Testing the Time-Reversal Modified Universality of the Sivers Function

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We derive the time-reversal modified universality for both quark and gluon Sivers functions from the parity and time-reversal invariance of QCD. We calculate the single transverse-spin asymmetry of inclusive lepton from the decay of W bosons in polarized proton-proton collision at the Brookhaven National Laboratory Relativistic Heavy Ion Collider (RHIC), in terms of the Sivers function. We find that, although the asymmetry is diluted from the W decay, the lepton asymmetry is at the level of several percent and is measurable for a good range of lepton rapidity at RHIC. We argue that this measurable lepton asymmetry at RHIC is an excellent observable for testing the time-reversal modified universality of the Sivers function.

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I. Introduction.—Much of the predictive power of perturbative quantum chromodynamics (QCD) is contained in factorization theorems [1]. They normally include two assertions. One is that a physical quantity can be factorized into perturbatively calculable short-distance hard parts convoluted with nonperturbative long-distance distribution functions. The other is the *universality* of the nonperturbative functions. Predictions follow when processes with different hard scatterings but the same distribution functions are compared. With one set of universal parton distribution functions (PDFs) the leading power collinear QCD factorization formalisms have been very successful in interpreting almost all existing data from high energy collisions with momentum transfers larger than a few GeV [2].

The phenomenon of single transverse-spin asymmetry (SSA), $A_N \equiv (\sigma(\vec{S}_\perp) - \sigma(-\vec{S}_\perp))/(\sigma(\vec{S}_\perp) + \sigma(-\vec{S}_\perp))$, defined as the ratio of the difference and the sum of the cross sections when the spin vector $\vec{S}_\perp$ is flipped, was first observed in the hadronic Λ^0 production at Fermilab in 1976 [3]. Large SSAs, as large as 30%, have been consistently observed in various experiments involving one polarized hadron at different collision energies [4], and presented a challenge to the leading power collinear QCD factorization formalism [5].

Two widely discussed theoretical approaches have been proposed to evaluate the observed SSAs in QCD. One generalizes the QCD collinear factorization approach to the next-to-leading power in the momentum transfer [6], and attributes the SSA to the quantum interference of scattering amplitudes with different numbers of active partons [7,8]. The size of the asymmetry is determined by new three-parton correlation functions [9]. This generalized collinear factorization approach is more relevant for the SSAs of cross sections whose momentum transfers $Q \gg \Lambda_{\rm QCD}$. The other approach factorizes $\sigma(\vec{S}_\perp)$ in terms of the transverse momentum dependent (TMD) parton distributions defined in Eq. (1) below [10–14]. It attributes the SSAs to the nonvanishing Sivers function [15], which is defined as the spin-dependent part of TMD parton distribution, or the Collins function if a final-state hadron was observed [16]. The TMD factorization approach is more suitable for cross sections with two very different momentum transfers, $Q_1 \gg Q_2 \gtrsim \Lambda_{\rm QCD}$. These two approaches each have their kinematic domain of validity; they were shown to be consistent with each other in the kinematic regime where they both apply [17].

However, there is one crucial difference between these two approaches besides the difference in kinematic regimes where they apply. The Sivers function could be process dependent, while all distribution functions in the collinear factorization approach are universal. It was predicted by Collins [10] on the basis of time-reversal and parity arguments that the quark Sivers function in semi-inclusive deep inelastic scattering (SIDIS) and in Drell-Yan process (DY) have the same functional form but an *opposite sign*, a time-reversal modified universality. In this Letter, we derive the same time-reversal modified universality for both quark and gluon Sivers function from the parity and time-reversal invariance of QCD.

The experimental check of this time-reversal modified universality of the Sivers function would provide a critical test of the TMD factorization approach [10–14]. Recently, the quark Sivers function has been extracted from data of SIDIS experiments [18]. Future measurements of the SSAs in DY production have been planned [19]. In this Letter, we present the SSAs of inclusive single lepton production from the decay of W bosons, and show that the lepton SSAs is significant and measurable for a good range of lepton rapidity at the Brookhaven National Laboratory Relativistic Heavy Ion Collider (RHIC). We find that the lepton SSAs are sharply peaked at transverse momentum $p_T \sim M_W/2$ with W mass M_W. This is because the most W bosons at RHIC have $q_T \ll M_W$. On the other hand, leptons from heavy quarkonium decay and other potential backgrounds are unlikely to be peaked at the $p_T \sim M_W/2$. Since the W production and DY share the same Sivers function, we argue that the SSA of inclusive high p_T

leptons at RHIC is an excellent observable for testing the time-reversal modified universality.

