Hadron Structure with Dimuon Production

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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 at Fermilab and J-PARC are also discussed.

Keywords: Drell-Yan, quarkonium production, parton distributions

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INTRODUCTION

While our current knowledge on the partonic substructures of nucleons and nuclei is obtained mostly from deep-inelastic scattering experiments, the dimuon production experiments also play an important and unique role in providing complementary information. 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 [1, 2, 3, 4] and nuclei [5, 6]. These results showed the surprising results that the antiquark distributions in the nuclei are not enhanced [5, 6], 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 \( d \) and \( \bar{u} \) distributions in the proton, and they map out the \( x \)-dependence of this asymmetry [2, 3, 4]. Pronounced nuclear dependences of quarkonium productions have been observed for \( J/\Psi \), \( \Psi' \), and \( \Upsilon \) resonances [7, 8, 9, 10]. It was found that these nuclear effects scale with the kinematic variable \( x_F \) rather than \( x_2 \) (the Bjorken-x of the parton in the nucleus), suggesting the importance of initial- and final-state interactions. A striking behavior of the nuclear dependence as a function of \( p_T \), reminiscent of the Cronin effect, was also observed. The nuclear Drell-Yan cross sections also exhibit \( x_F \) as well as \( p_T \) dependences [6, 11, 12, 13], which are weaker than the quarkonium nuclear dependences but can provide information on the energy loss of quarks traversing the nucleus [14]. The differential cross sections for Drell-Yan [15], charmonium [16], and bottomonium [17] productions have also been reported. In addition, the decay


Angular distributions for Drell-Yan [11, 18], J/Ψ [19], and Ψ resonances [20] have been measured. Information on D and B meson productions and decays has also been extracted through either the dimuon measurement [21, 22, 23] or the open-aperture dihadron measurement [24]. Several review articles covering some of these results are available [11, 25, 26]. In this article, we will focus on the recent results from experiment E866 and future prospect of dimuon experiments at Fermilab and J-PARC.

**RECENT RESULTS FROM E866**

**Angular distributions of proton-induced Drell-Yan**

Despite the success of perturbative QCD in describing the Drell-Yan cross sections, it remains a challenge to understand the angular distributions of the Drell-Yan process. Assuming dominance of the single-photon process, a general expression for the Drell-Yan angular distribution is [27]

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

(1)

where $\theta$ and $\phi$ denote the polar and azimuthal angle, respectively, of the $l^+$ in the dilepton rest frame. In the “naive” Drell-Yan model, where the transverse momentum of the quark is ignored and no gluon emission is considered, $\lambda = 1$ and $\mu = \nu = 0$ are obtained. QCD effects [28] and non-zero intrinsic transverse momentum of the quarks [29] can both lead to $\lambda \neq 1$ and $\mu, \nu \neq 0$. However, $\lambda$ and $\nu$ should still satisfy the relation $1 - \lambda = 2\nu$ [27]. This so-called Lam-Tung relation, obtained as a consequence of the spin-1/2 nature of the quarks, is analogous to the Callan-Gross relation [30] in deep-inelastic scattering.

The first measurement of the Drell-Yan angular distribution was performed by the NA10 Collaboration for $\pi^- + W$ with the highest statistics at 194 GeV/c [31, 32]. The $\cos^2 \phi$ angular dependences showed a sizable $\nu$, increasing with dimuon transverse momentum ($p_T$) and reaching a value of $\approx 0.3$ at $p_T = 2.5$ GeV/c. The Fermilab E615 Collaboration subsequently performed a measurement of $\pi^- + W$ Drell-Yan production at 252 GeV/c with broad coverage in the decay angle $\theta$ [33]. The E615 data showed that the Lam-Tung relation, $2\nu = 1 - \lambda$, is clearly violated.

