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DIMUON PRODUCTION IN PROTON-NUCLEUS INTERACTIONS

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ABSTRACT

Results from the Fermilab experiments E772 and E789 on the Drell-Yan cross sections, quarkonia production, and open-charm production are presented. These data provide information on the parton distributions in the nucleons and nuclei. They also shed light on the origin of the J/Ψ suppression observed in heavy ion collisions. The physics motivation and the proposed measurements for a new experiment to probe the sea quark distributions in the proton are also discussed.

1. Introduction

One of the most active research areas in medium- and high-energy nuclear physics in recent years is the study of the parton distributions in the nucleons and nuclei. Lepton induced deep inelastic scattering (DIS) has been the major experimental tool for such studies, and it has led to many important discoveries.

The famous EMC effect¹, reported more than 10 years ago, provided the first clear evidence that the parton distributions in the nuclei are different from those in the nucleon. The EMC effect was subsequently confirmed by other high statistics DIS experiments²⁻⁵, which also revealed the striking shadowing effect at small x . Using polarized electron or muon beams incident on polarized targets, experimenters at SLAC⁶ and CERN⁷ measured the spin-dependent structure functions and found the surprising result that the quarks carry only a small fraction of the proton's spin. More recently, the NMC collaboration reported⁸ that the Gottfried Sum Rule⁹ was apparently violated, indicating that the $\bar{u}$ and $\bar{d}$ sea quark distributions in the proton are not identical, contrary to the conventional wisdom of a symmetric $\bar{u}$ and $\bar{d}$ sea distributions.

Detection of high-mass lepton pairs produced in hadron-hadron or hadron-nucleus collisions offers another means to probe the parton distributions in the nucleons and nuclei. There are mainly two distinct processes contributing to the production of high-mass dileptons. The first is the Drell-Yan process¹⁰, an electromagnetic process involving the annihilation of a quark-antiquark pair into a virtual photon followed by

an emission of a lepton pair. The momentum and mass distributions of the lepton pairs reflect the parton distributions in the projectile and the target hadrons. Indeed, experiments on the Drell-Yan process, together with the DIS data, have provided nearly all inputs to the parton distributions in the hadrons¹¹. In particular, structure functions of the unstable π and K mesons are determined only from the Drell-Yan experiments¹². One important advantage of the Drell-Yan process is the possibility to isolate a specific component of the structure functions by selecting an appropriate beam particle type. For example, with a proton beam, the Drell-Yan yield at large x_F ($x_F > 0.2$) is predominantly sensitive to the $\bar{u}$ distribution in the target hadron. This is in contrast to DIS, for which the cross section is proportional to the sum of the quark and antiquark distributions. The Drell-Yan process can therefore be used to study selectively the sea quark distributions of nucleons and nuclei and to provide information not accessible to the DIS measurements¹³.

Another process contributing to high-mass lepton pairs is the production of quarkonia, such as $J/\psi, \psi', \Upsilon, \Upsilon', \Upsilon''$, which subsequently decay into $\mu^+\mu^-$ or e^+e^- . The underlying mechanisms for quarkonia production are strong interactions involving gluon-gluon fusion ($gg \rightarrow Q\bar{Q}$) and quark-antiquark annihilation ($q\bar{q} \rightarrow Q\bar{Q}$), where q, g, Q denote the light quarks (u, d, s), gluon, and heavy quarks (c, b), respectively. At center-of-mass energies well above the thresholds for $Q\bar{Q}$ production, the gluon-gluon fusion process gives the dominant contribution. This suggests the possibility of probing the gluon distributions in the nucleon and nuclei via quarkonia production¹⁴. Neither DIS nor Drell-Yan process is sensitive to the gluon distributions, hence quarkonia production provides a rather unique means to probe the distributions in the nucleon and nuclei.

Another motivation for studying the quarkonia production is related to the so-called ' J/ψ -suppression' effect in heavy ion collision. It was predicted that the yield for J/ψ production in heavy-ion central collisions could be suppressed due to the onset of quark-gluon plasma¹⁵. Such J/ψ -suppression effect was indeed observed later in experiments¹⁶ at CERN, although many different interpretations of this effect have been offered. To provide further insight to the origins of J/ψ -suppression, it is useful to obtain data of quarkonia production in proton-nucleus collision, where the formation of quark-gluon plasma is not expected.

