# **Large-x PDFs and the Drell-Yan Process**

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**Abstract.** Dimuon production has been studied in a series of fixed-target experiments at Fermilab during the last two decades. Highlights from these experiments, together with recent results from the Fermilab E866 experiment, are presented. Future prospects for studying the parton distributions in the nucleons and nuclei using dimuon production are also discussed.

**Keywords:** Drell-Yan, quarkonium production, parton distributions

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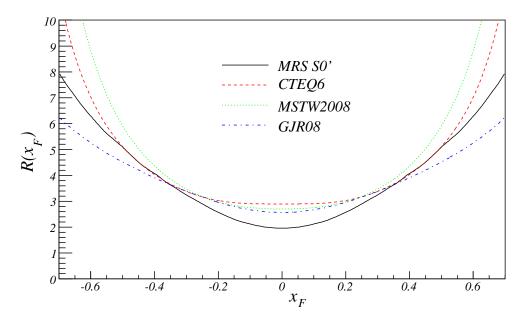
#### INTRODUCTION

The Drell-Yan process [1], in which a charged lepton pair is produced in a hadron-hadron interaction via the electromagnetic  $q\bar{q} \rightarrow l^+l^-$  process, has provided unique information on parton distributions. In particular, the Drell-Yan process has been used to determine the antiquark contents of nucleons and nuclei [2], as well as the quark distributions of pions, kaons, and antiprotons [3]. Such information is difficult, if not impossible, to obtain from DIS experiments. As the Drell-Yan process can be well described by next-to-leading order QCD calculations [4], a firm theoretical framework exists for utilizing the Drell-Yan process to extract the parton distributions.

During the last two decades, a series of fixed-target dimuon production experiments (E772, E789, E866) have been carried out using 800 GeV/c proton beam at Fermilab. At 800 GeV/c, the dimuon data contain Drell-Yan continuum up to dimuon mass of  $\sim$  15 GeV as well as quarkonium productions (J/ $\Psi$ ,  $\Psi'$ , and  $\Upsilon$  resonances). The Drell-Yan process and quarkonium productions often provide complementary information, since Drell-Yan is an electromagnetic process via quark-antiquark annihilation while the quarkonium production is a strong interaction process dominated by gluon-gluon fusion at this beam energy.

The Fermilab dimuon experiments covers a broad range of physics topics. The Drell-Yan data have provided informations on the antiquark distributions in the nucleons [5, 6, 7, 8] and nuclei [9, 10]. These results showed the surprising results that the antiquark distributions in the nuclei are not enhanced [9, 10], contrary to the predictions of models which explain the EMC effect in term of nuclear enhancement of exchanged mesons. Moreover, the Drell-Yan cross section ratios p + d/p + p clearly establish the flavor asymmetry of the  $\bar{d}$  and  $\bar{u}$  distributions in the proton, and they map out the x-dependence of this asymmetry [6, 7, 8]. Pronounced nuclear dependences of quarkonium productions have been observed for  $J/\Psi$ ,  $\Psi'$ , and  $\Upsilon$  resonances [11, 12, 13, 14].

Several review articles covering some of these results are available [2, 15, 16]. In this article, we will focus on the recent results from experiment E866 and future prospect of dimuon experiments at Fermilab and J-PARC.

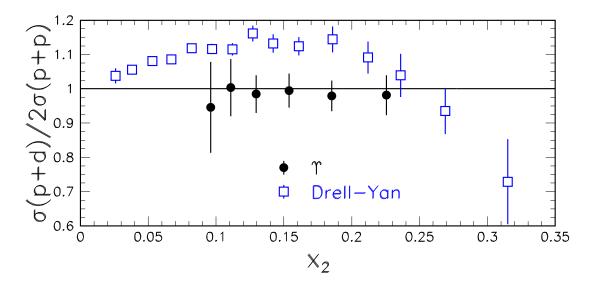


**FIGURE 1.** Prediction of the ratio  $(p+p \to W^+ + x)/(p+p \to W^- + x)$  at  $\sqrt{s}$  of 500 GeV using various PDFs.

## FLAVOR STRUCTURE OF LIGHT-QUARK SEA

In the CERN NA51 [17] and Fermilab E866 [6, 7, 8] experiments on proton-induced dimuon production, a striking difference was observed for the Drell-Yan cross sections between p+p and p+d. As the underlying mechanism for the Drell-Yan process involves quark-antiquark annihilation, this difference has been attributed to the asymmetry between the up and down sea quark distributions in the proton. From the  $\sigma(p+d)_{DY}/2\sigma(p+p)_{DY}$  ratios the Bjorken-x dependence of the sea-quark  $d/\bar{u}$  flavor asymmetry has been extracted [6, 7, 8, 17].