The NA10 and E615 results on the Drell-Yan angular distributions strongly suggest that new effects beyond conventional perturbative QCD are present. Brandenburg, Nachtmann and Mirke suggested that a factorization-breaking QCD vacuum may lead to a correlation between the transverse spin of the antiquark in the pion and that of the quark in the nucleon [34]. This would result in a non-zero $\cos^2 \phi$ angular dependence consistent with the data. Several authors have also considered higher-twist effects from quark-antiquark binding in pions [35, 36]. However, the model is strictly applicable only in the $x_\pi \rightarrow 1$ region, while the NA10 and E615 data exhibit nonperturbative effects over a much broader kinematic region.

More recently, Boer pointed out [37] that the $\cos^2 \phi$ angular dependences observed in NA10 and E615 could be due to the $k_T$-dependent parton distribution function $h_1^\perp$. This so-called Boer-Mulders function [38] is an example of a novel type of $k_T$-dependent...
parton distribution function, and it characterizes the correlation of a quark’s transverse spin and its transverse momentum, $k_T$, in an unpolarized nucleon.

To shed additional light on the origins of the NA10 and E615 Drell-Yan angular distributions, we have analyzed $p+p$ and $p+d$ Drell-Yan angular distribution data at 800 GeV/c from Fermilab E866. There has been no report on the azimuthal angular distributions for proton-induced Drell-Yan – all measurements so far have been for polar angular distributions [11, 19, 20]. Moreover, proton-induced Drell-Yan data provide a test of theoretical models. For example, the $\cos 2\phi$ dependence is expected to be much reduced in proton-induced Drell-Yan if the underlying mechanism involves the Boer-Mulders functions. This is due to the expectation that the Boer-Mulders functions are small for the sea-quarks. However, if the QCD vacuum effect [34] is the origin of the $\cos 2\phi$ angular dependence, then the azimuthal behavior of proton-induced Drell-Yan should be similar to that of pion-induced Drell-Yan. Finally, the validity of the Lam-Tung relation has never been tested for proton-induced Drell-Yan, and the present study provides a first test.

**FIGURE 1.** Parameters $\lambda, \mu, \nu$ and $2\nu - (1 - \lambda)$ vs. $p_T$ in the Collins-Soper frame. Solid circles are for E866 $p+d$ at 800 GeV/c, crosses are for NA10 $\pi^- + W$ at 194 GeV/c, and diamonds are E615 $\pi^- + W$ at 252 GeV/c. The error bars include the statistical uncertainties only.
The Fermilab E866 experiment was performed using the upgraded Meson-East magnetic pair spectrometer. Details of the experimental setup have been described elsewhere [2, 3, 4]. An 800 GeV/c primary proton beam with up to $2 \times 10^{12}$ protons per 20-second beam spill was incident upon 50.8 cm long cylindrical stainless steel target flask containing liquid deuterium. The detector system consisted of four tracking stations and a momentum analyzing magnet. From the momenta of the $\mu^+$ and $\mu^-$, kinematic variables of the dimuons ($x_F, m_{\mu\mu}, p_T$) were readily reconstructed. The muon angles $\theta$ and $\phi$ in the Collins-Soper frame [39] were also calculated. To remove the quarkonium background, only events with $4.5 < m_{\mu\mu} < 9$ GeV/c$^2$ or $m_{\mu\mu} > 10.7$ GeV/c$^2$ were analyzed. A total of $\sim 54,000$ $p + p$ and $\sim 118,000$ $p + d$ Drell-Yan events covering the decay angular range $-0.5 < \cos \theta < 0.5$ and $-\pi < \phi < \pi$ remain.

