Measurement of Angular Distributions of Drell-Yan Dimuons in $p+p$ 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 hydrogen target. The polar and azimuthal angular distribution parameters have been extracted over the kinematic range $4.5 < m_{\mu\mu} < 15$ GeV/c^2 (excluding the Υ resonance region), $0 < p_T < 4$ GeV/c, and $0 < x_F < 0.8$. The $p+p$ angular distributions are similar to those of $p+d$, and both data sets are compared with models which attribute the $\cos 2\phi$ distribution either to the presence of the transverse-momentum-dependent Boer-Mulders structure function $h_1^\perp$ or to QCD effects. The data indicate the need to include QCD effects before reliable information on the Boer-Mulders function can be extracted. The validity of the Lam-Tung relation in $p+p$ Drell-Yan is also tested.

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The study of the transverse momentum dependent (TMD) parton distribution functions of the nucleon has received much attention in recent years as it provides new perspectives on the hadron structure and QCD [1]. One of these TMD distribution functions, first considered by Sivers [2], represents the correlation between the quark's transverse momentum, $k_\perp$, and the transverse spin of the nucleon, $S_\perp$. This so-called Sivers function, $f_{1T}^\perp(x, k_\perp^2)$, where x is the fraction of proton's momentum carried by the quark, is time-reversal odd (T-odd) and can arise from initial- or final-state interactions [3]. More generally, the requirement of gauge invariance of parton distributions was shown to provide nontrivial phases leading to the existence of T-odd distribution functions [4, 5]. Recent measurements of the semi-inclusive deep-inelastic scattering (SIDIS) by the HERMES [6] and COMPASS [7] collaborations have shown clear evidence for the presence of the T-odd Sivers functions. These data also allow the first determination [8] of the magnitude and flavor structure of the Sivers functions.

Another T-odd distribution function is the Boer-Mulders function, $h_1^\perp(x, k_\perp^2)$, which signifies the correlation between $k_\perp$ and the quark transverse spin, $s_\perp$, in an unpolarized nucleon [9]. The Boer-Mulders function is the chiral-odd analog of the Sivers function and also owes its existence to the presence of initial/final state interactions [10]. While the Sivers function is beginning to be quantitatively determined from the SIDIS experiments, very little is known about the Boer-Mulders function so far.

Several model calculations have been carried out for the Boer-Mulders functions. In the quark-diquark model, it was shown that the Boer-Mulders functions are identical to the Sivers functions when only the scalar diquark configuration is considered [10, 11]. More recently, calculations taking into account both the scalar and the axial-vector diquark configurations found significant differences in flavor dependence between the Sivers and Boer-Mulders functions [12]. In particular, the u and d valence quark Boer-Mulders functions are predicted to be both negative, while the Sivers function is negative for the u and positive for the d valence quarks. Other calculations using the MIT bag model [13], the relativistic constituent quark model [14], the large-N_c model [15], and lattice QCD [16] also predict negative signs for the u and d valence Boer-Mulders functions. Burkardt recently pointed out [17] that the negative signs for the Boer-Mulders functions are expected for both nucleons and pions. The model predictions for the same signs of the u and d Boer-Mulders functions remain to be tested experimentally. Furthermore, the striking prediction [4] that the T-odd Boer-Mulders functions in the SIDIS process will change their signs for the Drell-Yan process also awaits experimental confirmation.

The Boer-Mulders functions can be extracted [18] from the azimuthal angular distributions in the unpolarized Drell-Yan process, $h_1 h_2 \to l^+ l^- x$. The general expression for the Drell-Yan angular distribution is [19]

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

where θ and ϕ 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 [18]. 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 [20] and E615 [21] 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 $p + d$ interactions at 800 GeV/c [22]. In contrast to pion-induced Drell-Yan, significantly smaller (but non-zero) cos2ϕ azimuthal angular dependence was observed in the $p + d$ reaction. 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 $p + d$ result suggests [22] that the Boer-Mulders functions for sea antiquarks are significantly smaller than those for valence quarks.

