NEW RESULTS FROM FERMILAB E866: FLAVOR ASYMMETRY IN THE NUCLEON SEA AND NUCLEAR EFFECTS IN J/ψ PRODUCTION

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The Fermilab dimuon experiment 866/NuSea measured both Drell-Yan and J/ψ yields from an 800 GeV/c proton beam incident on hydrogen, deuterium, beryllium, iron, and tungsten. Over 330,000 Drell-Yan muon pairs were recorded from the liquid hydrogen and deuterium targets. From these data, the ratio of anti-down ($\bar{d}$) to anti-up ($\bar{u}$) quark distributions in the proton sea is determined over a wide range in Bjorken-x. A strong x dependence is observed in the ratio $\bar{d}/\bar{u}$, showing substantial enhancement of $\bar{d}$ with respect to $\bar{u}$ for $x < 0.2$. Approximately 2.7 million J/ψ events were recorded off of the nuclear targets covering a wide range in x_F and p_T. From these data, the nuclear dependence of J/ψ production can be evaluated.

1 Flavor Asymmetry in the Nucleon Sea

Until recently, it has been generally assumed that $\bar{d}(x) = \bar{u}(x)$ in the proton for lack of experimental evidence to the contrary even though no symmetry requires this equality. This assumption may be evaluated by use of the expression

$$\int_0^1 \left[F_2^p(x) - F_2^n(x)\right] \frac{dx}{x} = \frac{1}{3} - \frac{2}{3}\int_0^1 \left[\bar{d}_p(x) - \bar{u}_p(x)\right] dx. \tag{1}$$

Here $F_2^p(x)$ and $F_2^n(x)$ are the proton and neutron inelastic structure functions, and $\bar{d}_p(x)$ and $\bar{u}_p(x)$ are the anti-down and anti-up quark distributions in the proton sea as a function of Bjorken-x. If the nucleon sea is flavor symmetric in the light quarks, the value of the integral on the left is 1/3, a result referred to as the Gottfried Sum Rule (GSR) [1]. In 1991 the New Muon Collaboration (NMC) at CERN presented evidence that the GSR is violated, based on deep inelastic muon scattering data from hydrogen (p) and deuterium (d). They reported a final value [2] of $\int_0^1 \left[F_2^p(x) - F_2^n(x)\right] \frac{dx}{x} = 0.235 \pm 0.026$, which implies that

$$\int_0^1 \left[\bar{d}_p(x) - \bar{u}_p(x)\right] dx = 0.147 \pm 0.039, \tag{2}$$

a considerable excess of $\bar{d}_p$ relative to $\bar{u}_p$.

Following publication of the NMC result, use of the Drell-Yan process was suggested [3] as a means by which the light antiquark content of the proton could be more directly probed. This was first done with hydrogen and deuterium targets by the CERN experiment NA51 [4]. They reported a final value of $\bar{u}/\bar{d} = 0.51 \pm 0.04 \pm 0.05$ at a single x value of $x = .18$.

Fermilab experiment 866 (E866) measured the Drell-Yan muon pair yield from 800 GeV/c proton bombardment of liquid hydrogen and deuterium targets. From these data, $\bar{d}/\bar{u}$ and $\bar{d} - \bar{u}$ in the proton over the range $0.015 < x < 0.345$ are extracted. A significant difference between the $\bar{d}$ and $\bar{u}$ distributions is found.

E866 used a modified version of the 3-dipole spectrometer [5] employed in previous experiments E605, E772, and E789. The extracted beam bombarded the target, then the remaining beam was intercepted by the beam dump. Immediately after the beam dump was an absorber wall which removed hadrons produced in the target and the dump. The detection system consisted of four tracking stations and a momentum analyzing magnet.

Over 330,000 Drell-Yan events were recorded, using three different spectrometer settings which were optimized for low, intermediate and high mass muon pairs. The data collected with the low and intermediate mass settings have systematic effects of a few percent which are currently being studied. The data from the high mass setting are relatively free from these effects due to the greatly reduced rates in the tracking chambers. Therefore, the analysis of the high mass data set was completed first and has been published [6].

In calculating the Drell-Yan yields, several small corrections were made. These included corrections for random coincidences between two unrelated, oppositely charged muons, background events from the target flask and beam line windows, differences in beam attenuation in the targets, differences in the target density, a small hydrogen contamination in the deuterium target and a rate dependent inefficiency. The total systematic error in the cross section ratio in the high mass data is less than $\pm 1\%$. We expect the final systematic uncertainty in the other data sets to be of similar size.