II. The QCD prediction.—The predictive power of the TMD factorization approach to the SSAs relies on the universality of the TMD parton distributions. For the lepton-hadron SIDIS, $\ell(l) + h(p, \vec{S}) \to \ell'(l') + h'(p') + X$, the factorized TMD quark distribution has the following gauge invariant operator definition [20],

$$f^{\rm SIDIS}_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2\mathbf{y}_\perp}{(2\pi)^3} e^{ixp^+y^- - i\mathbf{k}_\perp\cdot\mathbf{y}_\perp}\langle p,\vec{S}|\bar{\psi}(0^-,\mathbf{0}_\perp) \times \Phi_n^\dagger(\{\infty,0\},\mathbf{0}_\perp)\Phi^\dagger_{\mathbf{n}_\perp}(\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\frac{\gamma^+}{2} \times \Phi_n(\{\infty,y^-\},\mathbf{y}_\perp)\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle, \tag{1}$$

where $y^+ = 0^+$ dependence is suppressed and the gauge links from the final-state interaction of SIDIS are

$$\Phi_n(\{\infty, y^-\}, \mathbf{y}_\perp) \equiv \mathcal{P}e^{-ig\int_{y^-}^{\infty} dy_1^- n^\mu A_\mu(y_1^-,\mathbf{y}_\perp)},$$
$$\Phi_{\mathbf{n}_\perp}(\infty, \{\mathbf{y}_\perp, \mathbf{0}_\perp\}) \equiv \mathcal{P}e^{-ig\int_{\mathbf{0}_\perp}^{\mathbf{y}_\perp} d\mathbf{y}'_\perp \mathbf{n}^\mu_\perp A_\mu(\infty,\mathbf{y}'_\perp)}, \tag{2}$$

where $\mathcal{P}$ indicates the path ordering and the direction $\mathbf{n}_\perp$ is pointed from $\mathbf{0}_\perp$ to $\mathbf{y}_\perp$. Here we define the light-cone vectors, $n^\mu = (n^+, n^-, \mathbf{n}_\perp) = (0, 1, \mathbf{0}_\perp)$ and $\bar{n}^\mu = (1, 0, \mathbf{0}_\perp)$, which project out the light-cone components of any four-vector V^μ as $V \cdot n = V^+$ and $V \cdot \bar{n} = V^-$.

For the DY, $h(p, \vec{S}) + h'(p') \to \gamma^*(Q)[\to \ell^+\ell^-] + X$, the factorized TMD quark distribution is given by

$$f^{\rm DY}_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2\mathbf{y}_\perp}{(2\pi)^3} e^{ixp^+y^- - i\mathbf{k}_\perp\cdot\mathbf{y}_\perp}\langle p,\vec{S}|\bar{\psi}(0^-,\mathbf{0}_\perp) \times \Phi_n^\dagger(\{-\infty,0\},\mathbf{0}_\perp)\Phi^\dagger_{\mathbf{n}_\perp}(-\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\frac{\gamma^+}{2} \times \Phi_n(\{-\infty,y^-\},\mathbf{y}_\perp)\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle \tag{3}$$

where the past pointing gauge links were caused by the initial-state interactions of DY production [10]. From Eqs. (1) and (3), it is easy to show that the collinear quark distributions are process independent,

$$\int d^2\mathbf{k}_\perp f^{\rm SIDIS}_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int d^2\mathbf{k}_\perp f^{\rm DY}_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}), \tag{4}$$

if the same renormalization scheme was used for the ultraviolet divergence of the $\mathbf{k}_\perp$ integration.

