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The Sivers asymmetry in Drell–Yan production at the J/Ψ peak at COMPASS

M. Anselmino [a], V. Barone [b,c], M. Boglione [a,*]

[a] Università di Torino and INFN-Torino, via Giuria 1, 10125 Torino, Italy
[b] Università del Piemonte Orientale, Viale T. Michel 11, I-15121 Alessandria, Italy
[c] INFN-Torino, via Giuria 1, 10125 Torino, Italy

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ABSTRACT

The abundant production of lepton pairs via J/Ψ creation at COMPASS, $\pi^{\pm} p^{\uparrow} \to J/\Psi\, X \to \ell^+\ell^- X$, allows a measurement of the transverse single spin asymmetry, $A_N^{J/\Psi}$, generated by the Sivers effect. The crucial issue of the sign change of the Sivers function in Drell–Yan lepton pair production, with respect to Semi Inclusive Deep Inelastic Scattering processes, can be addressed in a different context. Assuming that the Sivers asymmetry is related to a universal and intrinsic property of the proton, predictions for the expected magnitude of $A_N^{J/\Psi}$, which turns out to be large, are given. A comparison with the suggested measurement of this single spin asymmetry – an important quantity by itself – should give valuable information.

The distribution, in momentum space, of unpolarized quarks and gluons inside a transversely polarized nucleon, first introduced by Sivers [1,2], is one of the eight leading-twist Transverse Momentum Dependent Partonic Distribution Functions (TMD-PDFs), which can be accessed through experiments and encode our information on the 3-Dimensional nucleon structure. The Sivers distribution for unpolarized quarks (or gluons) with transverse momentum $\boldsymbol{k}_\perp$ inside a proton with 3-momentum $\boldsymbol{p}$ and spin $\boldsymbol{S}$, is defined as

$$\hat{f}_{q/p^{\uparrow}}(x, \boldsymbol{k}_\perp) = f_{q/p}(x, k_\perp) + \frac{1}{2}\, \Delta^N f_{q/p^{\uparrow}}(x, k_\perp)\, \boldsymbol{S} \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp) = f_{q/p}(x, k_\perp) - \frac{k_\perp}{m_p}\, f_{1T}^{\perp q}(x, k_\perp)\, \boldsymbol{S} \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)\,, \tag{1}$$

where $f_{q/p}(x, k_\perp)$ is the unpolarized TMD-PDF and $\Delta^N f_{q/p^{\uparrow}} = (-2k_\perp/m_p)\, f_{1T}^{\perp q}$ is the Sivers function.

The Sivers function is one of the best known polarized TMD-PDFs and has a clear experimental signature [3–5]. It is of particular interest for several reasons; one expects it to be related to fundamental intrinsic features of the nucleon and to basic QCD properties. In fact, the Sivers distribution relates the motion of unpolarized quarks and gluons to the nucleon spin $\boldsymbol{S}$; then, in order to build a scalar, parity invariant quantity, $\boldsymbol{S}$ must couple to the only other available pseudo-vector, that is the parton orbital angular momentum, $\boldsymbol{L}_q$ or $\boldsymbol{L}_g$. Another peculiar feature of the Sivers distribution is that its origin at partonic level can be traced in QCD interactions between the quarks (or gluons) active in inelastic high energy interactions and the nucleon remnants [6,7]; thus, it is expected to be process dependent and have opposite sign in Semi Inclusive Deep Inelastic Scattering (SIDIS) and Drell–Yan (D–Y) processes [8,9]. This important prediction remains to be tested.

In fact, one might still wonder whether the Sivers effect originates directly from an intrinsic property of the proton, rather than being mediated through initial or final state interactions, which lead to the opposite signs in SIDIS and D–Y processes [6–9]. It is tempting to relate the Sivers effect, at least for valence quarks, to their orbital motion, which, in turn, must be linked to the parent proton spin. In such a case one expects a universality of the Sivers asymmetry. Thus, it is important to find processes in which measurable Single Spin Asymmetries can be generated by the Sivers asymmetric distribution (1) and study them.

* Corresponding author.
E-mail address: boglione@to.infn.it (M. Boglione).

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Usually, the Sivers distribution can be accessed through the study of azimuthal asymmetries in polarized SIDIS and D–Y processes. These have been clearly observed in the last years, in SIDIS, by the HERMES [3] and COMPASS [4] Collaborations, allowing extractions of the SIDIS Sivers function [10–12]. However, no information could be obtained on the D–Y Sivers function, as no polarized D–Y process had ever been measured.

Asymmetries related to the Sivers effect can also be measured in the so called generalised D–Y processes [13,14], that is the creation of lepton pairs via vector bosons, $p\,p \to W^\pm X \to \ell^\pm \nu X$ and $p\,p \to Z^0 X \to \ell^+\ell^- X$. Also in this case one expects a Sivers function opposite to that observed in SIDIS.

Recently, first few data from D–Y weak boson production at RHIC, $p^\uparrow p \to W^\pm/Z^0 X$, have become available [15]. They show some azimuthal asymmetry which hints, with large errors and sizeable uncertainties, at a sign change between the Sivers function observed in these generalised D–Y processes and the SIDIS Sivers function, although much caution is still necessary [16]. More data on genuine D–Y processes, $\pi^\pm p^\uparrow \to \gamma^* X \to \ell^+\ell^- X$, are expected soon from the COMPASS Collaboration. However, also in this case, due to the energy of the COMPASS experiment, $\sqrt{s} = 18.9$ GeV, and the accepted safe region for D–Y events, $M \gtrsim 4$ GeV/c^2, where M is the invariant mass of the lepton pair, only a limited number of events, and consequently large statistical errors, are expected, as it is confirmed by first data [17].