Future fixed-target dimuon experiments have been proposed at the 120 GeV Fermilab Main Injector (FMI) and the 50 GeV J-PARC facilities. The Fermilab proposal [18], E906, has been approved and is expected to start data-taking around 2011. Two dimuon proposals (P04 [19] and P24 [20]) have also been submitted to the J-PARC for approval. The lower beam energies at FMI and J-PARC present opportunities for extending the  $d/\bar{u}$  and the nuclear antiquark distribution measurements to larger x (x > 0.25). For given values of  $x_1$  and  $x_2$ , the Drell-Yan cross section is proportional to 1/s, hence a gain of  $\sim$  16 times in the Drell-Yan cross sections can be obtained at the J-PARC energy of 50 GeV. Since the perturbative process gives a symmetric  $d/\bar{u}$  while non-perturbative processes are necessary to generate an asymmetric  $d/\bar{u}$  sea, it would be very important to extend the Drell-Yan measurements to kinematic regimes beyond the current limits. Another advantage of lower beam energies is that a much more sensitive study of the partonic energy loss in nuclei could be carried out using the Drell-Yan nuclear dependence [21].



**FIGURE 2.** The E866  $\sigma(p+d)/2\sigma(p+p)$  cross section ratios for  $\Upsilon$  resonances as a function of  $x_2$ . The corresponding ratios for Drell-Yan cross sections are also shown. The error bars are statistical only.

To disentangle the  $\bar{d}/\bar{u}$  asymmetry from the possible charge-symmetry violation effect [22, 23], one could consider W boson production in p+p collision at RHIC. An interesting quantity to be measured is the ratio of the  $p+p\to W^++x$  and  $p+p\to W^-+x$  cross sections [24]. It can be shown that this ratio is very sensitive to  $\bar{d}/\bar{u}$ . An important feature of the W production asymmetry in p+p collision is that it is completely free from the assumption of charge symmetry. Another advantage of W production in p+p collision is that no nuclear effects need to be considered. Finally, the W production is sensitive to  $\bar{d}/\bar{u}$  flavor asymmetry at a  $Q^2$  scale of  $\sim 6500~{\rm GeV^2/c^2}$ , significantly larger than all existing measurements. This offers the opportunity to examine the QCD evolution of the sea-quark flavor asymmetry. Figure 1 shows the predictions [25] for p+p collision at  $\sqrt{s}=500~{\rm GeV}$ . The MRS S0' corresponds to the  $\bar{d}/\bar{u}$  symmetric parton distributions, while the other three parton distribution functions are from recent global fits with asymmetric  $\bar{d}/\bar{u}$  sea-quark distributions. Figure 1 clearly shows that W asymmetry measurements at RHIC could provide an independent determination of  $\bar{d}/\bar{u}$ . First results from the LHC are also expected soon, and will provide additional information [25].

Unlike the electromagnetic Drell-Yan process, quarkonium production is a strong interaction dominated by the subprocess of gluon-gluon fusion at 800 GeV beam energy. Therefore, the quarkonium production cross sections are primarily sensitive to the gluon distributions in the colliding hadrons. The  $\Upsilon$  production ratio,  $\sigma(p+d\to\Upsilon)/2\sigma(p+p\to\Upsilon)$ , is expected to probe the gluon content in the neutron relative to that in the proton [26].

The  $\sigma(p+d)/2\sigma(p+p)$  ratios for  $\Upsilon(1S+2S+3S)$  production are shown in Fig. 2 as a function of  $x_2$  [27]. These ratios are consistent with unity, in striking contrast to the corresponding values for the Drell-Yan process, also shown in Fig. 2. The difference between the Drell-Yan and the  $\Upsilon$  cross section ratios clearly reflect the different underlying mechanisms in these two processes. For  $\Upsilon$  production, the dominance of the gluon-

gluon fusion subprocess at this beam energy implies that  $\sigma(p+d\to\Upsilon)/2\sigma(p+p\to\Upsilon)\approx \frac{1}{2}(1+g_n(x_2)/g_p(x_2))$ . Figure 2 shows that the gluon distributions in the proton  $(g_p)$  and neutron  $(g_n)$  are very similar over the  $x_2$  range  $0.09 < x_2 < 0.25$ . The overall  $\sigma(p+d\to\Upsilon)/2\sigma(p+p\to\Upsilon)$  ratio, integrated over the measured kinematic range, is  $0.984\pm0.026({\rm stat.})\pm0.01({\rm syst.})$ . The  $\Upsilon$  data indicate that the gluon distributions in the proton and neutron are very similar.