Over the past seven years, a series of experiments (E772, E789, E866) have been proposed at Fermilab for high statistics measurements of dimuons produced in proton-nucleus interaction at 800 GeV/c. Although the E772 experiment was originally proposed with a specific goal to study the sea-quark distributions in the nuclei, information on the quarkonia production in $p - A$ collision was obtained simultaneously. In the E789 experiment, measurements of the J/ψ production were extended to a significantly wider kinematic range and results on the D meson production were also obtained.

Results from the E772 and E789 experiment will be presented in this paper. The implications of these data on the parton distributions in nucleons and nuclei, and on the origin of J/ψ suppression will be discussed. A new proposal, E866, is expected to shed more light on the violation of the Gottfried Sum Rule observed by the NMC

Figure 1: Schematics of the Fermilab E605/E772/E789 spectrometer

group. The physics motivation and the anticipated results from the E866 experiment will also be discussed.

2. The Experiments

The E772/E789 experiments were performed at the Meson East channel at Fermilab using 800 GeV/c proton beam incident on a variety of liquid or solid targets. The reaction products were detected with the spectrometer shown in Figure 1. This spectrometer, originally built for the experiment E605 to detect high mass lepton and hadron pairs¹⁷, contains two large analyzing magnets allowing an excellent mass resolution. By placing a copper beam dump inside the first magnet, high intensity proton beam (up to 10^{12} protons/spill) could be utilized without exceeding the rate capability of various detectors. The electromagnetic and hadron calorimeters, together with the muon station counters, provide particle identifications for electrons, hadrons, and muons.

For dimuon detection, the experiment could be run in the closed-aperture configuration, in which large amounts of absorber materials were inserted inside the first magnet. This configuration enables the detectors to withstand high interaction rates. Furthermore, the presence of the absorbers shortens the flight-path over which the pions could decay into muons, hence greatly reducing a major source of muon backgrounds. An obvious disadvantage of the close-aperture configuration is the deterioration of the momentum resolution and some care is required to design an optimal absorber configuration. Figure 2a) shows the dimuon mass spectrum obtained in E772¹⁸ with the closed-aperture configuration. For comparison, the dimuon spectrum from the open-aperture run of E789¹⁹ is shown in Figure 2b). Both spectra are not corrected for spectrometer acceptance. The open-aperture run gives a very good J/ψ mass resolution of $\sigma \sim 16$ MeV, but the magnitude of the continuum under the ψ' peak is significantly greater than that in the closed-aperture configuration,

Figure 2: Dimuon mass spectra from a) the E772 closed-aperture run, b) the E789 open-aperture run, and c) the E789 beam-dump measurement. Dihadron mass spectrum from E789 is shown in d), in which the $D \rightarrow K\pi$ peak is seen.

indicating some contributions from pions decaying in flight.

Dimuons from the interactions of proton beam with the copper beam dump could also be measured. The interaction rate and spectrometer acceptance for such ‘dump dimuons’ are very large. Figure 2c) shows the J/ψ peak clearly observed in the beam dump dimuons spectrum measured in the E789 experiment²⁰. As discussed later, the beam dump dimuon data provide valuable informations for J/ψ production at very large x_F region ($x_F \rightarrow 1$).

A major upgrade of the spectrometer was carried out for the E789 experiment by installing 16 planes of silicon strip detectors for reconstructing the decay vertices. This allowed the observation of B mesons via the $B \rightarrow J/\psi$ decays. It also enabled us to detect the open-charm D^0 mesons through the $D^0 \rightarrow K\pi$ decay channel. Figure 2d) shows the dihadron spectrum measured in E789²¹. The D^0 peak is clearly identified following the selection of events with decay vertices well separated from the interaction point. As discussed in a later section, the nuclear effect of D meson production provides useful insight for understanding the origin of the J/ψ suppression effect.