A recent analysis [23] indicated that the E866 $p + d$ data are consistent with the u and d Boer-Mulders functions having the same signs, as predicted by various models. However, the $p + d$ data alone cannot provide an unambiguous determination of the flavor dependence of the Boer-Mulders functions. Moreover, it was recently pointed out [24, 25] that QCD processes would lead to a sizeable $\cos 2\phi$ effect which has not been taken into account in the extractions [18, 23, 26] of Boer-Mulders functions from the Drell-Yan data. In this paper we report the Drell-Yan angular distributions of the $p+p$ reaction at 800 GeV/c, which provides further constraints on the flavor dependence of the Boer-Mulders functions [26]. We also compare the $\cos 2\phi$ dependences of $p+p$ and $p+d$ data with the prediction of QCD.

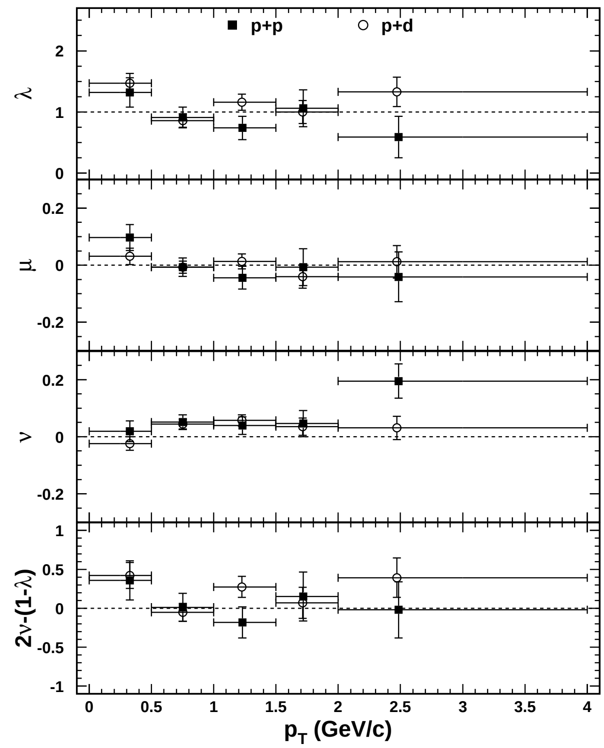

FIG. 1: Parameters λ, μ, ν and $2\nu - (1-\lambda)$ vs. p_T in the Collins-Soper frame. Solid squares (open circles) are for E866 $p + p$ ($p + d$) at 800 GeV/c. The vertical error bars include the statistical uncertainties only.

The Fermilab E866 experiment was performed using the upgraded Meson-East magnetic pair spectrometer [27]. An 800 GeV/c primary proton beam with up to 2×10^{12} protons per 20 s beam spill was incident upon one of three identical 50.8 cm long target 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 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 [27] on liquid hydrogen and empty targets were used in this analysis. The detector system consisted of four track-

TABLE I: Mean values of the λ, μ, ν parameters and the quantity $2\nu - (1-\lambda)$ for the $p+p$, $p+d$, and $\pi^- + W$ Drell-Yan measurements.

	$p+p$ 800 GeV/c (E866)	$p+d$ 800 GeV/c (E866)	$\pi^- + W$ 194 GeV/c (NA10)
$\langle\lambda\rangle$	0.85 ± 0.10	1.07 ± 0.07	0.83 ± 0.04
$\langle\mu\rangle$	-0.026 ± 0.019	0.003 ± 0.013	0.008 ± 0.010
$\langle\nu\rangle$	0.040 ± 0.015	0.027 ± 0.010	0.091 ± 0.009
$\langle 2\nu - (1-\lambda)\rangle$	-0.07 ± 0.10	0.12 ± 0.07	0.01 ± 0.04

ing 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 μ^+ and μ^-, kinematic variables of the dimuons ($x_F, m_{\mu\mu}$, and p_T, where x_F is the fraction of the c.m. momentum carried by dimuon of mass $m_{\mu\mu}$, and p_T is the dimuon transverse momentum) were readily reconstructed. The muon angles θ and ϕ in the Collins-Soper frame [28] were also calculated. To eliminate the J/Ψ and Υ resonance background, dimuon events with $m_{\mu\mu} < 4.5$ GeV/c^2 and 9.0 GeV/c^2 $< m_{\mu\mu} < 10.7$ GeV/c^2 were rejected in the analysis. A total of ≈54,000 $p+p$ Drell-Yan events covering the decay angular range $-0.5 < \cos\theta < 0.5$ and $-\pi < \phi < \pi$ remain. Detailed Monte Carlo simulations of the experiment using the MRST98 parton distribution functions [29] for NLO Drell-Yan cross sections have shown good agreement with the data for a variety of measured quantities.

