and making $u_v^p(x) - d_v^p(x)$ sufficiently singular near $x = 0$ that the observed value for the GSR is obtained.[6,12]
4. Suggestions that "nuclear" effects in deuterium, which was necessarily employed as a neutron target in Ref. 2, strongly influence the experimental result. It should be noted that different authors do not agree on the sign of the effect, though most believe it to be small. We will not deal with this issue further.[10,13,14]

Because the values of $u^p(x)$ and $d^p(x)$ are relatively large and are not known to sufficient precision, the measurement of $F_2^p(x) - F_2^n(x)$ cannot be used to reliably obtain $\overline{d}^p(x) - \overline{u}^p(x)$; hence one must rely on the GSR and settle for an integral over x of the u, d sea quark difference.

On the other hand, the Drell-Yan process with incident nucleons can be made extremely sensitive to the antiquark distribution of the target. This point has been raised in the literature[4,15] as a procedure to further investigate the physics behind the observed GSR violation. The E772 collaboration has already made use of this fact to reanalyze data obtained in FNAL E772 and have submitted a paper[16] for publication in *Phys. Rev. Lett.*, which is attached as Appendix 1 to this proposal. It is easy to show (with reasonable assumptions) that, apart from shadowing corrections, the ratio of Drell-Yan yield per nucleon from a target with Z protons and N neutrons compared to the yield from deuterium is

$$\left.\frac{Y_{\mathrm{DY}/A}^{p+A}}{Y_{\mathrm{DY}/2}^{p+\mathrm{D}}}\right|_{x_F>0.2} = 1 + \frac{N-Z}{A}\left[\frac{\overline{d}^p(x) - \overline{u}^p(x)}{\overline{d}^p(x) + \overline{u}^p(x)}\right] \quad , \tag{4}$$

where $x_F \equiv x_b - x_t$, x_b is the fraction of momentum carried by the incident quark and x_t is the fraction of momentum carried by the target antiquark.

In E772 the ratio of the Drell-Yan yield from nuclear targets (C, Ca, Fe, and W) compared to deuterium was measured. It was established that there is little A dependence in the antiquark structure functions as a function of A apart from shadowing, which occurs at the same level as observed in DIS (Appendix 2). Unfortunately, from the point of view of Eq. (4), the values of $(N - Z)/A$ are small for all the E772 targets save W, where $[(N - Z)/A]_W = 0.195$. However, even with this unfavorable situation, it is possible to obtain results that are inconsistent with most attempts to date to reconcile the GSR violation via the $\overline{d}(x) \neq \overline{u}^p(x)$ route. Table I lists the measured result and compares it to various predictions. Questions may be raised about nuclear effects in W, but the obvious qualitative result is that there is no evidence for $\overline{d}(x) \neq \overline{u}(x)$ in the data.

Table I

x	Δ^a	Δ^b	Δ^c	Δ^d	Δ^e
0.040	-0.10 ± 0.077	0.17	0.11	0.065	0.064
0.071	-0.15 ± 0.071	0.29	0.20	0.080	0.092
0.120	-0.07 ± 0.067	0.46	0.33	0.085	0.121
0.168	0.15 ± 0.15	0.68	0.46	0.083	0.144
0.215	0.31 ± 0.36	0.75	0.58	0.078	0.167
0.267	0.05 ± 0.86	0.84	0.68	0.073	0.184

$\Delta \equiv \frac{\overline{d}^p(x) - \overline{u}^p(x)}{\overline{d}^p(x) + \overline{u}^p(x)}$

[a] Ref. 16, Attachment 1
[b] Ref. 4
[c] Ref. 5
[d] Ref. 6, Distribution D_0
[e] Ref. 6, Distribution D_-

Thus, it appears that there is an interesting problem. A large violation of the GSR has been established and at present there is no clear support for values of $\overline{d}^p(x) > \overline{u}^p(x)$ that are sufficiently large to account for the observed violation.

The values of $\overline{d}(x)$ and $\overline{u}(x)$ are intrinsic properties of the nucleon and therefore should be measured as precisely as practicable over a broad range in x. It naturally arises in the nonperturbative regime that $\overline{d}^p(x) > \overline{u}^p(x)$—for example, from virtual mesons—but that approach, while promising, has not yet yielded a quantitative account of the GSR violation. We believe that it is important to make a direct measurement of $\overline{d}^p(x)/\overline{u}^p(x)$ to confront various models of the structure of the nucleon. In particular, it may be a fruitful way to examine the relative contribution of nonperturbative processes on the measured structure functions.

The Proposed Experiment

We propose to greatly improve the experimental knowledge of $\overline{d}^p(x)/\overline{u}^p(x)$ via precision measurement of the ratio of DY yields from protons on protons to protons on deuterium.

$$\left.\frac{Y_{\mathrm{DY}}^{p+p}}{Y_{\mathrm{DY}/2}^{p+\mathrm{D}}}\right|_{x_F>0.2} \cong 1 - \left[\frac{\overline{d}^p(x) - \overline{u}^p(x)}{\overline{d}^p(x) + \overline{u}^p(x)}\right] \quad . \tag{5}$$

In addition to being five times more sensitive than our earlier measurement on W, it uses the lightest possible nuclei, thereby minimizing any nuclear effects that could obscure extraction of the structure function ratios. The left-hand side of Eq. (5) can be measured as a function of x with experimental systematic errors that will be, at most, $\pm 1.5\%$. The range in x to be investigated is $0.04 \leq x \leq 0.3$. The upper limit arises because the sea distribution is a rapidly falling function of x $[\sim (1-x)^8]$. The lower limit arises from the fact that we require the DY dilepton pair $(\mu^+\mu^-)$ to have a mass appreciably greater (4 GeV) than the mass of the ψ' (3.69 GeV). Achieving the same level of precision in the $(p+p)/(p+\mathrm{D})$ ratio as was obtained in the W/C ratio fixes the ratio $[\overline{d}(x) - \overline{u}(x)]/[\overline{d}(x) + \overline{u}(x)]$ to the accuracy shown in Table II. At this level of accuracy, all the parameterizations shown in Table I would be directly confronted.