Figure 1 shows the results [18] on the angular distribution parameters $\lambda, \mu$, and $\nu$ vs. $p_T$. To extract these parameters, the Drell-Yan data were grouped into 5 bins in $\cos \theta$ and 8 bins in $\phi$ for each $p_T$ bin. A least-squares fit to the data using Eq. 1 to describe the angular distribution was performed. Only statistical errors are shown in Fig. 1. For comparison with the $p + d$ Drell-Yan data, the NA10 $\pi^- + W$ data at 194 GeV/c and the E615 $\pi^- + W$ data at 252 GeV/c are also shown in Fig. 1. To test the validity of the Lam-Tung relation, also shown in Fig. 1 is the quantity $2\nu - (1 - \lambda)$, for
all three experiments. For \( p + d \) at 800 GeV/c, Fig. 1 shows that \( \lambda \) is consistent with 1, in agreement with previous studies \([11, 19, 20]\), while \( \mu \) and \( \nu \) deviate only slightly from zero. This is in contrast to the pion-induced Drell-Yan results, in which much larger values of \( \nu \) are found. It is also interesting to note that while E615 clearly establishes the violation of the Lam-Tung relation, the NA10 and the \( p + d \) data are largely consistent with the Lam-Tung relation.

The \( p + d \) results put constraints on theoretical models that predict large \( \cos 2\phi \) dependence originating from QCD vacuum effects. They also suggest that the Boer-Mulders function \( h_1^+ \) for sea quarks is significantly smaller than for valence quarks. A recent analysis \([40]\) of the \( p + d \) \( \cos 2\phi \) data showed that the sea-quark Boer-Mulders functions are indeed smaller by a factor \( \sim 5 \) than the valence-quark Boer-Mulders functions. This analysis also indicated that the E866 \( p + d \) data are consistent with the \( u \) and \( d \) Boer-Mulders functions having the same signs. However, the \( p + d \) data alone can not provide an unambiguous determination of the flavor dependence of the Boer-Mulders functions. A comparison of the \( p + p \) and \( p + d \) data would further constrain the flavor dependence of the Boer-Mulders functions.

Figure 2 shows the preliminary result of \( \nu \) for \( p + p \) reaction at 800 GeV/c. Also shown in Fig. 2 are the E866 \( p + d \) and the NA10 \( \pi^- + W \) data at 194 GeV/c. The data are fitted with the expression suggested by Boer \([37]\):

\[
\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2},
\]

where \( \kappa_1 \) is proportional to the product of the \( h_1^+ \) functions for the projectile and the target, and \( M_C \) is a constant fitting parameter. Boer obtained \( \kappa_1 = 0.47 \pm 0.14 \) and \( M_C = 2.4 \pm 0.5 \) GeV/c\(^2\) for fitting the NA10 data, as shown in Fig. 2. A fit to the E866 \( p + p \) and \( p + d \) data for \( M_C = 2.4 \) GeV/c\(^2\) yields \( \kappa_1 = 0.21 \pm 0.055 \) and \( \kappa_1 = 0.11 \pm 0.04 \), respectively. These data should provide additional information on the origins of the azimuthal angular dependence of Drell-Yan, as well as the flavor dependence of the Boer-Mulders functions.

**\( \Upsilon \) production for \( p + p \) and \( p + d \) interactions**

In the CERN NA51 \([41]\) and Fermilab E866 \([2, 3, 4]\) 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 \([2, 3, 4, 41]\).

The Fermilab E866 dimuon experiment also recorded a large number of \( \Upsilon \rightarrow \mu^+\mu^- \) events. Unlike the electromagnetic Drell-Yan process, quarkonium production is a strong interaction dominated by the subprocess of gluon-gluon fusion at this beam energy \([42, 43]\). Therefore, the quarkonium production cross sections are primarily sensitive to the gluon distributions in the colliding hadrons. The \( \Upsilon \) production ratio, \( \sigma(p + d \rightarrow \)
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.

$\Upsilon(1S+2S+3S)$ production is expected to probe the gluon content in the neutron relative to that in the proton [44]. While it is generally assumed that the gluon distributions in the proton and neutron are identical, this assumption is not based on any fundamental symmetry and has not been tested experimentally. A possible mechanism for generating different gluon distributions in the proton and neutron, as pointed out by Piller and Thomas [44], is the violation of charge symmetry in the quark and antiquark distributions in the nucleons. A precise measurement of the $\sigma(p+d \rightarrow \Upsilon)/2\sigma(p+p \rightarrow \Upsilon)$ ratios would provide a constraint on the asymmetry of gluon distribution in the proton versus that in the neutron.