The upcoming Fermilab E906 experiment is expected to provide a precise measurement of the  $\sigma(p+d\to J/\Psi)/2\sigma(p+p\to J/\Psi)$  ratio. These data should further test the equality of the gluon distributions in the proton and neutron. Moreover, these data could identify EMC effects for deuteron. It is interesting to note that analogous ratios measured in DIS and the Drell-Yan can not be used to determine the EMC effects for deuteron, since different parton distributions are being probed for the hydrogen and the deuterium targets. If one assumes that the gluon distributions are identical in proton and neutron, then any deviation of the  $\sigma(p+d\to J/\Psi)/2\sigma(p+p\to J/\Psi)$  ratio from unity would be attributed to the EMC effects of gluon distributions in deuteron.

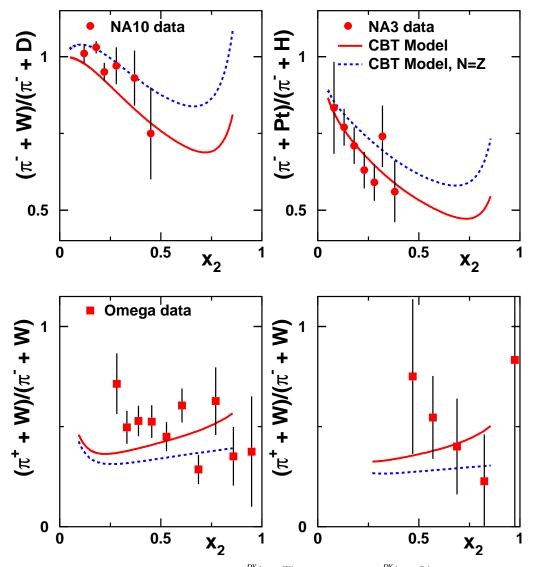
#### FLAVOR DEPENDENCE OF THE EMC EFFECT

Despite a quarter century of significant experimental and theoretical effort, the specific origins of the observed A dependence of the nuclear quark distributions have yet to be unambiguously identified. Attempts to explain the EMC effect have led to a large collection of theoretical models [28, 29], many of which are capable of describing the essential features of the data, however the underlying physics mechanisms in each model are often very different.

A new calculation of the modifications of nucleon quark distributions in the nuclear medium has recently been reported [30, 31]. In this approach by Cloët, Bentz and Thomas (CBT), the Nambu–Jona-Lasinio model is used to describe the coupling of the quarks in the bound nucleons to the scalar and vector mean fields inside a nucleus. These nucleon quark distributions are then convoluted with a nucleon momentum distribution in the nucleus to generate the nuclear quark distributions [30]. An important feature of this model is that for  $N \neq Z$  nuclei (where N and Z refer to the number of neutrons and protons) the isovector–vector mean field (usually denoted by  $\rho^0$ ) will affect the up quarks differently from the down quarks in the bound nucleons. Therefore, this model has a novel prediction that the u and d quarks have distinct nuclear modifications for  $N \neq Z$  nuclei.

Semi-inclusive DIS (SIDIS) on heavy nuclear targets, in which the flavor of the struck quark is tagged by the detected hadron, is a promising experimental tool to search for the flavor-dependent EMC effect. Recently, Lu and Ma [32] pointed out that charged lepton SIDIS off nuclear targets and the deuteron can be used to probe the flavor content of the nuclear quark sea, which can help distinguish between the various models of the EMC effect. Indeed, a SIDIS experiment [33] aiming at a precise determination of flavor dependence of the EMC effect has also been proposed at the upgraded 12 GeV JLab facility.

The flavor dependence of the EMC effect is a promising experimental observable to distinguish among the plethora of models that can describe the EMC effect. As



**FIGURE 3.** The existing data for the ratios  $\frac{\sigma^{DY}(\pi^-+W)}{\sigma^{DY}(\pi^-+D)}$  (upper left),  $\frac{\sigma^{DY}(\pi^-+Pt)}{\sigma^{DY}(\pi^-+H)}$  (upper right) and  $\frac{\sigma^{DY}(\pi^++W)}{\sigma^{DY}(\pi^-+W)}$  (lower) versus the predictions using nuclear PDFs of the CBT model for tungsten (red solid) and N=Z nuclear matter (blue dashed).

discussed earlier, the nuclear dependence of proton-induced Drell-Yan process measured at Fermilab has shown the surprising results that the antiquark distributions in the nuclei are not enhanced [9, 10], contrary to the predictions of many EMC models. Pion-induced Drell-Yan process provides another experimental tool with which search for flavor-dependent effects in the nuclear modification of the nucleon structure functions [34].