Following Refs. [18,19] we propose here to measure the lepton pair production at COMPASS at the peak of the J/Ψ production, where the number of events is greatly enhanced. Notice that the spin-parity quantum numbers of J/Ψ are the same as for a photon.

Let us start from the usual D–Y process. According to the TMD factorisation scheme, the cross section for this process, $h_1\,h_2 \to q\,\bar{q}\,X \to \ell^+\ell^- X$, in which one measures the four-momentum q of the lepton pair, can be written, at leading order, as [20,21]:

$$\frac{d\sigma^{h_1h_2\to\ell^+\ell^-X}}{dy\,dM^2\,d^2\boldsymbol{q}_T} = \hat{\sigma}_0 \sum_q e_q^2 \int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, f_{\bar{q}/h_1}(x_1, k_{\perp 1})\, f_{q/h_2}(x_2, k_{\perp 2}) \tag{2}$$

where the $\sum_q$ runs over all relevant quarks and antiquarks and we have adopted the usual variables:

$$q = (q_0, \boldsymbol{q}_T, q_L) \qquad q^2 = M^2 \qquad y = \frac{1}{2}\ln\frac{q_0+q_L}{q_0-q_L} \qquad s = (p_1+p_2)^2\,. \tag{3}$$

The $f_{q/h}(x, k_\perp)$ are the unpolarized TMD-PDFs and $e_q^2\,\hat{\sigma}_0$ is the cross section for the $q\,\bar{q} \to \ell^+\ell^-$ process:

$$e_q^2\,\hat{\sigma}_0 = e_q^2\,\frac{4\pi\alpha^2}{9M^2}\,. \tag{4}$$

$\boldsymbol{k}_{\perp 1}$ and $\boldsymbol{k}_{\perp 1}$ are the parton transverse momenta, while the parton longitudinal momentum fractions are given at $\mathcal{O}(k_\perp/M)$, by

$$x_{1,2} = \frac{M}{\sqrt{s}}\,e^{\pm y} \quad \text{so that} \quad x_F = \frac{2\,q_L}{\sqrt{s}} = x_1 - x_2 = \left(x_1 - \frac{M^2}{s\,x_1}\right) = \left(\frac{M^2}{s\,x_2} - x_2\right),$$
$$y = \frac{1}{2}\ln\frac{x_1}{x_2} = \ln\frac{x_1\sqrt{s}}{M}\,. \tag{5}$$

Eq. (2) holds in the kinematical region:

$$q_T^2 \ll M^2 \qquad k_\perp \simeq q_T\,. \tag{6}$$

In the case in which one of the hadrons, say $h_2^\uparrow$, is polarized, Eq. (2) simply modifies by replacing $f_{q/h_2}(x_2, k_{\perp 2})$ with $\hat{f}_{q/h_2^\uparrow}(x_2, \boldsymbol{k}_{\perp 2})$ as given in Eq. (1). We then have the Sivers single transverse spin asymmetry:

$$A_N = \frac{d\sigma^{h_1h_2^\uparrow\to\ell^+\ell^-X} - d\sigma^{h_1h_2^\downarrow\to\ell^+\ell^-X}}{d\sigma^{h_1h_2^\uparrow\to\ell^+\ell^-X} + d\sigma^{h_1h_2^\downarrow\to\ell^+\ell^-X}} \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \tag{7}$$

$$= \frac{\sum_q e_q^2 \int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, \boldsymbol{S}\cdot(\hat{\boldsymbol{p}}_2 \times \hat{\boldsymbol{k}}_{\perp 2})\, f_{\bar{q}/h_1}(x_1, k_{\perp 1})\, \Delta^N f_{q/h_2^\uparrow}(x_2, k_{\perp 2})}{2\sum_q e_q^2 \int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, f_{\bar{q}/h_1}(x_1, k_{\perp 1})\, f_{q/h_2}(x_2, k_{\perp 2})}\,. \tag{8}$$

When the lepton pair production occurs via $q\,\bar{q}$ annihilation into a vector meson V rather than a virtual photon γ^*, Eqs. (2), (4) and (8) still hold, with the replacements [18]:

$$16\pi^2\alpha^2 e_q^2 \to (g_q^V)^2\,(g_\ell^V)^2 \qquad \frac{1}{M^4} \to \frac{1}{(M^2 - M_V^2)^2 + M_V^2\,\Gamma_V^2}\,, \tag{9}$$

where g_q^V and g_ℓ^V are the V vector couplings to $q\,\bar{q}$ and $\ell^+\ell^-$ respectively. Γ_V is the width of the vector meson and the new propagator is responsible for a large increase in the cross section at $M^2 = M_V^2$.

We then have:

$$A_N^V = \frac{\sum_q (g_q^V)^2 \int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, \boldsymbol{S}\cdot(\hat{\boldsymbol{p}}_2 \times \hat{\boldsymbol{k}}_{\perp 2})\, f_{\bar{q}/h_1}(x_1, k_{\perp 1})\, \Delta^N f_{q/h_2^\uparrow}(x_2, k_{\perp 2})}{2\sum_q (g_q^V)^2 \int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, f_{\bar{q}/h_1}(x_1, k_{\perp 1})\, f_{q/h_2}(x_2, k_{\perp 2})}\,. \tag{10}$$

We propose to use Eq. (10) for lepton pair production at COMPASS, $\pi^\pm p^\uparrow \to \ell^+\ell^- X$, at the J/Ψ peak, $M^2 = M_{J/\Psi}^2$. There are several reasons which make this channel very interesting and promising, as well as some reasons of attention and caution.