Figure 1 shows the angular distribution parameters λ, μ, and ν vs. p_T. To extract these parameters, the Drell-Yan data were grouped into 5 bins in $\cos\theta$ and 8 bins in ϕ for each p_T bin. A least-squares fit to the data using Eq. 1 to describe the angular distribution was performed. The extracted values of λ, μ, ν are insensitive to their values used in the Monte Carlo simulation. 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. Analysis performed by allowing the beam angles to vary within their ranges of uncertainty has shown that the systematic errors are small compared to the statistical errors. The E866 $p+d$ Drell-Yan data are also shown in Fig. 1 for comparison with the E866 $p+p$ data. The $p+d$ data contain a total of ≈118,000 events covering an identical $\cos\theta$ range. The p_T-averaged values of $\langle\lambda\rangle, \langle\mu\rangle$, and $\langle\nu\rangle$ for $p+p$, $p+d$, and the NA10 $\pi^- + W$ data [20] are listed in Table I. Within statistics, the angular distributions of $p+p$ are consistent with those of $p+d$. Also shown in Fig. 1 and Table I is the quantity $2\nu - (1-\lambda)$, which should vanish if the Lam-Tung relation is valid. While QCD effects can lead to $\lambda \neq 1$ and $\mu, \nu \neq 0$, Lam and Tung showed [30] that the relation $1 - \lambda = 2\nu$ is largely unaffected by QCD corrections. Table I shows that while $\langle\lambda\rangle$ deviates from 1 and $\langle\nu\rangle$ is nonzero for the E866 $p+p$ and the NA10 $\pi^- + W$ Drell-Yan data, the Lam-Tung relation is indeed quite well satisfied within statistical uncertainty for all p_T. This differs from the observation of a significant violation of the Lam-Tung relation at large p_T by the E615 collaboration in the $\pi^- + W$ reaction at 252 GeV/c [21].

Figure 2 shows the parameter ν vs. p_T for the $p+p$ and $p+d$ Drell-Yan data. The solid curves are calculations [23, 26] for $p+p$ and $p+d$ using parametrizations of the Boer-Mulders functions deduced from a fit to the $p+d$ Drell-Yan data. The predicted larger values of ν for $p+p$ compared to $p+d$ in the region of $p_T \sim 1.5$ GeV/c are not observed (the predicted $p+p/p+d$ ratio, R, for $0.5 < p_T < 2.0$ GeV/c, is ~ 2, while the data give $R = 1.0 \pm 0.5$). Furthermore, the shape of the predicted p_T dependence differs from that of the data, resulting in a reduced χ^2 value of 3.2 for 5 degrees of freedom (probability of 0.7%). This strongly suggests that there could be other mechanisms contributing to the $\cos 2\phi$ azimuthal angular dependence at large p_T. In recent papers [24, 25], the QCD contribution to the $\cos 2\phi$ azimuthal angular dependence is given as

$$\nu = \frac{Q_\perp^2/Q^2}{1 + \frac{3}{2}Q_\perp^2/Q^2}, \tag{2}$$

where $Q_\perp$ is the dimuon transverse momentum. The predicted QCD contribution, the same for $p+p$ and $p+d$ due to the identical kinematic coverage for the two reactions, is shown as the dot-dashed curve in Fig. 2. A comparison between the QCD prediction with the data gives a reduced χ^2 of 1.0 for 5 degrees of freedom (probability of 42%) for $p+p$ and a reduced χ^2 of 1.9 (probability of 9%) for $p+d$. From Fig. 2 it is evident that the QCD contribution is expected to become more important at high p_T while the Boer-Mulders functions contribute primarily at lower p_T. An analysis combining both effects is required in order to extract reliably the Boer-Mulders functions from the $p+p$ and $p+d$ data. It is worth noting that the $\pi^- + W$ Drell-Yan data [20, 21] also show large values of ν at large p_T, consistent with the presence of QCD effects.

