The Sivers asymmetry in $J/\Psi$ and lepton pair production at COMPASS

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The abundant production of lepton pairs via $J/\Psi$ creation at COMPASS, $\pi^\pm p^\uparrow \rightarrow J/\Psi X \rightarrow \ell^+\ell^-X$, allows a measurement of the transverse Single Spin Asymmetry generated by the Sivers effect. The crucial issue of the sign change of the Sivers function in lepton pair production, with respect to Semi Inclusive Deep Inelastic Scattering processes, can be solved. Predictions for the expected magnitude of the Single Spin Asymmetry, which turns out to be large, are given.

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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 $k_\perp$ inside a proton with 3-momentum $p$ and spin $S$, is defined as

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

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

The Sivers distribution is one of the best known polarized TMD-PDFs and has a clear experimental signature [3, 4]. 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 $S$; then, in order to build a scalar, parity invariant quantity, $S$ must couple to the only other available pseudo-vector, that is the parton orbital angular momentum, $L_q$ or $L_g$. 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 [3, 4], 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 [5, 6]. This important prediction remains to be tested.

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 the first extraction of the SIDIS Sivers function [9, 11]. 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 generalized D-Y processes [12, 13], that is the creation of lepton pairs via vector bosons, $pp \rightarrow W^\pm X \rightarrow \ell^+\ell^-X$ and $pp \rightarrow Z^0 X \rightarrow \ell^+\ell^-X$. 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, $p^\uparrow p \rightarrow W^\pm/Z^0 X$, have become available [14]. 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. More data on genuine D-Y processes, $\pi^\pm p^\uparrow \rightarrow \gamma^* X \rightarrow \ell^+\ell^-X$, 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.

Following Refs. 15, 16 and 12, 13 we propose here to measure the lepton pair production at COMPASS at the peak of the $J/\Psi$ production, where the number of events is greatly enhanced. Notice that the spin-parity quantum numbers of $J/\Psi$ are the same as for a photon.

Let us start from the usual D-Y. According to the TMD factorisation scheme, the cross section for this process, $h_1 h_2 \rightarrow q \bar{q} X \rightarrow \ell^+\ell^- X$, in which one measures the four-momentum $q$ of the lepton pair, can be written, at leading
order, as \[17\] \[18\]:

\[
\frac{d\sigma_{h_1 h_2 \rightarrow \ell^+ \ell^-}}{dy dM^2 d^2 q_T} = \hat{\sigma}_0 \sum_q e_q^2 f_{q/h_1}(x_1, k_{1\perp}) f_{\bar{q}/h_2}(x_2, k_{2\perp})
\]

(3)

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

\[
q = (q_0, q_T, q_L) \quad q^2 = M^2 \quad y = \frac{1}{2} \ln \frac{q_0 + q_L}{q_0 - q_L} \quad s = (p_1 + p_2)^2.
\]

(4)

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

\[
e_q^2 \hat{\sigma}_0 = e_q^2 \frac{4\pi \alpha^2}{9M^2}.
\]

(5)

\(k_{\perp}\) and \(k_{1\perp}\) are the parton transverse momenta, while the parton longitudinal momentum fractions are given by

\[
x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}, \quad \text{so that} \quad x_F = \frac{2q_L}{\sqrt{s}} = x_1 - x_2 = \left(1 - \frac{2M^2}{sx_1}\right) = \left(\frac{M^2}{sx_2} - x_2\right), \quad y = \frac{1}{2} \ln \frac{x_1}{x_2} = \ln \frac{x_1\sqrt{s}}{M}.
\]

(6)

Eq. (3) holds in the kinematical region:

\[
q_T^2 \ll M^2 \quad k_{\perp} \simeq q_T.
\]

(7)

In the case in which one of the hadrons, say \(h_2\), is polarized, Eq. (3) simply modifies by replacing \(f_{q/h_2}(x_2, k_{1\perp})\) with \(\hat{f}_{q/h_2}(x_2, k_{1\perp})\) as given in Eq. (1). We then have the Sivers single transverse spin asymmetry:

\[
A_N = \frac{\frac{d\sigma_{h_1 h_2 \rightarrow \ell^+ \ell^-}}{dy dM^2 d^2 q_T} - \frac{d\sigma_{h_1 h_2' \rightarrow \ell^+ \ell^-}}{dy dM^2 d^2 q_T}}{\frac{d\sigma_{h_1 h_2' \rightarrow \ell^+ \ell^-}}{dy dM^2 d^2 q_T} + \frac{d\sigma_{h_1 h_2'' \rightarrow \ell^+ \ell^-}}{dy dM^2 d^2 q_T}} = \frac{\Delta f_{q/h_1}(x_1, k_{1\perp})}{2f_{q/h_1}(x_1, k_{1\perp})} \frac{d\sigma_{q\bar{q} \rightarrow V}(x_1, k_{1\perp})}{d\sigma_{\ell^+ \ell^-}}
\]

