

**Measurement of Angular Distributions of Drell-Yan Dimuons in  $p + d$  Interactions at 800 GeV/c**

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We report a measurement of the angular distributions of Drell-Yan dimuons produced using an 800 GeV/c proton beam on a deuterium target. The muon angular distributions in the dilepton rest frame have been measured over the kinematic range  $4.5 < m_{\mu\mu} < 15$  GeV/c<sup>2</sup>,  $0 < p_T < 4$  GeV/c, and  $0 < x_F < 0.8$ . No significant  $\cos 2\phi$  dependence is found in these proton-induced Drell-Yan data, in contrast with the situation for pion-induced Drell-Yan data. The data are compared with expectations from models which attribute the  $\cos 2\phi$  distribution to a QCD vacuum effect or to the presence of the transverse-momentum-dependent Boer-Mulders structure function  $h_1^\perp$ . Constraints on the magnitude of the sea-quark  $h_1^\perp$  structure functions are obtained.

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The Drell-Yan process [1], in which a charged lepton pair is produced in a high-energy hadron-hadron interaction via the  $q\bar{q} \rightarrow l^+l^-$  process, has been a testing ground for perturbative QCD and a unique tool for probing parton distributions of hadrons. The Drell-Yan production cross sections can be well described by next-to-leading order QCD calculations [2]. This provides a firm theoretical framework for using the Drell-Yan process to determine the antiquark content of nucleons and nuclei [3], as well as the quark distributions of pions, kaons, and antiprotons [4].

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 [5]

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

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 [6] and nonzero intrinsic transverse momentum of the quarks [7] can both lead to  $\lambda \neq 1$  and  $\mu, \nu \neq 0$ . However,  $\lambda$  and  $\nu$  should still satisfy the relation  $1 - \lambda = 2\nu$  [5]. 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 [8] in deep-inelastic scattering. While QCD effects can significantly modify the Callan-Gross relation, the Lam-Tung relation is predicted to be largely unaffected by QCD corrections [9].

The first measurement of the Drell-Yan angular distribution was performed by the NA10 Collaboration for  $\pi^- + W$  at 140, 194, and 286 GeV/c, with the highest statistics at 194 GeV/c [10]. 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/ $c$  (see Fig. 1). The observed behavior of  $\nu$  could not be described by perturbative QCD calculations which predict much smaller values of  $\nu$  [6]. 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  $\theta$  [11]. The E615 results showed that  $\lambda$  deviates from 1 at large values of  $x_\pi$  (the Bjorken  $x$  of the incident pions), and both  $\mu$  and  $\nu$  have large nonzero values. Furthermore, the E615 data showed that the Lam-Tung relation,  $2\nu = 1 - \lambda$ , is clearly violated (see Fig. 1).

The NA10 and E615 results on the Drell-Yan angular distributions strongly suggest that new effects beyond conventional perturbative QCD are present. Several attempts have been made to interpret these data. Brandenburg, Nachtmann, and Mirkes 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 [12]. This would result in a nonzero  $\cos 2\phi$  angular dependence consistent with the data. As pointed out by Boer *et al.*, a possible source for a factorization-breaking QCD vacuum is helicity flip in the instanton model [13]. Several authors have also considered higher-twist effects from quark-antiquark binding in pions

[14,15], motivated by earlier work of Berger and Brodsky [16]. This model predicts behavior of  $\mu$  and  $\nu$  in qualitative agreement with the data. 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 [17] 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 [18] 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. If such correlations are present for both quark and antiquark, they may combine with the transverse spin correlation characteristic of quark-antiquark annihilation in QED to establish a preferred transverse momentum direction producing the  $\cos 2\phi$  dependence. The Boer-Mulders function has an interesting property of being a naive time-reversal odd object and owes its existence to the presence of initial or final state interactions [19]. The Boer-Mulders function is the analog of the Collins fragmentation function [20], which describes the correlation between the transverse spin of a quark and the transverse momentum of the particle into which it hadronizes. Model calculations for the nucleon (pion) Boer-Mulders functions have been carried out [21–24] in the framework of quark-diquark (quark-spectator-antiquark) model, and can successfully describe the  $\nu$  behavior observed in NA10 [24].