The $\sigma(p+d)/2\sigma(p+p)$ ratios for $\Upsilon(1S+2S+3S)$ production are shown in Fig. 3 as a function of $x_2$. Most of the systematic errors cancel for these ratios, with a remaining $\approx 1\%$ error from the rate dependence and target compositions [4]. Figure 3 shows that these ratios are consistent with unity, in striking contrast to the corresponding values [4] for the Drell-Yan process, also shown in Fig. 3. The difference between the Drell-Yan and the $\Upsilon$ cross section ratios clearly reflect the different underlying mechanisms in these two processes. The Drell-Yan process, dominated by the $u-\bar{u}$ annihilation subprocess, leads to the relation $\sigma(p+d)_{DY}/2\sigma(p+p)_{DY} \approx \frac{1}{2}(1 + \bar{u}_n(x_2)/\bar{u}_p(x_2)) = \frac{1}{2}(1 + \bar{d}_p(x_2)/\bar{u}_p(x_2))$, where $\bar{q}_{p,n}$ refers to the $\bar{q}$ distribution in the proton and neutron, respectively. For $\Upsilon$ production, the dominance of the gluon-gluon fusion subprocess at this beam energy implies that $\sigma(p+d \rightarrow \Upsilon)/2\sigma(p+p \rightarrow \Upsilon) \approx \frac{1}{2}(1 + g_n(x_2)/g_p(x_2))$. Figure 3 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 $\sigma(p+d \rightarrow \Upsilon)/2\sigma(p+p \rightarrow \Upsilon)$ ratio, integrated over the measured kinematic range, is $0.984 \pm 0.026$(stat.)$ \pm 0.01$(syst.). The $\Upsilon$ data indicate that the gluon distributions in the proton and neutron are very similar. These results are consistent with no charge symmetry breaking effect in the gluon distributions.
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 [45], E906, has been approved and is expected to start data-taking around 2011. Two dimuon proposals (P04 [46] and P24 [47]) have also been submitted to the J-PARC for approval. The lower beam energies at FMI and J-PARC present opportunities for extending the \( \bar{d}/\bar{u} \) 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 \( \bar{d}/\bar{u} \) while non-perturbative processes are necessary to generate an asymmetric \( \bar{d}/\bar{u} \) 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 [14].

The dimuon physics program at J-PARC is proposed to be carried out in several stages. Since 30 GeV proton beam will be available at the initial phase of J-PARC, the first measurements will focus on \( J/\Psi \) production at 30 GeV. This will be followed by measurements of Drell-Yan and quarkonium production at 50 GeV after the beam energy is upgraded to 50 GeV. Experiments using polarized target could already be performed with unpolarized beams. When polarized proton beam becomes available at J-PARC, a rich and unique program on spin physics could also be pursued at J-PARC using the dimuon spectrometer.

An important feature of \( J/\Psi \) production using 30 or 50 GeV proton beam is the dominance of the quark-antiquark annihilation subprocess. This is in striking contrast to \( J/\Psi \) production at 800 GeV (Fermilab E866) or at 120 GeV (Fermilab E906), where the gluon-gluon fusion is the dominant process. This suggests an exciting opportunity to use \( J/\Psi \) production at J-PARC as an alternative method to probe antiquark distribution.

With the possibility to accelerate polarized proton beams at J-PARC, 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 program. 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 RHIC-Spin program will likely provide the first results on polarized Drell-Yan. However, the high luminosity and the broad kinematic coverage for the large-\( x \) region at J-PARC would allow some unique measurements to be performed in the J-PARC dimuon experiments.

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