(8)

When the lepton pair production occurs via \(q \bar{q}\) annihilation into a vector meson \(V\) rather than a virtual photon \(\gamma^*\), Eqs. (3), (5) and (9) still hold, with the replacements [13]:

\[
16\pi^2\alpha^2 e_q^2 \rightarrow (g_q^V)^2 (g_{\ell^+}^V)^2 \quad \frac{1}{M^4} \rightarrow \frac{1}{(M^2 - M_V^2)^2 + M_V^4 \Gamma_V^2},
\]

(10)

where \(g_q^V\) and \(g_{\ell^+}^V\) are the \(V\) vector couplings to \(q \bar{q}\) and \(\ell^+ \ell^-\) respectively. \(\Gamma_V\) 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:

\[
A_N^V = \frac{\sum_q (g_q^V)^2 \int d^2 k_{1\perp} d^2 k_{2\perp} \delta^2(k_{1\perp} + k_{2\perp} - q_T) S \cdot \vec{p}_2 \times \vec{k}_{1\perp}) f_{q/h_1}(x_1, k_{1\perp}) \Delta f_{q/h_1}(x_2, k_{2\perp})}{2 \sum_q (g_q^V)^2 \int d^2 k_{1\perp} d^2 k_{2\perp} \delta^2(k_{1\perp} + k_{2\perp} - q_T) f_{q/h_1}(x_1, k_{1\perp}) f_{q/h_1}(x_2, k_{2\perp})}.
\]

(11)

We propose to use Eq. (11) for lepton pair production at COMPASS, \(\pi^+ p^+ \rightarrow \ell^+ \ell^- X\), at the \(J/\Psi\) peak, \(M^2 = M_J^2\). There are several reasons which make this channel very interesting and promising.

1) At COMPASS energy one has \(x_1 x_2 = M_J^2/M^2 \simeq 0.027\). Due to this relation both \(x_1\) and \(x_2\) must be greater than 0.027 and one of them must be greater than \(0.027 \simeq 0.16\). At small values of \(x_F\) or \(y\) one has approximately \(x_1 \simeq x_2 \approx 0.16\). It is then reasonable to expect that the main channel for the \(J/\Psi\) production is indeed \(q \bar{q}\) annihilation (rather than gluon fusion).

2) The COMPASS data which have been taken in 2015 and are being analysed refer to the \(\pi^- p^+ \rightarrow \ell^+ \ell^- X\) process at \(\sqrt{s} = 18.9\) GeV. Their interesting feature is that the dominant contribution to the asymmetry (11) is given by a \(\bar{u}\) quark from the \(\pi^-\) and a \(u\) quark from the proton, both of them valence quarks. All other contributions would always involve a sea quark and, in the central rapidity region, are strongly suppressed.
3) Other production mechanisms of $J/\Psi$ might contribute, like gluon fusion. However, while they might enhance the unipolar cross section, the denominator of $A_N^{V}$, it is very unlikely that they significantly affect the numerator of $A_N^{V}$; in fact the gluon Sivers function is expected to be small, if not zero \[19\]. Thus, such contributions might decrease the value of $A_N^{V}$, but they cannot alter the conclusion that it mainly originates from the valence quark Sivers functions.

Then we have, for central rapidity $\pi^- p^\dagger \to J/\Psi X \to \ell^+ \ell^- X$ processes:

$$A_N^{J/\Psi} (\pi^-; x_1, x_2, q_T) \simeq \frac{\int d^2k_{1\perp} d^2k_{1\perp} \varepsilon^2 (k_{1\perp} + k_{1\perp} - q_T) S \cdot (\hat{p}_2 \times \hat{k}_{1\perp}) f_{u/p} (x_1, k_{1\perp}) \Delta N^{f_{u/p}} (x_2, k_{1\perp})}{\int d^2k_{1\perp} d^2k_{1\perp} \varepsilon^2 (k_{1\perp} + k_{1\perp} - q_T) f_{u/p} (x_1, k_{1\perp}) f_{u/p} (x_2, k_{1\perp})}$$