To shed additional light on the origins of the NA10 and E615 Drell-Yan angular distributions, we have analyzed  $p + d$  Drell-Yan angular distribution data at 800 GeV/ $c$  from Fermilab E866. There are several physics motivations for this study. First, there has been no report on the azimuthal angular distributions for proton-induced Drell-Yan data—all measurements so far have been for polar angular distributions [3,25]. Second, proton-induced Drell-Yan data provide a stringent test of theoretical models. For example, the  $\cos 2\phi$  dependence is expected to be much reduced in proton-induced Drell-Yan data 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 [17]. However, if the QCD vacuum effect [12] is the origin of the  $\cos 2\phi$  angular dependence, then the azimuthal behavior of proton-induced Drell-Yan data should be similar to that of pion-induced Drell-Yan data. Third, the validity of the Lam-Tung relation has never been tested for proton-induced Drell-Yan data, and the present study provides a first test.

The Fermilab E866 experiment was performed using the upgraded Meson-East magnetic pair spectrometer. Details of the experimental setup have been described elsewhere [26]. An 800 GeV/ $c$  primary proton beam with up to  $2 \times 10^{12}$  protons per beam spill was incident upon one of three identical 50.8 cm long cylindrical stainless steel target

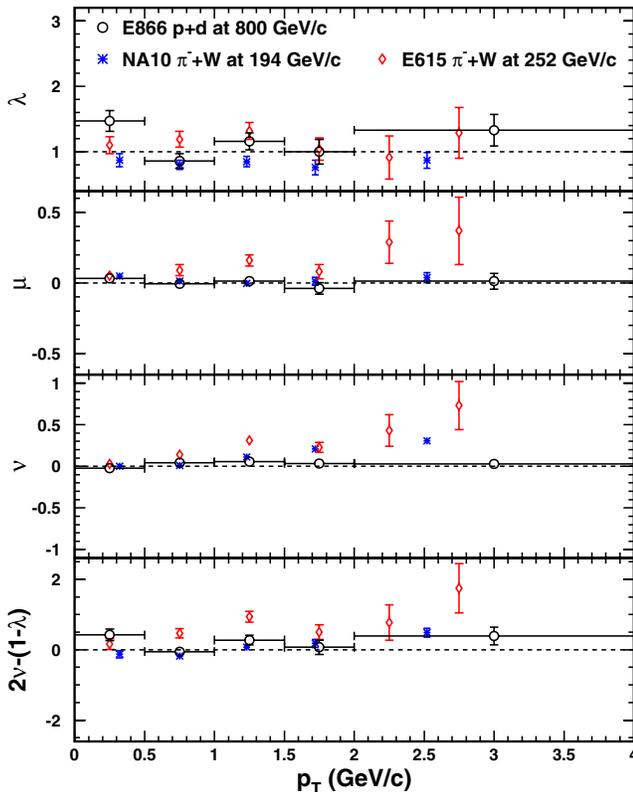


FIG. 1 (color online). Parameters  $\lambda$ ,  $\mu$ ,  $\nu$ , and  $2\nu - (1 - \lambda)$  vs  $p_T$  in the Collins-Soper frame. Open circles are for E866  $p + d$  at 800 GeV/ $c$ , crosses are for NA10  $\pi^- + W$  at 194 GeV/ $c$ , and diamonds are E615  $\pi^- + W$  at 252 GeV/ $c$ . The error bars include the statistical uncertainties only.

flasks containing either liquid hydrogen, liquid deuterium, or vacuum. A copper beam dump located inside the second dipole magnet (SM12) absorbed protons that passed through the target. Downstream of the beam dump was an absorber wall that completely filled the aperture of the magnet. This absorber wall removed hadrons produced in the target and the beam dump.

Several settings of the currents in the three dipole magnets (SM0, SM12, SM3) were used in order to optimize acceptance for different dimuon mass regions. Data collected with the “low mass” and “high mass” settings [26] on liquid deuterium and empty targets were used in this analysis. The detector system consisted of four tracking stations and a momentum analyzing magnet (SM3). Tracks reconstructed by the drift chambers were extrapolated to the target using the momentum determined from the bend angle in SM3. The target position was used to refine the parameters of each muon track.

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 [27] were also calculated. To eliminate the  $J/\psi$  and  $\Upsilon$  resonances background, dimuon events with  $m_{\mu\mu} < 4.5$  GeV/ $c^2$  and  $9.0 < m_{\mu\mu} < 10.7$  GeV/ $c^2$  were rejected in the analysis. The minimal  $Q^2$  ( $m_{\mu\mu}^2$ ) of 20 GeV $^2$  ensures the applicability of perturbative QCD. A total of 118 000  $p + d$  Drell-Yan events covering the decay angular range  $-0.5 < \cos\theta < 0.5$  and  $-\pi < \phi < \pi$  remain. Detailed Monte Carlo simulations for the experiment using the MRST98 parton distribution functions [28] for next-to-leading-order Drell-Yan cross sections have shown good agreements with the data for a variety of measured quantities.