3. Drell-Yan Process in Proton-Nucleus Interaction

The expression for the Drell-Yan cross section is

$$\frac{d^2\sigma}{dx_1 dx_2} = K \left(\frac{4\pi\alpha^2}{9M^2} \right) \sum_i e_i^2 (q_i^B(x_1) \bar{q}_i^T(x_2) + \bar{q}_i^B(x_1) q_i^T(x_2)), \quad (1)$$

where $q_i, \bar{q}_i$ are the structure functions for quark and antiquark of flavor i (for simplicity, the Q^2 dependence of the structure functions is not explicitly shown). x_1 and x_2 are the fractions of the momenta of the beam (B) and target (T) hadrons carried by the quark and antiquarks. M is the mass of the dimuon and e_i is the quark charge. The factor K takes into account the contributions from higher order diagrams. It is recalled that the $F_2(x)$ measured in DIS experiments is given as

$$F_2(x) = \sum_i e_i^2 x (q_i^T(x) + \bar{q}_i^T(x)). \quad (2)$$

From Eqs. (1) and (2), the Drell-Yan process appears to be more complicated than the DIS, since it involves two combinations of the structure functions from the beam hadron and the target hadron. Nevertheless, at the kinematic region of $x_1 > 0.2$ and $x_F > 0.1$ ($x_F = x_1 - x_2$), the second term in Eq. (1) has negligible contribution and to a very good approximation the proton-induced Drell-Yan cross section is proportional to

$$\sum_i e_i^2 q_i^B(x_1) \bar{q}_i^T(x_2). \quad (3)$$

Unlike the DIS process which is sensitive to both the quark and the antiquark distributions, the proton-induced Drell-Yan process probes only the antiquarks in the target nuclei. Therefore, an accurate measurement of the nuclear dependence of the Drell-Yan cross section would be sensitive to any possible variation of antiquark distributions from nucleon to nuclei¹³.

Prior to the E772 experiments, several proton-induced and pion-induced Drell-Yan experiments^{22,23} have been performed to study the nuclear effects. Although the results were consistent with a linear nuclear dependence, the statistical accuracies of these experiments were relatively low. Furthermore, due to the presence of valence quark and antiquark in the beam, the pion-induced Drell-Yan process²³ does not selectively probe the antiquark distributions in the target nuclei.

In the E772 experiment, approximately 0.6×10^6 dimuon events with $9 \text{ GeV} \geq M_{\mu^+\mu^-} \geq 4 \text{ GeV}$ or $M_{\mu^+\mu^-} \geq 11 \text{ GeV}$ have been collected from the proton interacting

Figure 3: Ratios of the Drell-Yan yield per nucleon from E772. Also shown are the DIS data and comparison with various EMC models.

on liquid deuterium and solid C, Ca, Fe and W targets. Much care was taken to control systematic errors under 2%. The spectrometer covers the kinematic range $x_F \geq 0.0$ and $x_2 \geq 0.04$. Figure 3 shows the E772 result¹⁸ on the ratios of the Drell-Yan cross sections on various nuclear targets over the liquid deuterium target. The nuclear dependence of the integrated Drell-Yan cross sections measured in E772 is well described by $A^{0.998 \pm 0.002}$, where A is the mass of the target nucleus. The absence of any enhancement of antiquark distribution at small x in heavy nuclei is in striking contrast to the predictions of the pion-excess models²⁴ and an early version of the quark-cluster model²⁵. The data are in good agreement with the rescaling model²⁶ and a later version of the quark-cluster model²⁷. The E772 data set a stringent limit on the magnitude of nuclear effect of antiquark distributions.

Figure 3 also shows the possible onset of the shadowing effect at small x_2 . It would be very useful to extend the Drell-Yan measurement to even lower x_2 , say, $x_2 = 0.01$, where very pronounced shadowing effects were observed^{4,5} in DIS. Recalling that $M_{\mu^+\mu^-}^2 = Sx_1x_2$, there are two ways to reach the very low x_2 region. One could either go to much higher energies, possible at the heavy ion collider at RHIC, or study dimuons at lower masses ($4 \text{ GeV} \geq M_{\mu^+\mu^-} \geq 2 \text{ GeV}$). The Drell-Yan yields at low masses are quite large, but some cautions are needed to separate the Drell-Yan process from the $J/\psi(\psi')$ production, as well as to determine the contributions from charm decays. The feasibility to extend the Drell-Yan measurements to smaller mass could be explored in the upcoming Fermilab experiment E866.