Table II

x	Error in $\frac{\bar{d}-\bar{u}}{\bar{d}+\bar{u}}$
0.040	0.015
0.072	0.015
0.120	0.015
0.168	0.03
0.215	0.07
0.267	0.17

The experiment is proposed to be carried out using essentially the same equipment as E772. This setup allowed a high statistics measurement of the ratio of Drell-Yan yield from a variety of nuclear targets. The experimental layout used in E772 is shown in Fig. 1. The RICH counter will not be used as muons are sufficiently well selected via their range. The three dipoles, SM0, SM12, and SM3, serve as a dimuon spectrometer. The first magnet, SM0, serves to open up the small opening angle of low-mass dimuon pairs, SM12 focuses high p_T muons into the downstream detectors, both SM12 and SM3 are used to measure the muon momentum. A hadron absorber (e^{-13}) of Cu, C, and CH_2 blocks is placed in the gap of SM12. In this configuration, the apparatus has an energy resolution of 150 MeV at the J/ψ and 200 MeV at the Υ and z vertex resolution is more than sufficient to reject dimuon pairs created in the beam dump.

The muon trajectories were measured in a variety of drift chambers, proportional and multiwire proportional counters. The MWPC chambers at Station 1 used in E772 have been replaced by new drift chambers. A set of scintillator hodoscopes at Stations 1, 2, 3, and 4 provide the fast level-1 and level-2 triggers.

The dimensions of the LD target used in E772 and shown in Fig. 2 are quite suitable for our purposes, and we would propose that the LH target be identical. The beam spot (8 mm × 2 mm) obtained during E772 running is sufficiently small that the diameter of the LD and LH targets could be reduced from 7.62 cm to 5 cm if this proves advantageous in their construction. The target windows should be kept as thin as was the case in the E772 LD target. The targets should be interchangeable into the beam position within the 40-s interval between beam spills. Provision for fixing a C target in the form of discs should also be provided, as shown in Fig. 2, for the purpose of tune-up and comparison to the E772 results.

By referring to the results of E772, a lower limit on the number of analyzed DY events can be determined with confidence. Table III lists the yield of analyzed Drell-Yan events per 10^{12} protons for each of three settings of the magnetic spectrometer. As most of the running would be done at the medium field setting, at least 4.5×10^4 analyzed DY events can be projected from each target with 10^{12} protons/spill and one month of data taking.

Table III

Field Setting	$\langle M_{\mu^+\mu^-} \rangle$ GeV	# of $DY^{pp*}/10^{12}$ p	# of $DY^{pD}/10^{12}$ p
Low	5.4	5	10
Medium	7.0	3	6
High	9.5	0.35	0.7

*The number of proton events is taken to 0.5 the number observed for deuterium.

The largest systematic error (±1.5%) in E772 came about from rate dependence in the muon tracking efficiency. It will be important to achieve a balance between this effect and increasing the flux beyond 10^{12} protons/pulse.

Since E772 was run, there has been further development of the dimuon spectrometer. In particular, E789 increased the acceptance for low-mass pairs by making a smaller beam dump. Hence, we expect considerably more low-mass events than obtained above based on the E772 results. The data acquisition system has been upgraded to be ten times faster than it was in E772 and thus should be capable of handling the projected higher rates. With 50-cm LH and LD targets, 10^{12} protons/spill, and four weeks of running (2×10^4 pulses), we find for 1.33×10^4 spills on LH, 0.67×10^4 spills on LD with Duke-Owens[18] structure functions, more than 200k DY events from each target. They are distributed in x as shown in Table IV.

This setup will also see dimuons from J/ψ, ψ', $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ decay. In Table V we show the yields from the proton target that prevail for the same conditions employed in Table IV, except that the J/ψ and Υ production cross sections are estimated from Refs. 20 and 21.

Table IV

x	DY Events (LH) ($\times 10^3$)	DY Events (LD) ($\times 10^3$)
0.05–0.10	166	194
0.10–0.15	36	44
0.15–0.20	3.2	3.7
0.20–0.25	0.51	0.59
0.25–0.30	0.15	0.17

Table V

x	J/ψ Events $\times 10^3$)	ψ' Events ($\times 10^3$)	$\Upsilon(1S)$
0.00–0.05	904	16.2	24
0.05–0.10	3192	55.9	73
0.10–0.15	3724	87.8	146
0.15–0.20	1862	58.5	213
0.20–0.25	266	21.3	233
0.25–0.30	3.2	2.5	279
0.30–0.35	—	—	233
0.35–0.40	—	—	180
0.40–0.45	—	—	106
0.45–0.50	—	—	67
0.50–0.55	—	—	33

The deuterium yields are comparable. Nuclear dependence of J/ψ and Υ production has been studied in E772 for targets heavier than deuterium,[22,23] but no data for the $p+p/p+\mathrm{D}$ ratio exist for either J/ψ or Υ.

Competing Experiments

A proton DY experiment to investigate $\overline{d}^p/\overline{u}^p$ was proposed[19] at CERN this spring. It was quickly approved and ran this summer, a testimony to the perceived importance of the subject. The CERN experiment followed a suggestion in Ref. 4 and measures the difference in the DY yield from LH and LD targets. The yield is measured at $x_F \sim 0$ and utilizes the following asymmetry

$$A_{\mathrm{DY}} \equiv \frac{2\sigma_{\mathrm{DY}}^{pp}}{\sigma_{\mathrm{DY}}^{p\mathrm{D}}} - 1 \quad . \tag{6}$$

The quantity A_{DY} is sensitive to the ratio of $\overline{d}^p(x)/\overline{u}^p(x)$ but also requires specification of $d^p(x_1)/u^p(x_1)$ in the incident proton. The measurement is therefore sensitive to particular models of the parton distribution but is not well suited for the extraction of $\overline{d}^p(x)/\overline{u}^p(x)$. The observed yield is centered about $x_1 = x_2 = 0.15$, and the experiment proposes to collect only 3×10^3 events from each of the LP and LD targets. The reason so few events are obtained is because they propose to take only 2×10^9 protons/spill, or some 2×10^{13} protons/day. We propose to take 10^{12} protons/spill or more, leading to 1.4×10^{15} protons/day. We are confident of 2×10^5 analyzed DY events from each target with a much more useful span of x_F and x_2.

Concluding Remarks

We can readily measure $\overline{d}^p(x)/\overline{u}^p(x)$ to the order of 1% accuracy for $0.05 \leq x \leq 0.15$ and with lesser statistical accuracy out to $x \simeq 0.3$. These measurements would be more precise than any existing or other proposed measurements of this quantity. High-statistics data on J/ψ and ψ' production, as well as a few thousand $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ events, from H and D targets will also be obtained.

The proposed experiment makes use of existing equipment, requires only two months of beam time (1 month of setup and checkout, 1 month of data taking). We request that FNAL construct the LD and LH targets consistent with our technical requirements and their safety concerns.