Figure 1 shows the angular distribution parameters  $\lambda$ ,  $\mu$ , and  $\nu$  versus  $p_T$ . 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. The primary contributions to the systematic errors are the uncertainties of the incident beam angles on target. The analysis has been performed allowing the beam angles to vary within their ranges of uncertainty. From this study, we found that the systematic errors are comparable to the statistical errors for each individual  $p_T$  bin. However, for the  $p_T$  averaged values  $\langle\lambda\rangle$ ,  $\langle\mu\rangle$ , and  $\langle\nu\rangle$ , the systematic errors are smaller than the statistical errors since they are not sensitive to the migration of events between adjacent  $p_T$  bins.

For comparison with the  $p + d$  Drell-Yan data, the NA10  $\pi^- + W$  Drell-Yan data at 194 GeV/ $c$  and the E615  $\pi^- + W$  Drell-Yan 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 [3,25], 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. Table I lists the mean values of  $\lambda$ ,  $\mu$ ,  $\nu$ , and  $2\nu - (1 - \lambda)$  for these three experiments. Again, the qualitatively different behavior of the azimuthal angular distributions for  $p + d$  versus  $\pi^- + W$  is evident. 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.

In an attempt to extract information on the magnitude of the  $h_1^\perp$  function from the NA10 data, Boer [17] assumed that  $h_1^\perp$  is proportional to the spin-averaged parton distribution function  $f_1$ :

$$h_1^\perp(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x), \quad (2)$$

where  $k_T$  is the quark transverse momentum,  $M_H$  is the mass of the hadron  $H$  (pion or nucleon), and  $M_C$  and  $C_H$  are constant fitting parameters. A Gaussian transverse momentum dependence of  $e^{-\alpha_T k_T^2}$  with  $\alpha_T = 1$  (GeV/ $c$ ) $^{-2}$  was assumed. The  $\cos 2\phi$  dependence then results from the convolution of the pion  $h_1^\perp/f_1$  term with the nucleon  $h_1^\perp/f_1$  term, and the parameter  $\nu$  is given as

$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}, \quad (3)$$

where  $\kappa_1 = C_{H_1} C_{H_2}/2$ , and  $H_1, H_2$  denote the two interacting hadrons. As shown in Fig. 2, a good description of the NA10 data is obtained with  $\kappa_1 = 0.47 \pm 0.14$  and  $M_C = 2.4 \pm 0.5$  GeV/ $c^2$ . A fit to the E615  $\nu$  data at 252 GeV/ $c$  using  $M_C = 2.4$  GeV/ $c^2$ , also shown in Fig. 2, gives  $\kappa_1 = 0.93 \pm 0.10$ . These large values of  $\kappa_1$  suggest sizable  $h_1^\perp$  functions for the valence antiquarks in the pion and for the valence quarks in the nucleon, but there is a puzzle in the interpretation since, according to Eq. (3),  $\nu$  should not depend on the beam energy.

A fit to the E866  $p + d$  data using Eq. (3) yields  $\kappa_1 = 0.11 \pm 0.04$  for  $M_C = 2.4$  GeV/ $c^2$ , as shown in Fig. 2. As

TABLE I. Mean values of the  $\lambda$ ,  $\mu$ ,  $\nu$  parameters and the quantity  $2\nu - (1 - \lambda)$  for three Drell-Yan measurements. The  $p_T$  dependence of these quantities is shown in Fig. 1. The kinematic coverages in  $x_1$  and  $x_2$  are also listed.