Let $|\alpha\rangle = |p, \vec{S}\rangle$ and $\langle\beta|$ be equal to the rest of the matrix element in Eq. (1) [9]. From the parity and time-reversal invariance of QCD, $\langle\alpha_P|\beta_P\rangle = \langle\alpha|\beta\rangle$ and $\langle\beta_T|\alpha_T\rangle = \langle\alpha|\beta\rangle$, where $|\alpha_P\rangle$ and $|\beta_P\rangle$, and $|\alpha_T\rangle$ and $|\beta_T\rangle$ are the parity and time-reversal transformed states from the states $|\alpha\rangle$ and $|\beta\rangle$, respectively, we derive

$$f^{\rm SIDIS}_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = f^{\rm DY}_{q/h^\uparrow}(x,\mathbf{k}_\perp,-\vec{S}) \tag{5}$$

and conclude that the spin-averaged TMD quark distributions are process independent. Following the notation of Ref. [18], we expand the TMD quark distribution as

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \equiv f_{q/h}(x,k_\perp) + \tfrac{1}{2}\Delta^N f_{q/h^\uparrow}(x,k_\perp)\vec{S}\cdot(\hat{p}\times\hat{\mathbf{k}}_\perp), \tag{6}$$

where $k_\perp = |\mathbf{k}_\perp|$, $\hat{p}$, and $\hat{\mathbf{k}}_\perp$ are the unit vectors of $\vec{p}$ and $\mathbf{k}_\perp$, respectively, $f_{q/h}(x, k_\perp)$ is the spin-averaged TMD distribution, and $\Delta^N f_{q/h^\uparrow}(x, k_\perp)$ is the Sivers function [15]. Substituting Eq. (6) into Eq. (5), we obtain

$$\Delta^N f^{\rm SIDIS}_{q/h^\uparrow}(x,k_\perp) = -\Delta^N f^{\rm DY}_{q/h^\uparrow}(x,k_\perp), \tag{7}$$

which confirms the Collins' prediction [10].

We define the gauge invariant TMD gluon distribution in SIDIS and in DY by replacing the quark operator $\bar{\psi}(\gamma^+/2)\psi$ in Eqs. (1) and (3) by the gluon operator $F^{+\mu}F^{+\nu}(-g_{\mu\nu})$, and the gauge links by those in the adjoint representation of SU(3) color [21]. From the parity and time-reversal invariance of the matrix elements of the TMD gluon distribution, we find, like Eq. (5),

$$f^{\rm SIDIS}_{g/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = f^{\rm DY}_{g/h^\uparrow}(x,\mathbf{k}_\perp,-\vec{S}). \tag{8}$$

Applying Eq. (6) to the gluon TMD distribution, we derive the same time-reversal modified universality for the gluon Sivers function,

$$\Delta^N f^{\rm SIDIS}_{g/h^\uparrow}(x,k_\perp) = -\Delta^N f^{\rm DY}_{g/h^\uparrow}(x,k_\perp). \tag{9}$$

The sign change of the Sivers function is a property of the gauge invariant TMD parton distributions.

III. Lepton SSAs from W production.—The SSAs of W production at RHIC, $A(p_A, \vec{S}_\perp) + B(p_B) \to W^\pm(q) + X$, were proposed in Refs. [22] to measure the Sivers function. However, it is difficult to reconstruct W bosons by current detectors at RHIC. We propose to use the SSAs of inclusive high p_T lepton from the decay of W bosons to measure the Sivers function.

The leading order (LO) spin-averaged W cross section, in terms of the TMD factorization, is given by

$$\frac{d\sigma_{AB\to W}}{dy_W d^2\mathbf{q}_\perp} = \sigma_0 \sum_{a,b}|V_{ab}|^2 \int d^2\mathbf{k}_{a\perp} d^2\mathbf{k}_{b\perp} f_{a/A}(x_a,k_{a\perp}) \times f_{b/B}(x_b,k_{b\perp})\delta^2(\mathbf{q}_\perp - \mathbf{k}_{a\perp} - \mathbf{k}_{b\perp}), \tag{10}$$

where y_W is the W rapidity, $\sigma_0 = (\pi/3)\sqrt{2}G_F M_W^2/s$ is the lowest order partonic cross section with the Fermi weak coupling constant G_F and $s = (p_A + p_B)^2$, $\sum_{ab}$ runs over all light (anti)quark flavors, V_{ab} are the Cabibbo-Kobayashi-Maskawa matrix elements for the weak interaction. The parton momentum fractions in Eq. (10) are given by