To explore the sensitivity of pion-induced Drell-Yan processes to a flavor-dependent EMC effect, we consider the three ratios  $\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)}$ ,  $\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)}$  and  $\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + H)}$ , where A represents a nuclear, D a deuteron and H a hydrogen target. Assuming isospin symmetry,

which implies  $u_{\pi^+}=d_{\pi^-}$ ,  $\bar{u}_{\pi^-}=\bar{d}_{\pi^+}$ ,  $\bar{u}_{\pi^+}=\bar{d}_{\pi^-}$ ,  $u_{\pi^-}=d_{\pi^+}$  and keeping only the dominant terms in each cross-section, one readily obtains

$$R_{\pm} = \frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)} \tag{1}$$

$$R_{A/D}^{-} = \frac{\sigma^{DY}(\pi^{-} + A)}{\sigma^{DY}(\pi^{-} + D)} \approx \frac{u_{A}(x)}{u_{D}(x)}$$
 (2)

$$R_{A/H}^{-} = \frac{\sigma^{DY}(\pi^{-} + A)}{\sigma^{DY}(\pi^{-} + H)} \approx \frac{u_{A}(x)}{u_{p}(x)},$$
 (3)

The up and down nuclear quark distributions are labeled by  $u_A$  and  $d_A$  respectively,  $u_D$  is the up quark distribution in the deuteron and  $u_p$  the up quark distribution in the proton. Eqs. 1-3 demonstrate that these Drell-Yan cross-section ratios are very sensitive to the flavor dependence of the EMC effect.

Fig. 3 shows the comparison [34] of the calculations of the pion-induced Drell-Yan cross-section ratios with the existing data. The top left panel shows the ratio of  $\frac{\sigma^{DY}(\pi^-+W)}{\sigma^{DY}(\pi^-+D)}$  from the NA10 experiment [35]. These plots contain both the  $P_{beam}=286$  and 140 GeV data sets, which are very similar. The calculations are performed at  $P_{beam}=286$  GeV, since most of the data was obtained at this energy. The PDFs of the CBT model [30, 31] at a fixed  $Q^2$  of 25 GeV  $^2$ , which is approximately the mean  $Q^2$  of the NA10 experiment, were used. The top right panel shows the ratio  $\frac{\sigma^{DY}(\pi^-+Pt)}{\sigma^{DY}(\pi^-+H)}$  from the NA3 experiment [36]. The data were collected using a 150 GeV  $\pi^-$  beam and the  $Q^2$  range covered was  $16.8 \le Q^2 \le 70.6$  GeV $^2$ . The calculations are performed for  $P_{beam}=150$  GeV and  $Q^2=25$  GeV $^2$ .

The solid curves in Fig. 3 are calculations using the flavor-dependent  $u_A(x)$  and  $d_A(x)$  from the CBT model with N/Z=1.5, corresponding approximately to the N/Z values for the Au, W and Pt nuclei. The dashed curves correspond to the calculated ratios using the nuclear PDFs from the CBT model for N=Z. Since  $u_A/u_D=d_A/d_D$  in this case, the dashed curves are representative of the predictions for flavor-independent EMC models. Figure 3 shows that the NA10 data do not exhibit a clear preference for the flavor-dependent versus flavor-independent nuclear PDFs. In contrast, the NA3 data strongly favor the calculations using flavor-dependent nuclear PDFs. The existing Drell-Yan data are not sufficiently accurate yet, although the NA3 data clearly favor the flavor-dependent over the flavor-independent nuclear PDFs. Precise future pion-induced Drell-Yan experiments can provide unique constraints that will help distinguish the various theoretical models and most importantly shed new light on the origins of the EMC effect.

#### TRANSVERSE SPIN AND DRELL-YAN PROCESS

The study of the transverse momentum dependent (TMD) parton distributions of the nucleon has received much attention in recent years as it provides new perspectives on the hadron structure and QCD [37]. These novel TMDs can be extracted from semi-inclusive deep-inelastic scattering (SIDIS) experiments. Recent measurements of the

SIDIS by the HERMES [38] and COMPASS [39] collaborations have shown clear evidence for the existence of the T-odd Sivers functions. These data also allow the first determination [40] of the magnitude and flavor structure of the Sivers functions and the nucleon transversity distributions.