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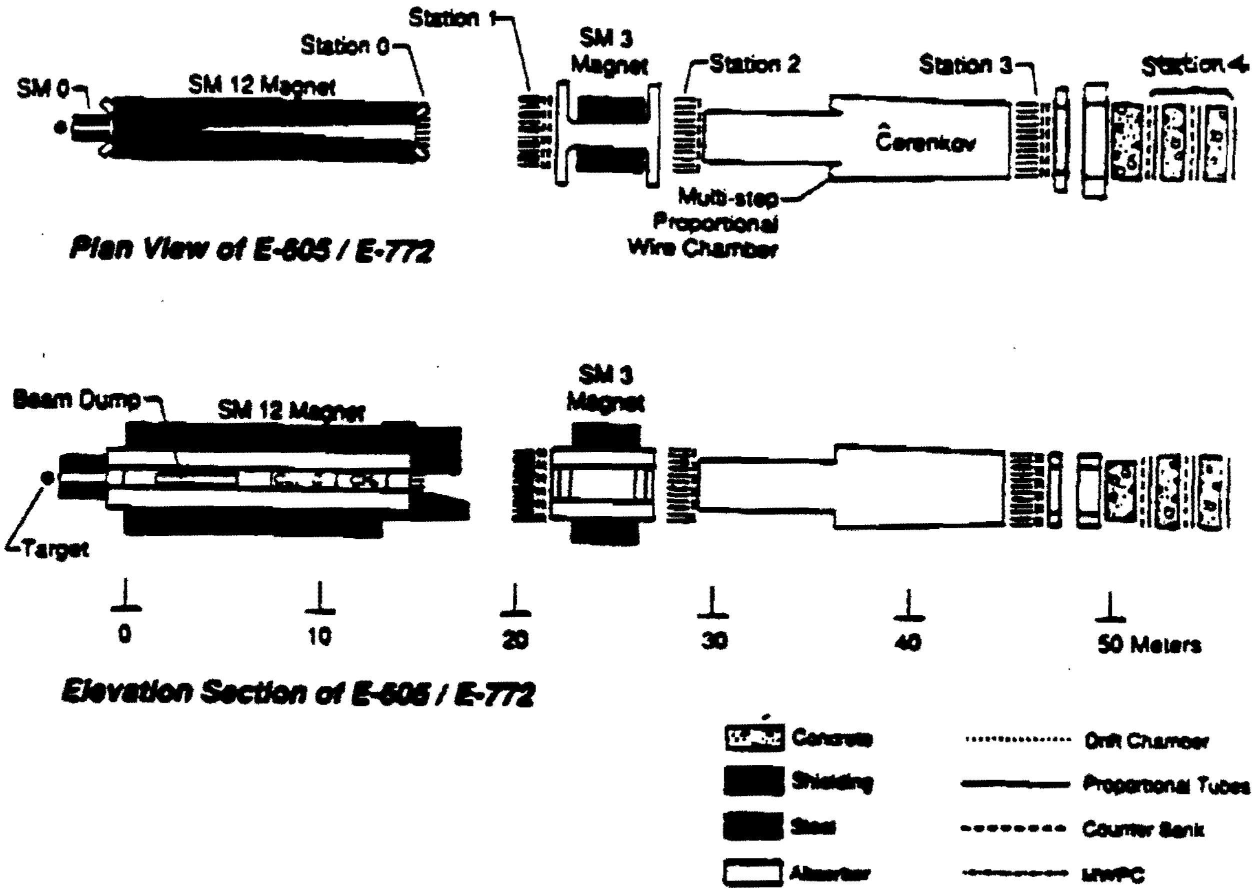

Figure 1: The E605/E772 spectrometer

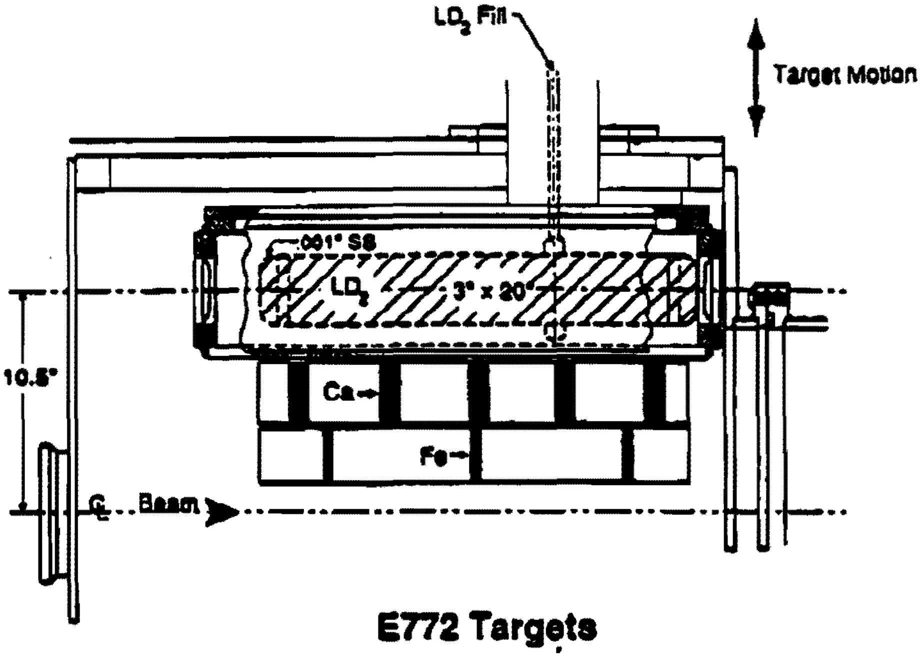

Figure 2. Target box array mounting arrangement of target disks.

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Appendix 1

TITLE: LIMIT ON THE D-BAR OVER U-BAR ASYMMETRY OF
THE NUCLEON SEA FROM DRELL-YAN PRODUCTION

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Limit on the $\bar{d}/\bar{u}$ Asymmetry of the Nucleon Sea from Drell-Yan Production

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Abstract

We present an analysis of 800 GeV proton-induced Drell-Yan production data from isoscalar (IS) targets ^2H and C, and from W, which has a large neutron excess. The ratio of cross sections per nucleon, $R = \sigma_W/\sigma_{IS}$, is sensitive to the ratio of antiquark distributions for target neutrons and protons, and through charge symmetr[illegible] the ratio, $\bar{d}(x)/\bar{u}(x)$, of structure functions of the proton. We find that R is close to unity in the range $0.04 \leq x \leq 0.27$, allowing upper limits to be set on the $\bar{d}/\bar{u}$ asymmetry. Additionally, the shape of differential cross section, $m^3 d^2\sigma/dx_F dm$, for ^2H at $x_F \approx 0$ shows no evidence of an asymmetric sea in the proton. We examine the implications of these data for various models of the violation of the Gottfried sum rule in deep-inelastic lepton scattering.