Several authors have considered the effects of initial-state interaction in the Drell-

Yan process^{28,29}. Multiple-scattering of partons will broaden the dimuon transverse momentum (P_T) distributions for interaction on a heavy nucleus. Such effect is indeed observed in the E772 experiment, as well as in the NA10 experiment²³ for 140 and 280 GeV pion beams, and it can be quantitatively explained by the multiple scattering model²⁹. Another possible effect of the initial-state interaction is to reduce the longitudinal momentum (x_F) of the dimuons. In fact, it has been suggested³⁰ that the nuclear effects at small x_2 observed in E772, as shown in Figure 3, can be understood by the energy-loss mechanism. However, the amount of energy loss needed to explain the data appears unrealistically high³¹. It is likely that the observed Drell-Yan nuclear dependence contain both the initial-state interaction effect, which is a function of x_F , and the nuclear structure function effect, which depends on x_2 . Future data to extend the measurements to smaller x_2 values and to higher energies will help to disentangle these two effects.

It is worth mentioning several yet unexplored areas in Drell-Yan physics which could be studied in the future. In addition to the small x_2 region discussed earlier, the large x_2 and x_F regions are also interesting. The suppression of the parton densities in nuclei at moderately large x_2 ($x_2 > 0.2$), as observed in the DIS experiments, still need to be confirmed by the Drell-Yan experiments. A peculiar behavior of the pion-induced Drell-Yan process was observed³² at large x_F ($x_F \rightarrow 1$), where the dimuons were produced with longitudinal polarization rather than the expected transverse polarization. Higher-twist effect was invoked to explain³³ the pion data. No data yet exist for proton-induced Drell-Yan polarization at $x_F \rightarrow 1$. As will be discussed in a later section, detection of dimuons produced in the beam dump could provide a means to measure the very small Drell-Yan cross sections at large x_2 and x_F . Another area of interest is to measure the spin-dependent structure functions in the nucleon via polarized Drell-Yan experiments. In particular, the polarization of the sea-quark distributions can be determined. Finally, as will be discussed in detail in section 5, measurement of the Drell-Yan ratio of hydrogen over deuterium targets will determine the $\bar{u}/\bar{d}$ in the proton.

4. Nuclear Dependence of Quarkonia Production

The nuclear dependences for the production cross sections of J/ψ , ψ' , and Υ measured in E772 are shown in Figure 4. In striking contrast to the very weak nuclear dependence of the Drell-Yan process, the quarkonia production has pronounced nuclear dependence. The nuclear effects for J/ψ production have been measured^{34,35} for various beam particles at several beam energies, but no ψ' or Υ data existed prior to E772. Figure 4 shows that, within statistics, the J/ψ and ψ' have similar nuclear dependences. The Υ production is also suppressed in heavy nuclei, but the effect is weaker than that of J/ψ and ψ' .

It is instructive to examine how the nuclear effect depends on the x_F and P_T of the quarkonia. By fitting the J/ψ nuclear dependence with the simple expression A^α , we show in Figure 5 the values of α as a function of x_F for data obtained in E772 and NA3³⁵. A strong x_F -dependence, showing α decreasing with increasing

Figure 4: Nuclear dependences of the Drell-Yan, J/Ψ , Ψ' , and Υ cross sections from E772.

x_F , is observed for both the E772 and the NA3 data. One implication of this strong x_F -dependence is that one should exercise caution while comparing the α parameters extracted from different experiments, since different ranges of x_F could be covered. It should be mentioned that very similar x_F -dependence has also been observed for light mesons and baryons production in $P - A$ interaction³⁶, suggesting that some mechanisms common to all hadron productions in the nuclear environment could be responsible for the observed effect.

Figure 5 shows that the P_T distribution of the J/Ψ is significantly broadened for heavy target nuclei. Figure 6 shows the amount of $\langle P_t^2 \rangle$ broadening observed in E772 for Υ production and Drell-Yan process. Once again, the pronounced P_T broadening effect for Υ production is reminiscent of the so-called 'Cronin Effect' observed in hadron productions in nuclei³⁷. The Cronin Effect was attributed to increased probability of parton multiple scattering in hadron-nucleus interaction. Figure 6 suggests that multiple scattering effect persists for the heaviest meson, Υ , studied so far in any experiment.