The $p+p$ Drell-Yan angular distributions have also been analyzed for other kinematic variables. Figure 3 shows the values of ν vs. $m_{\mu\mu}, x_F, x_1$, 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 5 bins in $\cos\theta$ and 8 bins in ϕ in order to extract the angular distribution parameters. The $p+d$ data are also shown for comparison. Figure 3 shows that the magnitude of ν for $p+p$ is consistent with that for $p+d$ for most of the kinematic regimes. These data provide

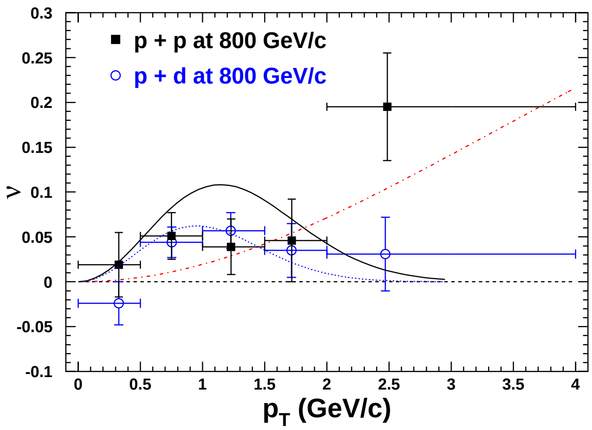

FIG. 2: (color online). Parameter ν vs. p_T in the Collins-Soper frame for the $p+p$ and $p+d$ Drell-Yan data. The solid and dotted curves are calculations [23] for $p+p$ and $p+d$, respectively, using parametrizations based on a fit to the $p+d$ data. The dot-dashed curve is the contribution from the QCD process (Eq. 2).

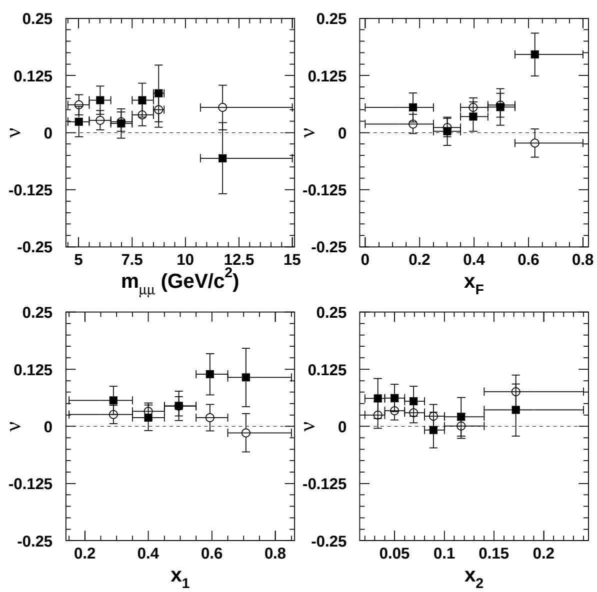

FIG. 3: Parameter ν vs. $m_{\mu\mu}$, x_F, x_1, and x_2 in the Collins-Soper frame for $p+p$ (solid squares) and $p+d$ (open circles) at 800 GeV/c. The vertical error bars correspond to the statistical uncertainties only.

further input for future extraction of the Boer-Mulders functions.

In summary, we report a measurement of the angular distributions of Drell-Yan dimuons for $p+p$ at 800 GeV/c. The pronounced $\cos 2\phi$ azimuthal angular dependence observed previously in pion-induced Drell-Yan is not observed in the $p+p$ reaction. The Lam-Tung relation remains valid for the $p+p$ Drell-Yan data. The overall magnitude of the $\cos 2\phi$ dependence for $p+p$ is consistent with, but slightly larger than that of $p+d$. The data suggest the presence of higher-order QCD corrections at high p_T, and it is important to take this contribution into account before reliable extraction of the Boer-Mulders functions could be obtained.