The resulting ratio of the Drell-Yan cross section per nucleon for $p + d$ to that for $p + p$ is shown in Fig. 1 as a function of x_2, the momentum fraction (Bjorken-x) of the target quark in the parton model. (The Bjorken-x of the beam parton is denoted by x_1.) To eliminate contributions from the J/ψ and Υ resonance families a cut on the muon pair mass, $M_{\mu^+\mu^-}$, was used. The data clearly show that the Drell-Yan cross section per nucleon for $p + d$ exceeds $p + p$ over an appreciable range in x_2.

The acceptance of the spectrometer was largest for $x_F = x_1 - x_2 > 0$. In this kinematic regime the Drell-Yan cross section ratio can be approximated by

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2} \frac{\left(1 + \frac{1}{4}\frac{d_1}{u_1}\right)}{\left(1 + \frac{1}{4}\frac{d_1}{u_1}\frac{\bar{d}_2}{\bar{u}_2}\right)} \left(1 + \frac{\bar{d}_2}{\bar{u}_2}\right). \tag{3}$$

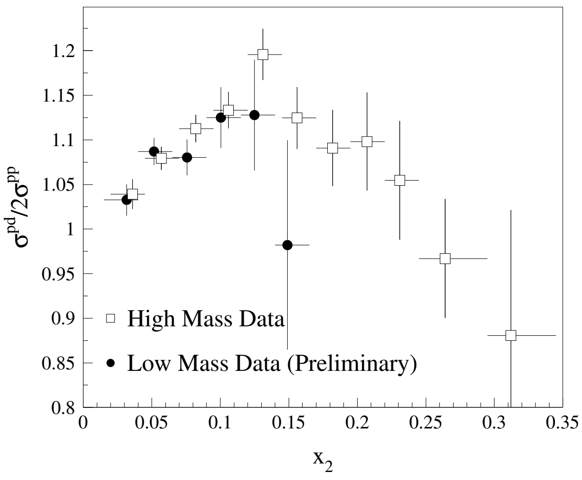

Figure 1: The ratio $\sigma^{pd}/2\sigma^{pp}$ of Drell-Yan cross sections *vs.* x_2. Shown are the E866 published results from the high mass data set and the E866 preliminary results from the low mass data set. The errors shown are statistical only. The systematic uncertainty in the high mass data is $\pm 1\%$.

The subscripts 1 and 2 denote the parton distributions in the proton as functions of x_1 and x_2, respectively. In the case that $\bar{d} = \bar{u}$, the ratio is 1. This equation illustrates the sensitivity of the Drell-Yan measurement to $\bar{d}/\bar{u}$ and implies an excess of $\bar{d}$ with respect to $\bar{u}$ for the data.

The ratio $\bar{d}/\bar{u}$ was extracted iteratively by calculating the leading order Drell-Yan cross section ratio using a set of parton distribution functions (PDF) as input and adjusting $\bar{d}/\bar{u}$ until the calculated cross section ratio agreed with the measured value from the high mass data. The extracted $\bar{d}/\bar{u}$ ratio is shown in Fig. 2 along with the CTEQ4M [7] parameterization. A qualitative feature of the data, not seen in either CTEQ4M or MRS(R2) [8], is the rapid decrease towards unity of the $\bar{d}/\bar{u}$ ratio beyond $x = 0.2$. At $x = 0.18$, the extracted $\bar{d}/\bar{u}$ ratio is somewhat smaller than the value obtained by NA51. Such a large $\bar{d}/\bar{u}$ asymmetry cannot arise from perturbative effects [9]. It has been suggested [10,11] that including the effects of virtual mesons can account for the asymmetry and this appears [12] to be correct.

To address the GSR violation observed by NMC, our extracted $\bar{d}/\bar{u}$ ratio is used together with the CTEQ4M value of $\bar{d}+\bar{u}$ to obtain $\bar{d}-\bar{u}$. Based on this, the integral of $\bar{d}-\bar{u}$ between $x^{\rm min}$ and 0.345 is calculated. Both $\bar{d}-\bar{u}$ and $\int_{x^{\rm min}}^{0.345} (\bar{d}-\bar{u})\, dx$ are shown in Fig. 3. The integral reaches a value of $0.068 \pm 0.007(stat) \pm 0.008(syst)$ at $x^{\rm min} = 0.02$. This may be compared with the CTEQ4M and MRS(R2) parameterizations which have values of 0.076 and 0.100, respectively, for the integral over the same region. Over the range $10^{-4} < x < 1$, CTEQ4M gives a value of 0.108 for the integral, and MRS(R2) gives 0.160. Above $x = 0.345$, it is unlikely there are significant contributions to the $\bar{d}-\bar{u}$ integral since the sea is relatively small in this region. It is clear, however, that significant contributions to the integral arise in the unmeasured region below $x = 0.02$.