Many theoretical models³⁸ have been proposed to explain the nuclear effects of J/ψ , ψ' , and Υ production seen in E772. The combined Drell-Yan, J/ψ , ψ' , and Υ data obtained in E772 impose a stringent test for all proposed models. In the following, we will briefly summarize the various models and discuss the various aspects of the data which can or cannot be explained by each model.

The striking shadowing effect observed in DIS at $x_2 < 0.05$ suggests that similar effects would also occur for quarkonium production³⁹. Unlike the case for Drell-Yan

Figure 5: The nuclear dependence parameter α for Drell-Yan and J/Ψ production as a function of x_F , x_2 and P_T . Also shown are the NA3 data at 200 GeV.

Figure 6: Increase of the average value of P_T^2 for Drell-Yan and Υ production in nuclear targets. The dashed curve is the fit to the Υ data with $\Delta P_T^2 = 0.16 (A^{1/3} - 2^{1/3}) \text{ GeV}^2/c^2$.

process, it is not evident how one can determine the x_2 values for quarkonium events. This is because indirect processes, such as χ production followed by $\chi \rightarrow J/\psi + \gamma$ decays, are known to have significant contributions to the observed J/ψ cross sections. Nevertheless, it is a reasonably good approximation to assume $M^2(J/\psi) = x_1 x_2 S$, which, together with $x_F = x_1 - x_2$, allow us to determine x_2 . Figure 5 shows α as a function x_2 . The J/ψ data from E772 correspond to very low values of x_2 and indeed exhibit features reminiscent of the shadowing seen in DIS. Furthermore, the Υ data in E772 correspond to relatively large x_2 values where shadowing effect is not important, hence the Υ cross section would be less suppressed, in agreement with the data. Nevertheless, the NA3 data, also shown in Figure 5, clearly shows the breakdown of x_2 scaling, which should be valid if the gluon shadowing is the underlying mechanism. This suggests that the shadowing effect alone cannot account for the experimental data.

The so-called ‘intrinsic charm’ model has been proposed⁴⁰ to explain the x_F dependence of the nuclear effects. In this model, J/ψ is produced via the hard QCD process together with a soft diffractive process which becomes increasingly important at large x_F . The diffractive process is due to the presence of a $c\bar{c}$ component in the proton beam. Since this component of the proton wave function is subject to nuclear absorption, J/ψ production at large x_F in heavy nuclei will be suppressed. The magnitude of the $c\bar{c}$ component in the proton is a parameter to be determined by experiments. In the E789 experiment²⁰, the J/ψ production cross section was measured at very forward x_F region ($0.2 \leq x_F \leq 0.95$) using the copper beam dump as the target. The shape of the differential cross section is well described by hard QCD process alone, and there is no evidence for a significant contribution from the diffractive process. It therefore appears that the intrinsic charm model cannot by itself account for the nuclear effects observed for quarkonia production.

Many authors have considered the effects of initial-state and final-state interactions for J/ψ production in nuclei⁴¹. The quark and gluon could undergo multiple scattering prior to the hard QCD process, similar to the situation for Drell-Yan process mentioned earlier. In addition, the $c\bar{c}$ or $b\bar{b}$ states produced in the hard QCD process could interact with the target nucleus or other ‘comoving’ hadrons. Through the final state interaction, the $c\bar{c}$ or $b\bar{b}$ states could convert into a pair of charmed hadrons or bottom hadrons and the yields for J/ψ and Υ will be suppressed. Furthermore, the scattering in the initial and final state will broaden the P_T distribution. Indeed, the $\Delta(P_T^2)$ for Υ production is proportional to $A^{1/3}$, shown as the dashed curve in Figure 6. The $A^{1/3}$ dependence in $\Delta(P_T^2)$ is consistent with the multiple-scattering picture. Another effect caused by the initial- and final-state interactions is the degradation of the longitudinal momentum of the quarkonia. This energy-loss mechanism could account for the observed x_F -dependence of the nuclear effect³⁰. However, the amount of energy loss, $dE/dZ = 1.5 \text{ GeV}/fm$, needed to explain the E772 J/ψ data appears to be significantly larger than the value $dE/dZ = 0.5 \text{ GeV}/fm$ determined from other considerations³¹.