PAC numbers: 13.85Qk, 12.38Qk, 25.40Ve

Recent precise measurements, by the New Muon Collaboration (NMC)[1], of the F_2 structure function in deep-inelastic muon scattering (DIS) from hydrogen and deuterium targets show that,

$$G_{0.004}^{0.8} \equiv \int_{0.004}^{0.8} (F_2^p - F_2^n)\frac{dx}{x} = 0.227 \pm 0.007 \pm 0.014.$$

When the integration is extended from zero to one the theoretical result $G_0^1 = \frac{1}{3}$ is known as the Gottfried Sum Rule (GSR)[2]. Assuming charge symmetry, its violation implies $\bar{d}(x) \neq \bar{u}(x)$ in the sea of the proton. The NMC result has led to many analyses[3-10] of the nucleon sea. For the purposes of the present paper we separate them into three groups: 1) modified structure functions[3-5] which reconcile the NMC data with the more conventional $SU(2)$-symmetric structure function analyses by allowing $\bar{d}(x) \neq \bar{u}(x)$, 2) explicit calculation of the up-down asymmetry in the sea arising from virtual mesons [5-9], and 3) a structure function analysis[10] which presumes an $SU(2)$ symmetric sea and utilizes the NMC data to constrain the experimentally unobserved region $x \leq 0.004$.

It is well established that the proton-induced Drell-Yan (DY) process in the Feynman-x range $x_F \gtrsim 0.1$ is sensitive to the antiquark distribution of the target nucleons, due to dominance of the term $u_{beam}\bar{u}_{target}$. Under these conditions proton bombardment of free proton and neutron targets could be used to extract the ratio,

$$R(x) = \frac{\sigma_{pn}(x)}{\sigma_{pp}(x)} \approx \frac{\bar{u}_n(x)}{\bar{u}_p(x)} \approx \frac{\bar{d}_p(x)}{\bar{u}_p(x)}. \tag{1}$$

A comparison of DY production from ^1H and ^2H is the best approximation to this ideal. Comparison of nuclear targets with different neutron excesses is less sensitive, but still very relevant to the issue of asymmetry in the nucleon antiquark sea. An approximation valid to ≤ 0.02 for the range of the present experiment is,

$$R_A(x) \equiv \frac{\sigma_A(x)}{\sigma_{IS}(x)} \approx 1 + \frac{(N-Z)}{A} \times \frac{\bar{d}(x) - \bar{u}(x)}{\bar{d}(x) + \bar{u}(x)} = 1 + \frac{(N-Z)}{A}\Delta(x), \qquad (2)$$

where σ is the cross section per nucleon, IS stands for isoscalar, and N, Z and A refer to a heavy target with a neutron excess. Unlike DIS studies of the GSR which determine an integral quantity, the DY process yields information about $\bar{q}(x)$.

We report here a new analysis from Fermilab Experiment E772, a precision study of the A-dependence of dimuon production from 800 GeV proton bombardment of nuclear targets[11-13]. We compare Drell-Yan production data from isoscalar targets, ^2H and C, to W which has a large neutron excess. From Eq. 2 one has $R_W(x) \approx 1 + 0.183\Delta(x)$. The ratio shown ... Fig. 1 was determined from sets of runs in which the three targets were alternately inserted in the beam at intervals of a few minutes. Relative normalization errors dominated by differences in rate dependence are less than 2%. Table 1 gives the mean values of mass and x_F corresponding to each x bin.

It is now well established from DIS that nuclear shadowing occurs in the range $x \leq 0.1$ when comparing low-A and high-A targets[14,15]. Evidence for shadowing has also been reported in the DY process from the present experiment[11]. Because W is significantly heavier than ^2H and C, the targets used to obtain σ_{IS}, we have corrected the smallest-x points of $R_W(x)$ for shadowing by the following procedure. First, an A-dependent shadowing factor, α_{SH}, was determined from the isoscalar targets ^2H, C, and Ca. Next, for $x \leq 0.1$, the pure shadowing contribution to R_W was calculated using $\sigma_A = \sigma_N \times A^{\alpha_{SN}}$. This value was subtracted from the experimental ratio to yield R_W plotted in Fig. 1 as open circles.

Also shown in Fig. 1 are calculated values of the DY ratio using several published models of the GSR violation. The exact expression for the ratio is evaluated using the full DY formula, not the approximation of Eq. 2. The structure functions of Ellis and Stirling[3] (ES), and of Eichten, Hinchliffe, and Quigg[5] (EHQ) have $\bar{d}(x) \neq \bar{u}(x)$, the flavor asymmetry being determined from the NMC data. The Kumano-Londergan[8] (KL), calculation is based on virtual pion contributions which naturally lead to flavor asymmetry. It should be noted that KL account for only 47% of the GSR violation via sea-quark contributions. All calculations were performed at the mean kinematic values given in Table 1, simulating the acceptance of the E772 spectrometer. Structure function evolution with Q^2 is small in the range of the present data and was not taken into account.

The ES and EHQ structure functions yield an asymmetry which is entirely inconsistent with R_W in the range $x \leq 0.15$. The KL calculation exhibits a smaller asymmetry in the sea and is consistent with the present data. Similarly the parton distributions of Martin, Stirling, and Roberts[10], where $\bar{d}(x) = \bar{u}(x)$ is assumed, yield $R \sim 1$ in agreement with the data (calculation not shown). One can use R_W in conjunction with Eq. 2 to set upper limits on $\Delta(x)$. These values (Table 1), which include the 2% normalization error and an estimate of the calculational error from Eq. 2, are determined at the 2σ statistical error level.