The difference between the NMC and E866 results for the $\bar{d}-\bar{u}$ integral raises the question of the compatibility of the two measurements. Figure 4 shows the NMC data for $F_2^p - F_2^n$ at $Q = 2$ GeV, together with the fits of MRS(R2) and CTEQ4M. Both PDF parameterizations give similar results for $F_2^p - F_2^n$. However, their agreement with the NMC data is poor in the region $0.15 < x < 0.4$. It is instructive to decompose $F_2^p(x) - F_2^n(x)$ into contributions from valence and sea quarks:

$$F_2^p(x) - F_2^n(x) = \frac{1}{3} x \left[u_v(x) - d_v(x)\right] + \frac{2}{3} x \left[\bar{u}(x) - \bar{d}(x)\right]. \tag{4}$$

Two PDF parameterizations of these contributions are also shown in Fig. 4. The valence contribution is positive, while the contribution from the sea is negative. The parameterizations give noticeably different values for the valence and sea contributions, though their net results for $F_2^p - F_2^n$ are very similar. As shown in Fig. 4, the E866 data provide a direct determination of the sea-quark contribution to $F_2^p - F_2^n$, and can be used to distinguish between different PDF parameterizations that produce

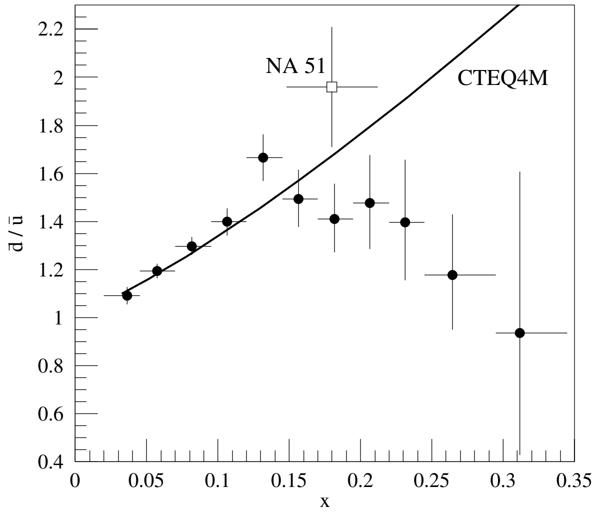

Figure 2: The ratio of $\bar{d}/\bar{u}$ in the proton as a function of x extracted from the E866 high mass cross section ratio. The curve is from the CTEQ4M parton distributions. The error bars indicate statistical errors only. An additional systematic uncertainty of ± 0.032 is not shown. The result from NA51 is also plotted as an open box.

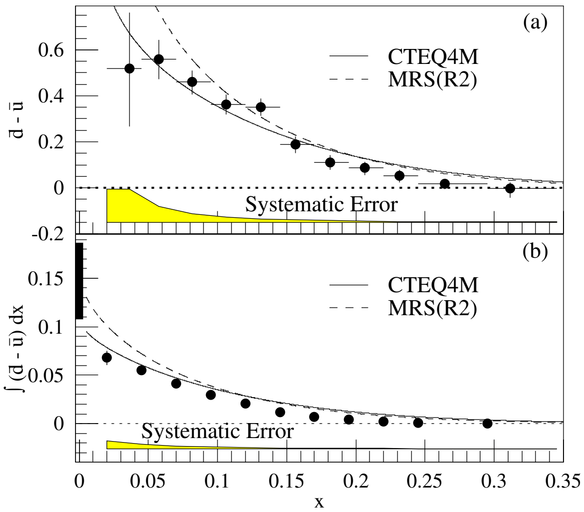

Figure 3: Values for (a) $\bar{d}-\bar{u}$ and (b) $\int_x^{0.345}\left(\bar{d}-\bar{u}\right)dx'$ in the proton versus x, extracted from the E866 high mass data. The curves represent the corresponding values obtained from two PDF parameterizations. The bar at 0.147 ± 0.039 on the left axis in (b) shows the result obtained by NMC for the integral from 0 to 1.

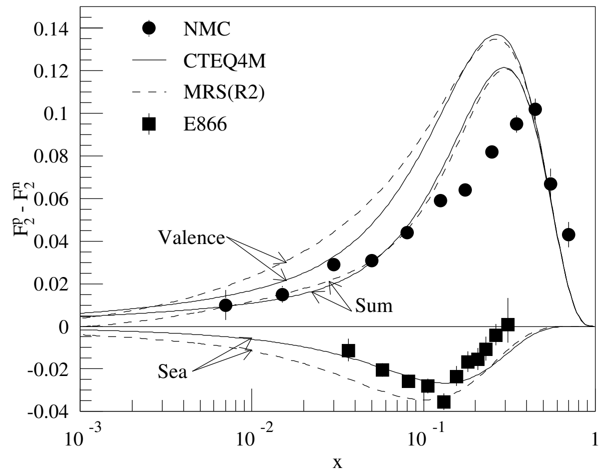

Figure 4: $F_2^p - F_2^n$ as measured by NMC compared with predictions based on the CTEQ4M and MRS(R2) parameterizations. Also shown are the E866 high mass results for the sea-quark contribution to $F_2^p - F_2^n$. For each prediction, the top (bottom) curve is the valence (sea) contribution and the middle curve is the sum.