From the above discussions, we conclude that none of the proposed mechanisms can account for all the nuclear effects seen in quarkonia production. It is very likely

Figure 7: The nuclear dependence parameter α for J/ψ and D productions from E772 and E789.

that several mechanisms contribute to the observed effects, and it is a challenge to disentangle the various contributions. Two recent measurements were done in E789 to help testing the various models. First, the J/ψ A -dependence measurement has been extended to negative x_F and very forward x_F region²⁰. Figure 7 shows the value of α determined from E772 and E789 over a wide range of x_F . It would be very interesting to compare the predictions of various models with these data. Second, the nuclear dependence of D^0 meson production has been measured²¹. Contrary to the situation for J/ψ production, there is no suppression for D^0 meson production at $x_F = 0$. One major difference between open-charm (D^0) and J/ψ production is that D^0 suffers very little final-state interaction. Unlike the J/ψ which can convert into a pair of charmed hadrons, the D mesons will last until they decay by weak interaction. Therefore, the lack of nuclear effect in D production strongly favors the models of the final-state interaction for J/ψ production in nuclei. It should be cautioned, however, that this does not exclude the gluon-shadowing model. At $x_F = 0$, the D meson is sensitive to rather large x_2 where no shadowing effect is expected. It would be interesting to extend the measurement to large x_F , where the D meson production is sensitive to small x_2 . Another very interesting region is the very negative x_F region for both the J/ψ and D meson production, feasible at the $P - A$ collider at RHIC.

5. Sea Quark Distributions in the Proton

The NMC collaboration reported⁸ the result of their measurement of the Gottfried

Sum⁹ in muon DIS. The Gottfried Sum is given as

$$I_G(x_1, x_2; Q^2) = \int_{x_1}^{x_2} dx (F_2^{\mu p}(x, Q^2) - F_2^{\mu n}(x, Q^2)) / x, \quad (4)$$

where $F_2^{\mu p}$ and $F_2^{\mu n}$ are the proton and neutron structure functions measured in muon DIS. Assuming charge symmetry for the parton distributions in the proton and neutron, F_2 can be expressed in terms of the valence and sea quark distributions of the proton. The Gottfried Sum becomes

$$I_G(x_1, x_2; Q^2) = \frac{1}{3} \int_{x_1}^{x_2} dx [u_v(x, Q^2) - d_v(x, Q^2)] + \frac{2}{3} \int_{x_1}^{x_2} dx [\bar{u}(x, Q^2) - \bar{d}(x, Q^2)]. \quad (5)$$

The integral in the first term of Eq.(4) gives the difference between the number of the up and down valence quarks in the proton. The second term in Eq.(4) vanishes under the assumption of a $\bar{u} - \bar{d}$ flavor-symmetric sea for the proton, and the Gottfried Sum Rule (GSR), $I_G(0, 1; Q^2) = 1/3$, is obtained. Based on their measurements of muon DIS on hydrogen and deuterium targets, the NMC has determined $I_G(0.004, 0.8; Q^2 = 4\text{GeV}^2) = 0.227 \pm 0.007$. Following an extrapolation to the unmeasured x -region, it was estimated $I_G(0, 1; Q^2 = 4\text{GeV}^2) = 0.240 \pm 0.016$, significantly different from $1/3$.

Many theoretical models⁴² have been proposed to account for the apparent violation of the GSR. These models in general fall into two categories. Models in the first category assume that the valence quark distributions in the proton are sufficiently singular at $x < 0.004$ such that a large contribution to the Gottfried Sum occurs at this region not probed by the NMC experiment. Therefore, the GSR is not violated and the assumption of $\bar{u}/\bar{d}$ symmetry in the proton remains valid in these models. The other category of theoretical models interpret the NMC result as evidence that the $\bar{u}$ and $\bar{d}$ distributions in the proton are different. Some empirical expressions for $\bar{d}(x) - \bar{u}(x)$ have been proposed. Several recent sets of parton distribution functions¹¹ explicitly allow $\bar{u}/\bar{d}$ asymmetry to account for the NMC result. The origin of the enhancement of $\bar{d}$ over $\bar{u}$ in the proton has been attributed to pion cloud, diquark clustering in the nucleon, as well as Pauli-blocking effect.