$$x_a = \frac{M_W}{\sqrt{s}} e^{y_W}, \qquad x_b = \frac{M_W}{\sqrt{s}} e^{-y_W} \tag{11}$$

to the leading power in $q_\perp^2/M_W^2$. The LO spin-dependent W cross section, $\Delta\sigma(\vec{S}_\perp) = [\sigma(\vec{S}_\perp) - \sigma(-\vec{S}_\perp)]/2$, is similarly given by

$$\frac{d\Delta\sigma(\vec{S}_\perp)_{A^\uparrow B\to W}}{dy_W d^2\mathbf{q}_\perp} = \frac{\sigma_0}{2}\sum_{a,b}|V_{ab}|^2\int d^2\mathbf{k}_{a\perp}d^2\mathbf{k}_{b\perp}\vec{S}_\perp\cdot(\hat{p}_A \times\hat{\mathbf{k}}_{a\perp})\Delta^N f^{\rm DY}_{a/A^\uparrow}(x_a,k_{a\perp})f_{b/B}(x_b,k_{b\perp}) \times\delta^2(\mathbf{q}_\perp-\mathbf{k}_{a\perp}-\mathbf{k}_{b\perp}). \quad (12)$$

The SSA of W production is then defined as

$$A_N^{(W)} \equiv \frac{d\Delta\sigma(\vec{S}_\perp)_{A^\uparrow B\to W}}{dy_W d^2\mathbf{q}_\perp}\Big/\frac{d\sigma_{AB\to W}}{dy_W d^2\mathbf{q}_\perp}, \quad (13)$$

whose sign depends on the sign of the Sivers function and the direction of the spin vector $\vec{S}_\perp$.

To evaluate the SSA in Eq. (13), we use the parametrization of TMD parton distributions in Ref. [18],

$$f_{q/h}(x,k_\perp) = f_q(x)\frac{1}{\pi\langle k_\perp^2\rangle}e^{-k_\perp^2/\langle k_\perp^2\rangle}, \quad (14)$$

$$\Delta^N f^{\rm SIDIS}_{q/h^\uparrow}(x,k_\perp) = 2\mathcal{N}_q(x)h(k_\perp)f_{q/h}(x,k_\perp), \quad (15)$$

$$h(k_\perp) = \sqrt{2e}\frac{k_\perp}{M_1}e^{-k_\perp^2/M_1}, \quad (16)$$

where $f_q(x)$ is the standard unpolarized parton distribution of flavor q, $\langle k_\perp^2\rangle$ and M_1 are fitting parameters, and $\mathcal{N}_q(x)$ is a fitted distribution given in Ref. [18]. By carrying out the integration $d^2\mathbf{k}_{a\perp}d^2\mathbf{k}_{b\perp}$ in Eqs. (10) and (12) analytically, we obtain,

$$A_N^{(W)} = \vec{S}_\perp\cdot(\hat{p}_A\times\mathbf{q}_\perp) \times\frac{2\langle k_s^2\rangle^2}{[\langle k_\perp^2\rangle+\langle k_s^2\rangle]^2}e^{-[(\langle k_\perp^2\rangle-\langle k_s^2\rangle)/(\langle k_\perp^2\rangle+\langle k_s^2\rangle)](\mathbf{q}_\perp^2/2\langle k_\perp^2\rangle)}\frac{\sqrt{2e}}{M_1} \times\frac{\sum_{ab}|V_{ab}|^2[-\mathcal{N}_a(x_a)]f_a(x_a)f_b(x_b)}{\sum_{ab}|V_{ab}|^2f_a(x_a)f_b(x_b)}, \quad (17)$$

where $\langle k_s^2\rangle = M_1^2\langle k_\perp^2\rangle/[M_1^2+\langle k_\perp^2\rangle]$ and the "$-$" sign in front of $\mathcal{N}_a(x_a)$ is from Eq. (7). For our numerical predictions below, we work in a frame in which the polarized hadron A moves in the $+z$ direction, choose $\vec{S}_\perp$, $\mathbf{q}_\perp$ along the y and x direction, respectively, and the GRV98LO parton distribution [23] for $f_q(x)$ evaluated at M_W to be consistent with the usage of the TMD distributions of Ref. [18].