A different and complimentary sensitivity of the DY process to the $\bar{d}/\bar{u}$ asymmetry has been applied to earlier data[16,3]. Here one uses the shape of the differential cross section versus x_F for a single target as evidence of differences between $p-p$ and $p-n$ DY production. The $p-p$ process is symmetric around $x_F = 0$ whereas the $p-n$ process is not, leading to an x_F asymmetry even for isoscalar targets. This allows the use of ^2H, hence avoiding unforeseen nuclear effects which could complicate the previous analysis. Figure 2 compares $m^3 d^2\sigma/dx_F dm$ for the ^2H data at a mean mass of 8.15 GeV with two versions of the ES structure functions, with and without the term which gives the $\bar{d}/\bar{u}$ asymmetry. The calculations were normalized to the large-x data with a K factor of 1.45. At $x_F = 0$ one is sensitive to the $\bar{d}/\bar{u}$ asymmetry at $x \approx 0.21$. Again there is no evidence for the suppression of the $x_F \leq 0$ cross section predicted by the ES structure functions with $\bar{d} \neq \bar{u}$. Based on the quality of the fits of Fig. 2 an upper limit for the $\bar{d}/\bar{u}$ asymmetry is given in Table 1.

In conclusion, from studies of the DY process we find no indication of a large SU(2) asymmetry in the antiquark sea of the nucleon. Clearly more precise proton-induced DY data are needed particularly to explore the region $x \geq 0.15$. Direct comparisons of hydrogen and deuterium targets would maximize the sensitivity to $\bar{d}/\bar{u}$ and minimize possible complications due to nuclear effects.

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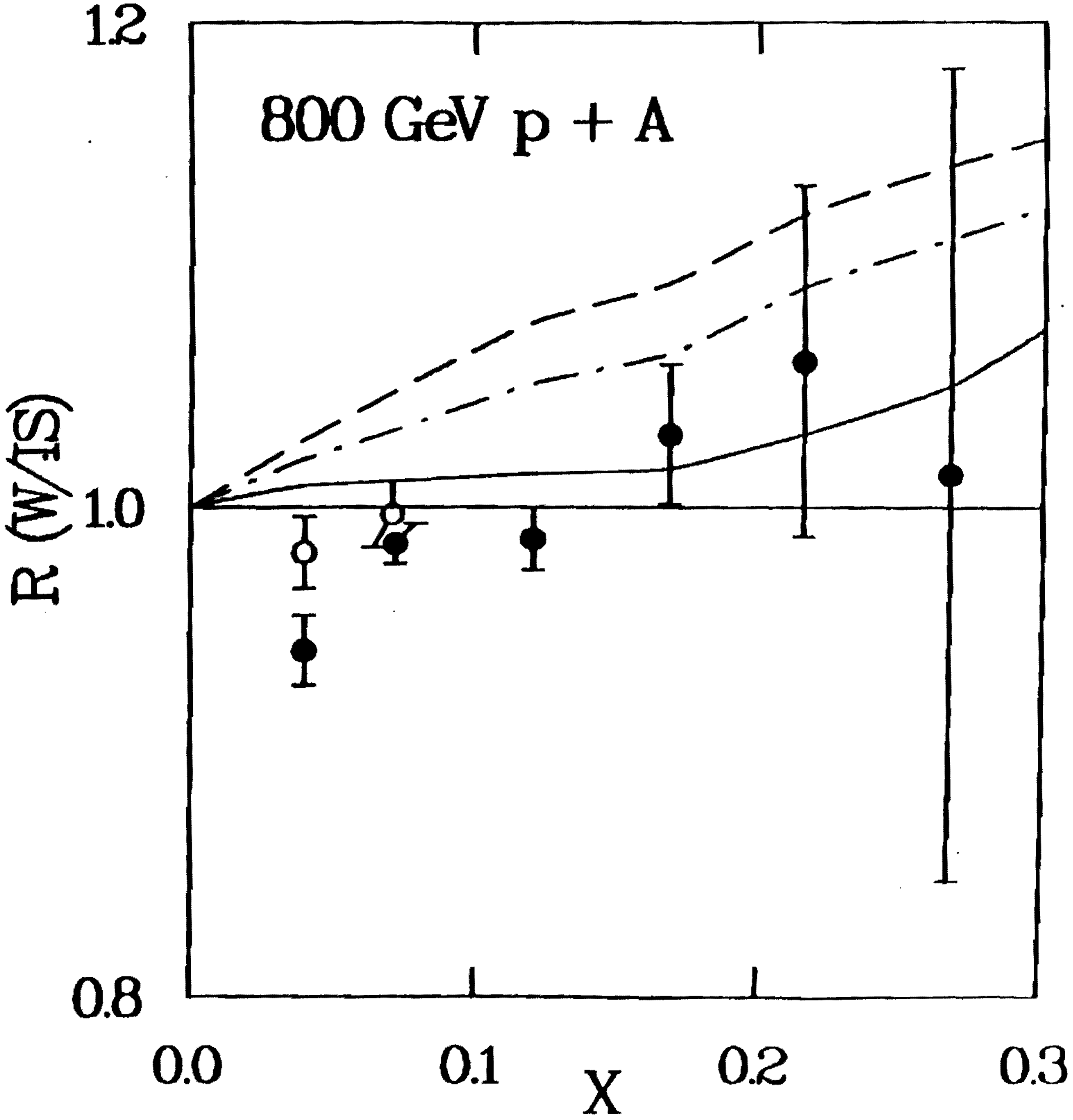
Table 1. Mean values of kinematic variables at each x bin of Fig. 1a as determined by the acceptance of the E772 spectrometer and the Drell-Yan cross section. The far right column gives the upper limit of $\Delta(x)$ at the 2σ statistical error level.