It has been proposed that the Drell-Yan process provides an independent and sensitive test of the possible $\bar{u}/\bar{d}$ asymmetry in the proton⁴³. Using a proton beam and restricting the kinematic regime to forward x_F ($x_F > 0.2$), it is straightforward to show that

$$2 \frac{\sigma_{DY}(p+p)}{\sigma_{DY}(p+d)} \simeq 1 - \frac{\bar{d}_p(x) - \bar{u}_p(x)}{\bar{d}_p(x) + \bar{u}_p(x)}. \quad (6)$$

A similar expression with a reduced sensitivity to the $\bar{u}/\bar{d}$ asymmetry can also be obtained for the ratio of Drell-Yan cross sections on neutron-rich targets versus isoscalar

Figure 8: Predictions of Drell-Yan cross section ratios for various models using Eq.(6). The expected sensitivities for E866 and the recent NA51 result are also shown.

targets. In fact, the E772 Drell-Yan data obtained with tungsten and isoscalar targets have been compared⁴⁴ with predictions from various models. More recently, the NA51 experiment reported⁴⁵ $2\sigma_{DY}(p+p)/\sigma_{DY}(p+d) = 0.91 \pm 0.02 \pm 0.02$ measured at 450 GeV near $x_F \simeq 0$ and $x = 0.18$, showing a large asymmetry of $\bar{u}/\bar{d} = 0.51 \pm 0.04 \pm 0.05$ in the proton. The E866 experiment at Fermilab is designed to measure the ratio $2\sigma_{DY}(p+p)/\sigma_{DY}(p+d)$ over a wide x range ($0.05 < x < 0.3$) at 800 GeV. Figure 8 shows the predictions for the ratio $2\sigma_{DY}(p+p)/\sigma_{DY}(p+d)$, using the expression in Eq. (6), for several models. The expected statistical accuracies for E866, together with the NA51 result, are also shown in Figure 8. The E866 experiment should provide a definitive test for the various models.

In addition to the DIS and the Drell-Yan processes, J/ψ and Υ production could also be sensitive to the sea-quark distributions in the nucleon. Using the semi-local duality model⁴⁶ and the lowest-order QCD cross sections for the $q\bar{q}$ annihilation and the gg fusion processes, the sensitivity of the proton-induced J/ψ and Υ production to the possible $\bar{u}/\bar{d}$ asymmetry has been studied⁴⁷. The ratio $R(x_F)$, defined as

$$R(x_F) = 2 \frac{d\sigma/dx_F (p+p \rightarrow J/\psi(\Upsilon))}{d\sigma/dx_F (p+d \rightarrow J/\psi(\Upsilon))} \quad (7)$$

would be equal to 1 for all models which assume $\bar{u}_p = \bar{d}_p$. On the other hand,

Figure 9: Predictions of $R(x_F)$ for J/ψ and Υ production at 800 GeV using various structure function sets.

$R(x_F)$ could deviate significantly from 1 if $\bar{u}_p \neq \bar{d}_p$, especially at large x_F where $q\bar{q}$ annihilation has a dominant contribution.

Figure 9 shows the predictions of $R(x_F)$ for J/ψ and Υ production with 800 GeV proton beam. Five different structure function sets^{11,42} have been used in the calculations. The solid curves correspond to the $\bar{u}/\bar{d}$ symmetric DO1.1 structure functions, and $R(x_F)$ is identically one in this case. Figure 9 shows that the measurement of $R(x_F)$ for Υ production at 800 GeV provides a sensitive test of models which predict different $\bar{u}/\bar{d}$ symmetry in the proton. In comparison, J/ψ production is less sensitive to the sea quark distributions due to the dominance of gg fusion at this energy. However, at lower beam energies, J/ψ production is more sensitive to the sea quark distributions as the $q\bar{q}$ annihilation starts to be important. We conclude that measurements of the Drell-Yan, J/ψ , and Υ cross section ratios on hydrogen and deuterium targets in the forward x_F region would provide a sensitive test of various theoretical models on the sea quark distributions of the proton.

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