	$p + d$ 800 GeV/ $c$ (E866)	$\pi^- + W$ 194 GeV/ $c$ (NA10)	$\pi^- + W$ 252 GeV/ $c$ (E615)
$\langle\lambda\rangle$	$1.07 \pm 0.07$	$0.83 \pm 0.04$	$1.17 \pm 0.06$
$\langle\mu\rangle$	$0.003 \pm 0.013$	$0.008 \pm 0.010$	$0.09 \pm 0.02$
$\langle\nu\rangle$	$0.027 \pm 0.010$	$0.091 \pm 0.009$	$0.169 \pm 0.019$
$\langle 2\nu - (1 - \lambda) \rangle$	$0.12 \pm 0.07$	$0.01 \pm 0.04$	$0.51 \pm 0.07$
$x_1$ range	$0.15 \rightarrow 0.85$	$0.2 \rightarrow 1.0$	$0.2 \rightarrow 1.0$
$x_2$ range	$0.02 \rightarrow 0.24$	$0.1 \rightarrow 0.4$	$0.04 \rightarrow 0.38$

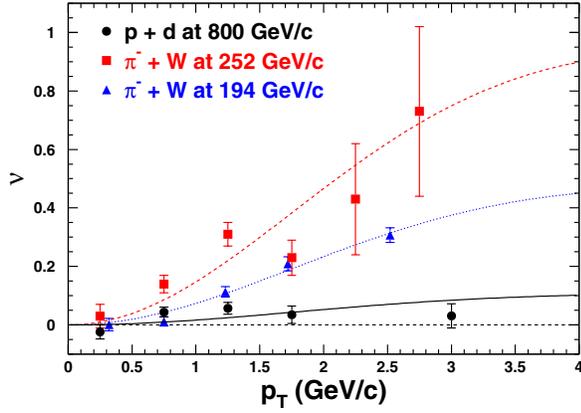


FIG. 2 (color online). Parameter  $\nu$  vs  $p_T$  in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. (3) and  $M_C = 2.4 \text{ GeV}/c^2$  are also shown.

noted earlier, proton-induced Drell-Yan data involves a valence quark annihilating with a sea quark. A comparison of the values of  $\kappa_1$  from proton-induced Drell-Yan data with those from pion-induced Drell-Yan data suggests that the ratio  $h_1^\perp/f_1$  for the nucleon sea quarks is substantially below that for valence quarks. More specifically, the value of  $C_H$  for the sea is approximately a factor 4–8 smaller than that for valence quarks.

The Drell-Yan angular distributions have also been analyzed for other kinematic variables. Figure 3 shows the values of  $\nu$  for  $p + d$  versus  $m_{\mu\mu}$ ,  $x_F$ ,  $x_1$ , and  $x_2$ , where  $x_1$  and  $x_2$  are the Bjorken  $x$  for the beam and target partons, respectively. Again, for each bin the data were divided into

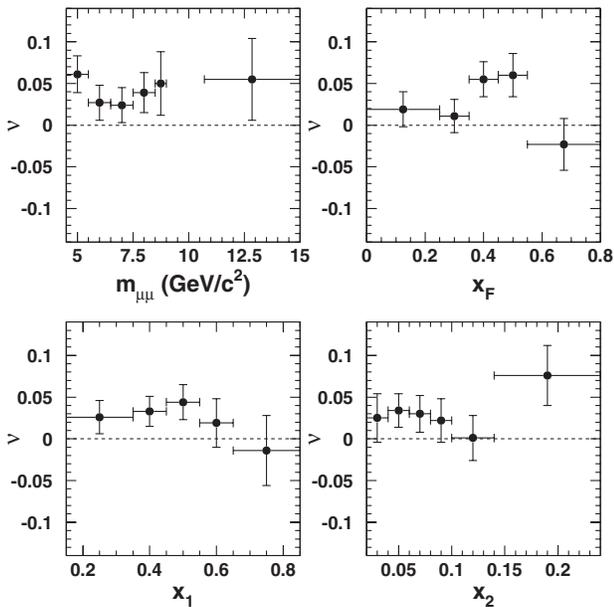


FIG. 3. Parameter  $\nu$  vs  $m_{\mu\mu}$ ,  $x_F$ ,  $x_1$ , and  $x_2$  in the Collins-Soper frame for  $p + d$  at 800 GeV/c. The error bars correspond to the statistical uncertainties only.

5 bins in  $\cos\theta$  and 8 bins in  $\phi$  in order to extract the angular distribution parameters. Figure 3 shows no significant dependence on these kinematic variables.

In summary, we report a measurement of the angular distributions of Drell-Yan dimuons for  $p + d$  at 800 GeV/c. The pronounced  $\cos 2\phi$  azimuthal angular dependence observed previously in pion-induced Drell-Yan data is not observed in the  $p + d$  reaction. The Lam-Tung relation, found to be strongly violated in the E615 pion-induced Drell-Yan data, remains largely valid for  $p + d$  Drell-Yan data. These 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 functions  $h_1^\perp$  for sea quarks are significantly smaller than those for valence quarks.

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