(12)

and, for $\pi^+ p^\dagger \to J/\Psi X \to \ell^+ \ell^- X$ processes:

$$A_N^{J/\Psi} (\pi^+; x_1, x_2, q_T) \simeq \frac{\int d^2k_{1\perp} d^2k_{1\perp} \varepsilon^2 (k_{1\perp} + k_{1\perp} - q_T) S \cdot (\hat{p}_2 \times \hat{k}_{1\perp}) f_{\bar{d}/p} (x_1, k_{1\perp}) \Delta N^{f_{\bar{d}/p}} (x_2, k_{1\perp})}{\int d^2k_{1\perp} d^2k_{1\perp} \varepsilon^2 (k_{1\perp} + k_{1\perp} - q_T) f_{\bar{d}/p} (x_1, k_{1\perp}) f_{\bar{d}/p} (x_2, k_{1\perp})}.$$  

(13)

Notice that the variables $x_1$ and $x_2$ are related to each other and one can use only one of them or the variable $x_F$ or $y$, Eq. \[6\] with $M^2 = M_{J/\Psi}^2$.

Eqs. (12) and (13) can be further evaluated, adopting, as usual, a Gaussian factorized form both for the unpolarized distribution and the Sivers functions, as in Ref. \[9\]:

$$f_{q/p} (x, k_{\perp}) = f_q (x) \frac{1}{\pi (k_{\perp}^2)} e^{-k_{\perp}^2 / (k_{\perp}^2)}$$

(14)

$$\Delta N^{f_{q/p}} (x, k_{\perp}) = 2 N_q (x) h(k_{\perp}) f_{q/p} (x, k_{\perp})$$

(15)

$$h(k_{\perp}) = \sqrt{2e M_1} e^{-k_{\perp}^2 / M_1^2}.$$  

(16)

where the $f_q (x)$ are the unpolarized PDFs, $M_1$ is a parameter which allows the $k_{\perp}$ Gaussian dependence of the Sivers function to be different from that of the unpolarized TMDs and $N_q (x)$ is a function which parameterizes the factorized $x$ dependence of the Sivers function. In such a case the $k_{\perp}$ integrations can be performed analytically in Eqs. (12) and (13), obtaining:

$$A_N^{J/\Psi} (\pi^-; x_2, q_T) = \frac{\langle k_{\perp}^2 \rangle^2}{\langle k_{\perp}^2 \rangle + \langle k_{\perp}^2 \rangle} \exp \left[ - \frac{q_T^2}{2 \langle k_{\perp}^2 \rangle} \left( \frac{\langle k_{\perp}^2 \rangle}{\langle k_{\perp}^2 \rangle + \langle k_{\perp}^2 \rangle} \right) \right] \frac{\sqrt{2e q_T}}{M_1} \times 2 N_u (x_2) S \cdot (\hat{p}_2 \times \hat{q}_T)$$

(17)

$$A_N^{J/\Psi} (\pi^-; x_2, q_T) = \frac{\langle k_{\perp}^2 \rangle^2}{\langle k_{\perp}^2 \rangle + \langle k_{\perp}^2 \rangle} \exp \left[ - \frac{q_T^2}{2 \langle k_{\perp}^2 \rangle} \left( \frac{\langle k_{\perp}^2 \rangle}{\langle k_{\perp}^2 \rangle + \langle k_{\perp}^2 \rangle} \right) \right] \frac{\sqrt{2e q_T}}{M_1} \times 2 N_d (x_2) S \cdot (\hat{p}_2 \times \hat{q}_T)$$

(18)

and

$$A_N^{J/\Psi} (\pi^+; x_2, q_T) = \frac{\langle k_{\perp}^2 \rangle^2}{\langle k_{\perp}^2 \rangle + \langle k_{\perp}^2 \rangle} \exp \left[ - \frac{q_T^2}{2 \langle k_{\perp}^2 \rangle} \left( \frac{\langle k_{\perp}^2 \rangle}{\langle k_{\perp}^2 \rangle + \langle k_{\perp}^2 \rangle} \right) \right] \frac{\sqrt{2e q_T}}{M_1} \times 2 N_d (x_2) S \cdot (\hat{p}_2 \times \hat{q}_T)$$