The TMD and transversity parton distributions can also be probed in Drell-Yan experiments. As pointed out [41] long time ago, the double transverse spin asymmetry in polarized Drell-Yan,  $A_{TT}$ , is proportional to the product of transversity distributions,  $h_1(x_q)h_1(x_{\bar{q}})$ . The single transverse spin asymmetry,  $A_N$ , is sensitive to the Sivers function [42],  $f_{1T}^{\perp}(x)$  of the polarized proton (beam or target). Even unpolarized Drell-Yan experiments can be used to probe the TMD distribution function, since the  $\cos 2\phi$  azimuthal angular dependence is proportional to the product of two Boer-Mulders functions [43],  $h_1^{\perp}(x_1)\bar{h}_1^{\perp}(x_2)$ . A unique feature of the Drell-Yan process is that, unlike the SIDIS, no fragmentation functions are involved. Therefore, the Drell-Yan process provides an entirely independent technique for measuring the TMD functions. Furthermore, the proton-induced Drell-Yan process is sensitive to the sea-quark TMDs and can lead to flavor separation of TMDs when combined with the SIDIS data. Finally, the intriguing prediction [44] that the T-odd TMDs extracted from DIS will have a sign-change for the Drell-Yan process remains to be tested experimentally.

No polarized Drell-Yan experiments have yet been performed. However, some information on the Boer-Mulders functions have been extracted recently from the azimuthal angular distributions in the unpolarized Drell-Yan process. The general expression for the Drell-Yan angular distribution is [45]

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{v}{2} \sin^2 \theta \cos 2\phi, \tag{4}$$

where  $\theta$  and  $\phi$  are the polar and azimuthal decay angle of the  $l^+$  in the dilepton rest frame. Boer showed that the  $\cos 2\phi$  term is proportional to the convolution of the quark and antiquark Boer-Mulders functions in the projectile and target [46]. This can be understood by noting that the Drell-Yan cross section depends on the transverse spins of the annihilating quark and antiquark. Therefore, a correlation between the transverse spin and the transverse momentum of the quark, as represented by the Boer-Mulders function, would lead to a preferred transverse momentum direction.

Pronounced  $\cos 2\phi$  dependences were indeed observed in the NA10 [47] and E615 [48] pion-induced Drell-Yan experiments, and attributed to the Boer-Mulders function. The first measurement of the  $\cos 2\phi$  dependence of the proton-induced Drell-Yan process was recently reported for p+p and p+d interactions at 800 GeV/c [49]. In contrast to pion-induced Drell-Yan, significantly smaller (but non-zero)  $\cos 2\phi$  azimuthal angular dependence was observed in the p+p and p+d reactions. While the pion-induced Drell-Yan process is dominated by annihilation between a valence antiquark in the pion and a valence quark in the nucleon, the proton-induced Drell-Yan process involves a valence quark in the proton annihilating with a sea antiquark in the nucleon. Therefore, the p+p and p+d results suggest [49, 50] that the Boer-Mulders functions for sea antiquarks are significantly smaller than those for valence quarks.

### **FUTURE PROSPECTS**

Future fixed-target dimuon experiments have been proposed at the 120 GeV Fermilab Main Injector and the 50 GeV J-PARC facilities. As discussed earlier, the Fermilab E906 experiment will extend the  $\bar{d}/\bar{u}$  asymmetry measurement to larger x region. Another goal of this experiment is to determine the antiquark distributions in nuclei at large x using nuclear targets. New information on the quark energy loss in nuclei is also expected. As discussed earlier, an advantage of lower beam energies is that a much more sensitive study of the partonic energy loss in nuclei could be carried out [21].

With the possibility to accelerate polarized proton beams at J-PARC [20], the spin structure of the proton can also be investigated with the proposed dimuon experiments. In particular, polarized Drell-Yan process with polarized beam and/or polarized target at J-PARC would allow a unique program on spin physics complementary to polarized DIS experiments and the RHIC-Spin programs. Specific physics topics include the measurements of T-odd Boer-Mulders distribution function in unpolarized Drell-Yan, the extraction of T-odd Sivers distribution functions in singly transversely polarized Drell-Yan, the helicity distribution of antiquarks in doubly longitudinally polarized Drell-Yan, and the transversity distribution in doubly transversely polarized Drell-Yan. It is worth noting that polarized Drell-Yan is one of the major physics program at the GSI Polarized Antiproton Experiment (PAX). The COMPASS experiment at CERN will also measure  $\pi^-$ -induced Drell-Yan on transversely polarized targets to extract Sivers functions from the Single-Spin-Asymmetry. Two recent Letter-of-Intent have also been submitted to RHIC for measuring polarized Drell-Yan at RHIC-Spin, one in collider mode and the other utilizing internal targets. It is clear that the Drell-Yan process will continue to provide unique information on parton distributions in the forseeable future.

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