In Figs. 1 and 2, we plot the A_N from Eq. (17) at $\sqrt{s} =$ 500 GeV. The W asymmetry is peaked at $q_T \ll M_W$ and is much larger than that of DY production [19]. This is because the u and d Sivers functions have an opposite sign, and they partially cancel each other in their contribution to the DY asymmetry, while they contribute to the W^+ and W^- separately. The large W^- asymmetry is caused by a large d Sivers function [18]. The negative d Sivers function in SIDIS gives the positive W^- asymmetry. The big difference in the rapidity dependence of SSA of W^+ and W^- production in Fig. 1 is also related to the strong flavor dependence of antiquark Sivers functions from Ref. [18]. Therefore, the rapidity dependence in Fig. 1 provides excellent information for the flavor separation as well as the functional form of the Sivers function if we could reconstruct the W bosons.

Integrating over (anti)neutrino from the W decay, we obtain the leading order cross section for the production of leptons of rapidity y and transverse momentum $\mathbf{p}_\perp$,

$$\frac{d\sigma_{A^\uparrow B\to\ell(p)}(\vec{S}_\perp)}{dyd^2\mathbf{p}_\perp} = \sum_{a,b}|V_{ab}|^2\int dx_a d^2\mathbf{k}_{a\perp} \times\int dx_b d^2\mathbf{k}_{b\perp}f^{\rm DY}_{a/A^\uparrow}(x_a,\mathbf{k}_{a\perp},\vec{S}_\perp) \times f_{b/B}(x_b,k_{b\perp})\frac{1}{16\pi^2\hat{s}}|\overline{\mathcal{M}}_{ab\to\ell}|^2 \times\delta(\hat{s}+\hat{t}+\hat{u}), \quad (18)$$

where $\hat{s}$, $\hat{t}$, and $\hat{u}$ are the Mandelstam variables and the leading order partonic scattering amplitude square, $|\overline{\mathcal{M}}_{ab\to\ell}|^2$, is given by

$$\frac{8(G_F M_W^2)^2}{3}\frac{\hat{u}^2}{(\hat{s}-M_W^2)^2+M_W^2\Gamma_W^2} \quad (19)$$

for partonic channels $ab = d\bar{u}$, $s\bar{u}$, $\bar{d}u$, $\bar{s}u$, or by the same one with the $\hat{u}^2$ replaced by $\hat{t}^2$ for the rest light flavor channels $ab = \bar{u}d$, $\bar{u}s$, $u\bar{d}$, $u\bar{s}$. Γ_W in Eq. (19) is the W leptonic decay width. Substituting Eq. (6) into Eq. (18), we derive both the spin-averaged and spin-dependent cross sections, from which we evaluate the SSAs of inclusive lepton production from W decay numerically.

In Figs. 3 and 4, we present our predictions for the inclusive lepton SSAs from the decay of W bosons at $\sqrt{s} =$ 500 GeV with $\vec{S}_\perp$, $\mathbf{p}_\perp$ along y and x direction, respectively. The lepton SSAs inherited all key features of the W asymmetry in Figs. 1 and 2. Although the W decay diluted the

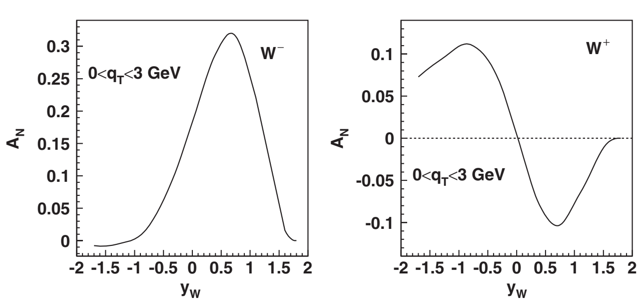

FIG. 1. A_N as a function of W-boson rapidity.