(19)

$$A_N^{J/\Psi} (\pi^+; x_2, q_T) = \frac{M_1^2 \langle k_{\perp}^2 \rangle}{M_1^2 + \langle k_{\perp}^2 \rangle}.$$  

(20)

where

$$\langle k_{\perp}^2 \rangle = \frac{M_1^2 \langle k_{\perp}^2 \rangle}{M_1^2 + \langle k_{\perp}^2 \rangle}.$$  

(21)

$A_N^{J/\Psi} (\pi^+; x_2, q_T)$ is the amplitude of the azimuthal modulation in the angle defined by $\mathbf{S} \cdot (\mathbf{p}_2 \times \mathbf{q}_T)$. For example, taking the proton moving in the $-z$ direction and $\mathbf{S} \equiv \uparrow$ along $+y$, in the $\pi^- p$ c.m. frame, one has $\mathbf{S} \cdot (\mathbf{p}_2 \times \mathbf{q}_T) = -\cos \phi$, where $\phi$ is the azimuthal angle of the $J/\Psi$.

Measurements of $A_N^{J/\Psi} (\pi^-; x_2, q_T)$ and $A_N^{J/\Psi} (\pi^+; x_2, q_T)$ give a direct access, respectively, to $N_u (x_2)$ and $N_d (x_2)$, and the corresponding Sivers functions, Eq. (13). We conclude with an estimate of these two quantities based on the Sivers functions extracted from SIDIS data. All quantities necessary to compute $A_N^{J/\Psi} (\pi^-; x_2, q_T)$ and $A_N^{J/\Psi} (\pi^+; x_2, q_T)$ can be found in Ref. \[11\] (Eq. (40) and third column of Table III), taking into account only the valence quark contributions. As the Sivers effect is expected to be process dependent and contribute with different signs to asymmetries in D-Y and SIDIS processes, the Sivers functions of Ref. \[11\] are used here with an opposite sign.
FIG. 1: Plots of $A_N^{J/Ψ}(π^−; x_F, q_T)$ (left) and $A_N^{J/Ψ}(π^+; x_F, q_T)$ (right) versus $x_F$, for three different values of $q_T$. These estimates are obtained according to Eqs. (17)–(20) of the text, using the parameters of Ref. [11], with a sign change for the Sivers functions.

FIG. 2: Plots of $A_N^{J/Ψ}(π^−; x_F, q_T)$ (left) and $A_N^{J/Ψ}(π^+; x_F, q_T)$ (right) versus $q_T$, for two different values of $x_F$. These estimates are obtained according to Eqs. (17)–(20) of the text, using the parameters of Ref. [11], with a sign change for the Sivers functions.

In Fig. 1 we plot $A_N^{J/Ψ}(π^−; x_F, q_T)$ (left plot) and $A_N^{J/Ψ}(π^+; x_F, q_T)$ (right plot), for different values of $q_T$, as functions of $x_F$ in the expected kinematical region of the COMPASS experiment. Similarly, in Fig. 2 we plot the asymmetries, for different values of $x_F$, versus $q_T$.

In both cases the Sivers asymmetries are large, with a well defined sign, driven by the sign of the Sivers functions of the proton valence quarks, $u$ quark for $A_N^{J/Ψ}(π^−)$ and $d$ quark for $A_N^{J/Ψ}(π^+)$. We consider these large values as a definite indication of the sign of the Sivers functions. Taking into account the uncertainty bands of the Sivers functions in Ref. [11] would change the expected magnitudes of $A_N^{J/Ψ}(π^−)$ and $A_N^{J/Ψ}(π^+)$, but not their signs. Notice that, in order to obtain better statistics, one could gather data over the full range of $q_T$ for which Eq. (7) holds; then the asymmetries are given by Eqs. (12) and (13) with numerator and denominator integrated over $q_T$ from 0 to, say, 1 GeV/$c$.

In conclusion, we propose a simple measurement of the single transverse spin asymmetry $A_N$ in the channel $π^+ p \rightarrow J/Ψ X \rightarrow ℓ^+ ℓ^− X$, for which abundant data have been already collected by the COMPASS Collaboration. Due to the kinematical feature of the experiment, the asymmetry is mainly generated by the Sivers distribution of unpolarized valence quarks inside the polarized proton and its sign reveals the sign of the corresponding Sivers function. Thus, the longstanding debate about the opposite sign of the Sivers function in SIDIS and Drell-Yan processes can be unambiguously solved.

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