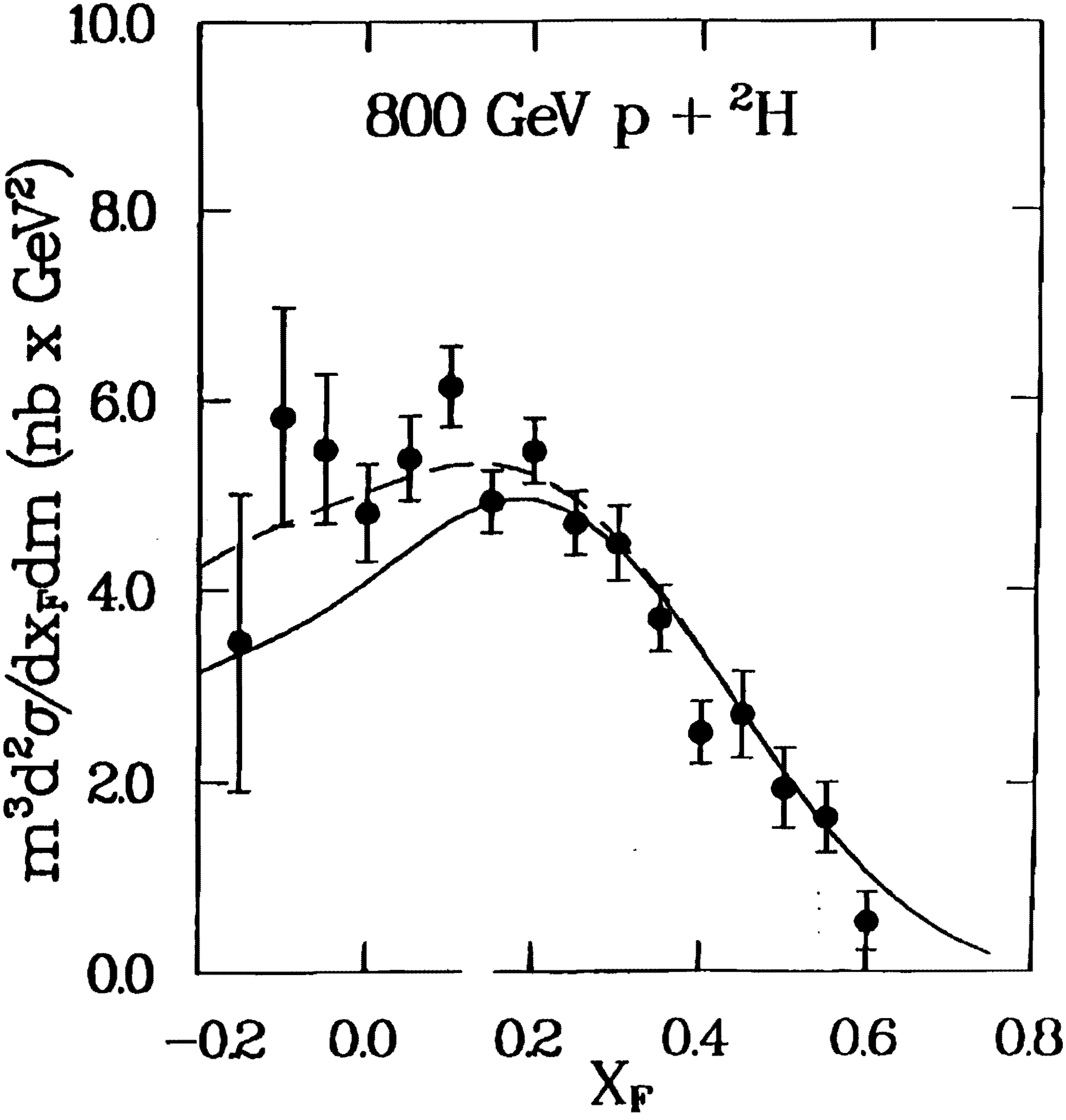
x	x_F	Mass	$\Delta_{UL}(x)$
0.040	0.370	4.94	0.19
0.072	0.295	6.24	0.27
0.120	0.155	7.32	0.22
0.168	0.115	8.36	0.77
0.215	0.152	10.9	1.5
0.267	0.162	13.1	2.3
≈0.21	≈0	8.15	0.4

Figure Captions.

Figure 1. The ratio $R_W \equiv \sigma_W/\sigma_{IS}$ versus x_{target}. The curves are calculations described in the text; Ellis and Stirling (dashed), Eichten, Hinchliffe, and Quigg (solid), and Kumano and Londergan (dot-dashed).

Figure 2. Differential cross section $m^3 d^2\sigma/dx_F dm(GeV^2 \times nb)$ for ^2H. The curves are calculations with the ES structure functions with (solid) and without (dashed) $\bar{d}/\bar{u}$ asymmetry.


800 GeV p + A
R (W/IS)
1.2
1.0
0.8
0.0
0.1
0.2
0.3
X


800 GeV p + ^{2}H
$m^3 d^2\sigma/dx_F dm$ (nb x GeV^2)
10.0
8.0
6.0
4.0
2.0
0.0
−0.2
0.0
0.2
0.4
0.6
0.8
X_F

Nuclear Dependence of Dimuon Production at 800 GeV

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A precise measurement of the atomic-mass dependence of dimuon production induced by 800-GeV protons is reported. Over 450 000 muon pairs with dimuon mass $M \geq 4$ GeV were recorded from targets of ^{2}H, C, Ca, Fe, and W. The ratio of dimuon yield per nucleon for nuclei versus ^{2}H, $R = Y_A/Y_{^2\text{H}}$, is sensitive to modifications of the antiquark sea in nuclei. No nuclear dependence of this ratio is observed over the range of target-quark momentum fraction $0.1 < x_t < 0.3$. For $x_t < 0.1$ the ratio is slightly less than unity for the heavy nuclei. These results are compared with predictions of models of the European Muon Collaboration effect.

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The European Muon Collaboration (EMC) observed a modification of the quark structure of nucleons bound in heavy nuclei by studying the deep-inelastic scattering (DIS) of leptons.[1] The original EMC effect has been confirmed[2,3] in the region of fractional quark momenta $0.3 < x < 0.6$. The region $x \leq 0.1$, however, remains a subject of active experimental[4,5] and theoretical[6] activity.

After many years of intense effort, there is no consensus on the origin of the EMC effect. Continuum dimuon production in high-energy hadron collisions, known as the Drell-Yan[7] (DY) process, provides an independent measure of the modification of the quark structure of nuclei.[8] Proton-induced DY production, for fractional longitudinal momentum (Feynman x), $x_F \geq 0.2$, is dominated by the quark-antiquark annihilation subprocess

$$q_p + \bar{q}_t \to l^+ l^- ,$$

where p and t indicate the beam proton and target nucleon, respectively. Although there are large QCD corrections to the simple DY electromagnetic vertex, the factorization property of the next-to-leading-order QCD calculation ensures a DY dimuon yield proportional to the antiquark content of the target nucleon.[9] Thus proton-induced DY production is complementary to DIS where both quarks and antiquarks contribute.

Previous studies of the A dependence of the DY process performed at Fermilab and CERN[10,11] lack the statistical precision of the nuclear DIS data. In this paper we report the results of Fermilab experiment 772, a 450000-event measurement of DY dimuon production from nuclei in a kinematic regime that is sensitive to the antiquark distribution in the target nuclei.