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[1] V. Barone, A. Drago, and P. G. Ratcliffe, Phys. Rep. **359**, 1 (2002).
[2] D. Sivers, Phys. Rev. D **41**, 83 (1990).
[3] S.J. Brodsky, D.S. Hwang, and I. Schmidt, Phys. Lett. B **530**, 99 (2002).
[4] J.C. Collins, Phys. Lett. B **536**, 43 (2002).
[5] X. Ji and F. Yuan, Phys. Lett. B **543**, 66 (2002).
[6] HERMES Collaboration, A. Airapetian *et al.*, Phys. Rev. Lett. **94**, 012002 (2005); M. Diefenthaler, arXiv: 0706.2242.
[7] COMPASS Collaboration, V. Yu. Alexakhin *et al.*, Phys. Rev. Lett. **94**, 202002 (2005); M. Alekseev *et al.*, arXiv: 0802.2160.
[8] W. Vogelsang and F. Yuan, Phys. Rev. D **72**, 054028 (2005); M. Anselmino *et al.*, Phys. Rev. D **72**, 094007 (2005); M. Anselmino *et al.*, arXiv:0807.0166.
[9] D. Boer and P.J. Mulders, Phys. Rev. D **57**, 5780 (1998).
[10] D. Boer, S.J. Brodsky, and D.S. Hwang, Phys. Rev. D **67**, 054003 (2003).
[11] L.P. Gamberg, G.R. Goldstein, and K.A. Oganessyan, Phys. Rev. D **67**, 071504(R) (2003); A. Bacchetta, A. Schäfer, and J.-J. Yang, Phys. Lett. B **578**, 109 (2004).
[12] L.P. Gamberg, G.R. Goldstein, and M. Schlegel, Phys. Rev. D **77**, 094016 (2008).
[13] F. Yuan, Phys. Lett. B **575**, 45 (2003).
[14] B. Pasquini, M. Pincetti, and S. Boffi, Phys. Rev. D **76**, 034020 (2007).
[15] P.V. Pobylitsa, hep-ph/0301236.
[16] M. Göckeler *et al.*, Phys. Rev. Lett. **98**, 222001 (2007).
[17] M. Burkardt and B. Hannafious, Phys. Lett. B **658**, 130 (2008).
[18] D. Boer, Phys. Rev. D **60**, 014012 (1999).
[19] C.S. Lam and W.K. Tung, Phys. Rev. D **18**, 2447 (1978).
[20] NA10 Collaboration, S. Falciano *et al.*, Z. Phys. C **31**, 513 (1986); M. Guanziroli *et al.*, Z. Phys. C **37**, 545 (1988).
[21] E615 Collaboration, J.S. Conway *et al.*, Phys. Rev. D **39**, 92 (1989).
[22] E866 Collaboration, L.Y. Zhu *et al.*, Phys. Rev. Lett. **99**, 082301 (2007).
[23] B. Zhang, Z. Lu, B.-Q. Ma, and I. Schmidt, Phys. Rev. D **77**, 054011 (2008).
[24] D. Boer and W. Vogelsang, Phys. Rev. D **74**, 014004 (2006).
[25] E.L. Berger, J.-W. Qiu, and R.A. Rodriguez-Pedraza,

Phys. Lett. B **656**, 74 (2007); Phys. Rev. D **76**, 074006 (2007).

[26] B. Zhang, Z. Lu, B.-Q. Ma, and I. Schmidt, arXiv: 0807.0503.

[27] E866 Collaboration, E.H. Hawker *et al.*, Phys. Rev. Lett. **80**, 3715 (1998); J.C. Peng *et al.*, Phys. Rev. D **58**, 092004 (1998); R.S. Towell *et al.*, Phys. Rev. D **64**, 052002 (2001).

[28] J.C. Collins and D.E. Soper, Phys. Rev. D **16**, 2219 (1977).

[29] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Eur. Phys. J. C **4**, 463 (1998).

[30] C.S. Lam and W.K. Tung, Phys. Rev. D **21**, 2712 (1980).