similar fits to the NMC data. As the direct determination of $\bar{d}(x) - \bar{u}(x)$ is smaller than obtained from either PDF set, the parameters must be adjusted to reduce the magnitude of both the sea and valence distributions in the interval $0.03 \leq x \leq 0.3$. This reduction will force an increase in the valence contribution to the integral from $x \leq 0.03$ and could therefore bring the results from E866 and NMC into better accord. Fig. 4 also suggests that the reason for the difference between the PDF fits and the NMC results in the interval $0.15 < x < 0.4$ is that the PDFs cannot accommodate the rapid variation in the asymmetry of the nucleon sea as a function of x revealed by E866.

2 Nuclear Effects in J/ψ Production

After the previous measurement was completed, the cryogenic targets were replaced with nuclear targets of beryllium, iron, and tungsten to study the nuclear effects of J/ψ production. Over 2.7 million J/ψ events and 60,000 ψ' events were observed. The J/ψ and ψ' yields for each target were compared to study their nuclear dependence. Since these events covered a wide range in both x_F ($-0.1 \leq x_F \leq 0.9$) and p_T ($0 \leq p_T \leq 4\ GeV/c$) it is possible to study the nuclear effects as a function of these kinematic variables.

One of the most obvious effects of J/ψ production inside of a nucleus is the fact that the cross section increases slower than linearly with the number of nucleons. A convenient way of quantifying the suppression of J/ψ production in a nucleus is in terms of α. Using the equation

$$\sigma_A = \sigma_{\text{nucleon}} \times A^{\alpha}, \tag{5}$$

one can see that $\alpha = 1$ indicates no suppression and as α decreases the suppression increases.

Fig. 5 shows that both J/ψ and ψ' production are suppressed in heavy nuclei. The decrease in α as x_F increases can be explained by parton energy loss while the overall suppression is probably due to the disassociation of the J/ψ or pre-J/ψ by the nucleus or by comoving light partons.

After the analysis of these data is completed, the J/ψ suppression will be studied as a function of different kinematic quantities such as p_T and x_2. By doing this it is hoped that the relative importance of different nuclear effects can be determined. This understanding will aid in the interpretation of J/ψ suppression, which is a possible signature of the quark-gluon plasma, in nucleus-nucleus collisions.

3 Conclusion

Fermilab E866 made high statistics measurements of dimuons from hydrogen, deuterium, and nuclear targets. Using the Drell-Yan yield from hydrogen and deuterium targets the Drell-Yan cross section

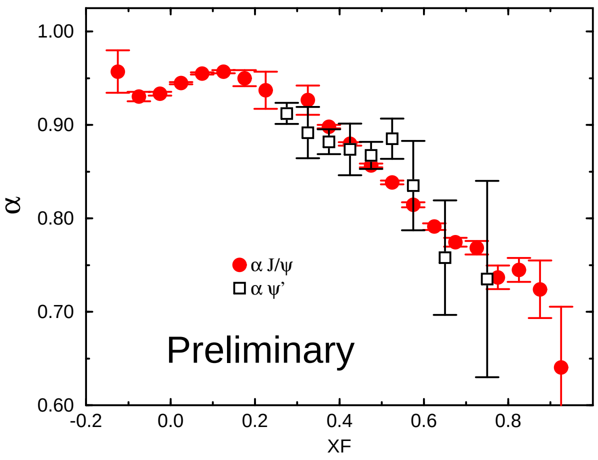

Figure 5: The value of α vs x_F. Shown are the preliminary results from E866 for the nuclear suppression in terms of α (equation 5) for the production of J/ψ (solid circles) and ψ' (open squares) as a function of x_F.

ratio per nucleon of $p + d$ to $p + p$ was measured. From this measurement the asymmetry of the light quark sea in the proton was extracted as a function of x. This ratio of $\bar{d}/\bar{u}$ is in qualitative agreement with both the NA51 and NMC measurements.

The measurement of J/ψ yields off of the nuclear targets shows that J/ψ production is suppressed in heavy nuclear targets. The strong nuclear suppression for the J/ψ has been measured over a large region in x_F and shows that suppression increases as x_F increases.

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