Experiment 772 used a modified version of the large spectrometer in the Meson East beam line at Fermilab which was originally constructed for experiment 605.[12] The magnetic fields of the three dipole magnets of the spectrometer were configured to optimize acceptance for three different regions of dimuon mass. The spectrometer was used in a closed-aperture configuration. A thick hadron absorber in front of the first active detector per-

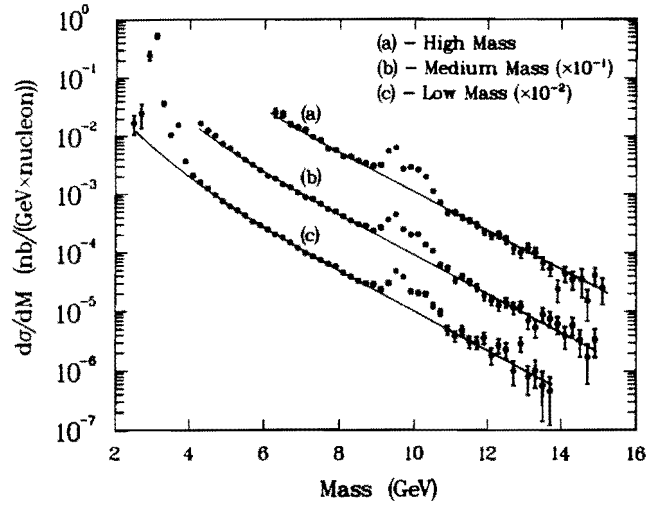

FIG. 1. Acceptance-corrected mass spectra at the three spectrometer settings for the ^{2}H target. The solid curves are calculations of the Drell-Yan cross section, normalized to the data, using the structure functions of Eichten *et al.* (Ref. 14).

mitted incident proton intensities of 10^{11} protons per second at the high-mass setting and 3×10^{10} at the low-mass magnet setting. A total luminosity of 3.5×10^{41} cm^{-2}/nucleon was recorded.

The 800-GeV proton beam, 8 mm wide by ≤ 2 mm high at the target, was monitored by position-sensitive rf cavities and ion chambers; position stability was typically better than 1 mm. Beam intensity was monitored by two secondary-emission detectors and a quarter-wave rf cavity. Two four-element scintillator telescopes viewing the target at 90° monitored the luminosity, the beam duty factor, and the data-acquisition live time.

The dimuon yields were measured for five targets, ^{2}H, C, Ca, Fe, and W. Care was taken to achieve a very accurate target-to-target relative normalization. Long-term drifts were canceled by interchanging the solid targets with the ^{2}H target every few minutes. The solid targets consisted of 7.28-cm-diam disks[13] distributed over a length of 50 cm, the length of the liquid-deuterium cell. Target thicknesses, ranging from 6% (W) to 15% (^{2}H) of an interaction length, were chosen to equalize rates in the spectrometer. Elemental assays of the targets and beam attenuation were included in the luminosity calculation.

The electronic trigger consisted of a pair of triple hodoscope coincidences having the topology of a $\mu^+\mu^-$ pair from the target. This trigger reduced the primary background of low-p_T muons from the target and beam dump. Typically 50 events per second were recorded of which ~ 1 was a valid dimuon event from the target. Electronic live time was kept above 98%.

Track reconstruction was performed on a Fermilab Advanced Computing Project parallel processor. Track reconstruction efficiency averaged $\sim 91\%$; the inefficiency was proportional to the instantaneous luminosity. Target-to-target rate-dependent corrections in reconstruction efficiency were applied. A small contamination ($\sim 3\%$) of random muon coincidences was subtracted by studying like-sign muon pairs. Target-out backgrounds were measured and found to be negligible.

10^6 muon pairs were tracked through a complete Monte Carlo simulation of the spectrometer to study the acceptance. The acceptance for the solid targets was slightly larger than that with the liquid-deuterium cell; a correction (0.9%) for this effect was applied to the data.

The systematic error in the ratio of yields from the solid targets versus deuterium is dominated by the uncertainty in the rate dependence (1.5%), acceptance (0.4%), deuterium thickness (0.4%), and beam attenuation (0.3%). All other contributions are negligible. This results in a total systematic error in the ratios of less than 2%. In the figures shown only statistical errors are indicated.

Acceptance-corrected mass spectra from the three spectrometer settings are shown for the ^{2}H target in Fig. 1. Also shown is a calculation of the DY cross section in the leading-log approximation $[q(x)\rightarrow q(x,M^2)]$ which was normalized to the data. The calculation, which employed the structure functions (set 1) of Eichten *et al.*,[14] gives an excellent account of the shape of the DY continuum. Figure 2 shows the Fe/^{2}H ratio as a function of dimuon mass, x_F, and transverse momentum. It is evident that the mass regions dominated by quarkonium resonances ($M\leq 4$ GeV and $9\leq M\leq 11$ GeV) have very different A dependences than the DY continuum; the A dependence of J/ψ, ψ', and Υ production will be described in a forthcoming publication. The dependence on transverse momentum is similar to that seen by NA10[11] at 280 GeV, but significantly less than that observed at 140 GeV.

Figure 3 shows the ratios of Drell-Yan yield per nucleon for each heavy target versus ^{2}H, $Y_A/Y_{^2\mathrm{H}}$, as a function of x_t for muon pairs with positive x_F. Mean values of x_F and transverse momentum are 0.26 and 0.95 GeV/c, respectively. The x_t ratios are based on mass regions free of contribution from decay of the quarkonium states, specifically, $4\leq M\leq 9$ GeV and $M\geq 11$ GeV. With these cuts the above calculation predicts that the fraction of the accepted DY events due to $q_p\bar{q}_t$ annihilation is ~ 0.95 at $x_t = 0.05$ and ~ 0.75 at $x_t = 0.3$.

No nuclear dependence of the antiquark ratio is observed over the range $x_t > 0.1$. A slight, but experimentally significant, depression of the ratio is seen in the heavier targets for $x_t < 0.1$. Figure 3 compares present data for W/^{2}H to the F_2 ratio Sn/^{2}H from the EMC.[4] The lepton-scattering data exhibit a more pronounced shadowing at small x_t. It is clearly of interest to know whether this difference can be understood in terms of current models of shadowing.[6] It is worth noting that $Q^2\geq 16$ GeV^2 for our data, which is significantly larger than in DIS.