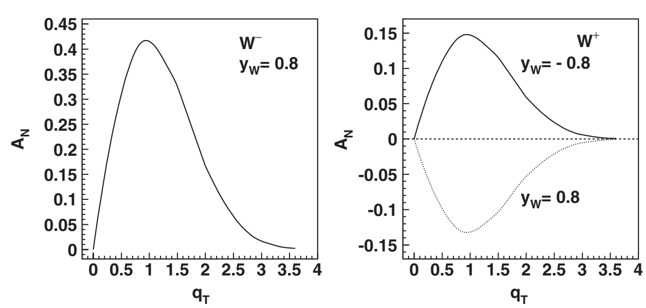

FIG. 2. A_N as a function of W-boson transverse momentum.

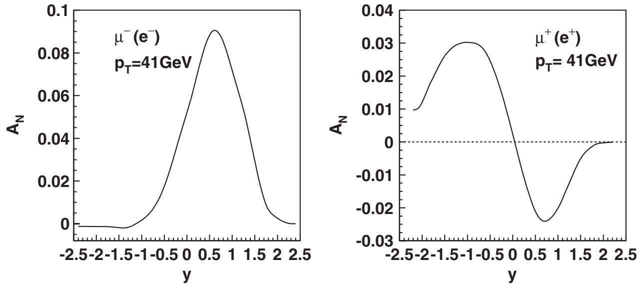

FIG. 3. A_N as a function of lepton rapidity.

size of the asymmetry, the lepton asymmetry is measurable at RHIC for a good range of rapidity. The difference in rapidity dependence in Fig. 3 could provide the excellent information on the Sivers functions and their flavor separation. In Fig. 4, the lepton SSAs are sharply peaked at $p_T \sim 41$ GeV, because the decay W boson has $q_T \sim 1$ GeV at RHIC, which should help control the potential background.

IV. Summary and conclusions.—In summary, we have derived the time-reversal modified universality for both quark and gluon Sivers functions from the parity and time-reversal invariance of the gauge invariant matrix elements that define the TMD parton distributions. We confirm the Collins' prediction for the sign change of the quark Sivers function in SIDIS and in DY [10]. The sign change of the Sivers function in SIDIS and in DY is a natural property of the gauge invariant TMD parton distributions in QCD. The corresponding sign change of the SSAs, if they could be factorized in terms of these TMD parton distributions, is a fundamental prediction of QCD.

We have calculated, in terms of the TMD factorization, the SSAs of W production as well as inclusive lepton production from the decay of W bosons in polarized proton-proton collision at RHIC energy. We find that although the asymmetry is diluted from the W decay, the lepton SSAs is at the level of several percent and measurable for a good range of lepton rapidity at RHIC. Because the lepton asymmetry is sharply peaked at the $p_T \sim 41$ GeV, the potential background could be strongly suppressed. Although both the lepton SSA discussed in this Letter and the SSA of DY [19] could test the sign change of the Sivers function, the lepton SSA with a good rapidity coverage could provide the test for individual quark flavor because of the weak interaction and our ability to measure the lepton SSAs from the decay of both W^+ and W^-. On the other hand, the SSA of DY is proportional to a *sum* of quark (antiquark) Sivers functions of all flavors weighted by the quark fractional charge square and the normal antiquark (quark) distribution. The sign and the size of SSA of DY depends on the relative sign and size of Sivers functions of *all* flavors. Therefore, we conclude that this measurable lepton SSAs at high p_T at RHIC is an excellent observable for measuring the Sivers functions of different flavors and for testing the time-reversal modified universality of the Sivers function.

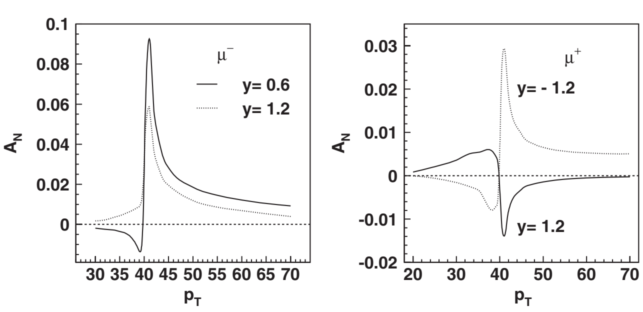

FIG. 4. A_N as a function of lepton transverse momentum.

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