Many of the theoretical attempts to calculate the

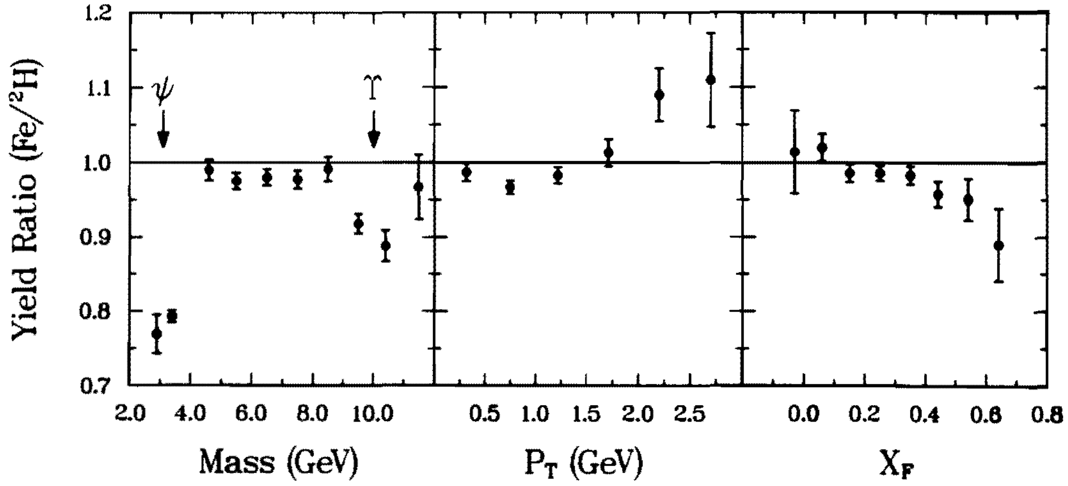

FIG. 2. Ratios of the dimuon yield per nucleon for Fe/^{2}H vs dimuon mass, p_T, and x_F. The p_T and x_F ratios only include data from the pure continuum mass region, $4 \leq M \leq 9$ GeV and $M \gtrsim 11$ GeV.

EMC effect fall into three general categories: pion-excess models, quark-cluster models, and rescaling models. These models can also be used to predict the nuclear dependence of DY dimuon production. The acceptance of the E772 spectrometer was taken into account in each of the following calculations.

The pion-excess model in its earliest forms[15-17] predicted a rise in the $F_2^{\rm Fe}/F_2^{^2\rm H}$ ratio at small x_t as well as a depletion for $x_t \gtrsim 0.2$. The small enhancement in the pion cloud surrounding a bound nucleon arises from a conjectured attractive p-wave π-N interaction in nuclear matter. The strength of this interaction is often characterized by the Landau-Migdal parameter g_0'; typical values found in the literature range around $g_0' \sim 0.6$–0.7. Figure 3 compares the results of a calculation[18] (using the structure functions of Ref. 14) with $g_0' = 0.6$ to the present Fe/^{2}H DY data; it is completely inconsistent with the data. The pion-excess model of Ref. 17, which uses a different pion distribution function, predicts a similar enhancement in the antiquark content of nuclei, in disagreement with our data.

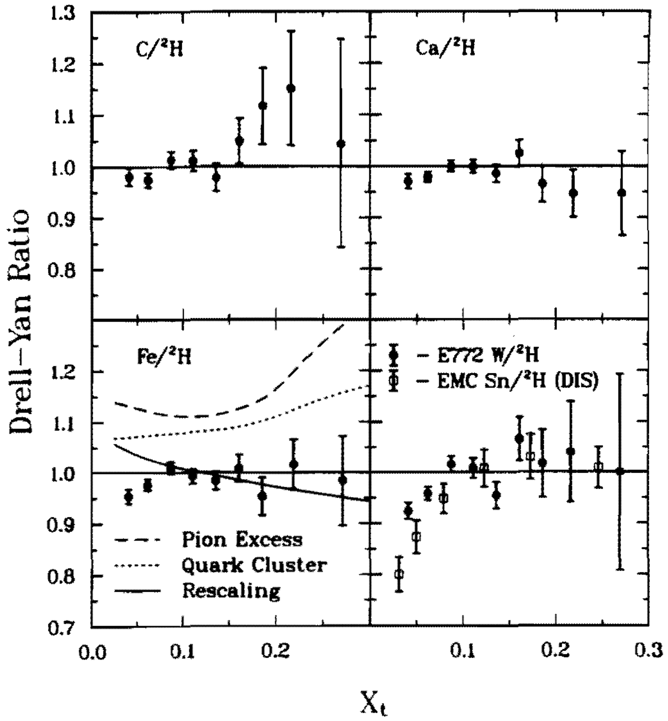

FIG. 3. Ratios of the Drell-Yan dimuon yield per nucleon, $Y_A/Y_{^2\rm H}$, for positive x_F. The curves shown for Fe/^{2}H are predictions of various models of the EMC effect. Also shown are the DIS data for Sn/^{2}H from the EMC (Ref. 4).

Quark-cluster models view the nucleus as composed of a combination of ordinary nucleons plus some fraction of multiquark ($6q$, $9q$, and higher) clusters formed by the overlap of nucleons. The uncertainties in these models come from the essentially unknown structure functions of multiquark clusters. In the model of Carlson and Havens,[19] for example, the parton structure functions were parametrized according to constituent counting rules. The gluon momentum fraction for the $6q$ cluster was constrained to be the same as for the free nucleon. This results in a significant enhancement of the sea even for a modest 15% $6q$-cluster fraction. The calculated DY ratio (Fig. 3) is in significant disagreement with the present data. An alternate but plausible assumption,[20] that the sea-to-glue momentum fraction in $6q$ clusters is the same as it is for nucleons, leads to a smaller enhancement of the DY ratio. However, such a calculation is still in disagreement with our data.

The rescaling model assumes that nuclear binding results in a phenomenon similar to the scaling violation associated with gluon emission.[21] Comparisons to the present DY data are made on the basis of the scale change of structure functions $f(x_t,Q^2) \rightarrow f(x_t,\xi Q^2)$, where $\xi \sim 2$ over the Q^2 range of our data. The calculation, shown in Fig. 3, yields a scaling violation similar to DIS.[5] It approximately fits the DY data, except in the range $x_t < 0.1$, where the approximations made in this model are known to break down.

In summary, this experiment has shown almost no nuclear dependence in the production of continuum dimuon pairs. In the context of the DY description of dimuon production this implies no modification of the antiquark sea in the range $0.1 < x_t < 0.3$. Models of the EMC effect which postulate a significant pion excess or antiquark enhancement in multiquark clusters are apparently ruled out. The Q^2 rescaling model is consistent with the present data. A slight, but experimentally significant, depletion of the yield is seen in the heavier targets for $x_t < 0.1$.

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