Transverse-Spin Drell-Yan Physics at RHIC

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Abstract

We describe the science case and opportunities for future dedicated studies on the single-transverse spin asymmetry in the Drell-Yan process at RHIC.

Authors

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1 Introduction

A fundamental property of Quantum Chromodynamics (QCD) is its asymptotic freedom at short distances. This is the regime where QCD has been subjected to the most stringent tests, and where in fact it has been established as our theory of the strong interactions. Thanks to asymptotic freedom, it is often possible to use QCD perturbation theory in treating the interactions of quarks and gluons that occur in high-energy hadronic processes. For many QCD observables at large momentum transfer, short-distance and long-distance phenomena may be separated to leading power in the momentum transfer. This is known as *factorization*. Hadronic cross sections become products of parton (quark and gluon) distribution functions and partonic hard-scattering cross sections. The former contain long-distance information on the structure of the proton, while the latter only depend on the large momentum transfer and are hence amenable to QCD perturbation theory. Measurements of the cross sections, when combined with perturbative calculations of the partonic hard-scattering cross sections, will therefore give insights into the structure of the proton. Usually, the parton distribution functions are universal, in the sense that for example the same parton distributions of a proton will appear in any hard-scattering process in which a proton participates. Much of what we know today about the inner structure of the nucleon is based on this approach, which is a cornerstone for the ongoing and future programs in high-energy nuclear and hadronic physics.

Over the past few years, theorists have studied a class of parton distribution functions that may be accessed in spin asymmetries for hard-scattering reactions involving a transversely polarized proton. These distributions, known as "Sivers functions" [**?**], express a correlation between a parton's transverse momentum inside the proton, and the proton spin vector. As such they contain information on orbital motion of partons in the proton. It was found that the Sivers functions are not universal in hard-scattering reactions. This by itself is nothing spectacular; however, closer theoretical studies have shown that the non-universality has a clear physical origin that may broadly be described as a rescattering of the struck parton in the color field of the remnant of the polarized proton [**?**, **?**, **?**, **?**, **?**]. Depending on the process, the associated color Lorentz forces will act in different ways on the parton. In deep-inelastic scattering (DIS), the final-state interaction between the struck parton and the nucleon remnant is attractive. In contrast, for the Drell-Yan process it becomes an initial-state interaction and is repulsive. As a result, the Sivers functions contribute with opposite signs to the single-spin asymmetries for these two processes [**?**, **?**, **?**, **?**]. This is a fundamental QCD prediction, directly rooted in the quantum nature of the interactions. It tests *all* concepts for analyzing hard-scattering reactions that we know of. Its verification is a milestone for the field of hadronic physics and is the motivation for this paper.

Sivers-type single-spin asymmetries have been observed in semi-inclusive DIS at HERMES [**?**] and COMPASS [**?**]. Equipped with the resulting information on the Sivers functions, it is now crucial to investigate the spin asymmetry in the Drell-Yan process. This has become a top priority for the world-wide hadronic physics community for the coming decade. The present paper will show that RHIC offers extremely favorable possibilities for studies of Drell-Yan transverse-spin asymmetries.

2 Physics Case

Studies of single-transverse spin asymmetries A_N actually have a long history, starting from the 1970s and 1980s when large "left-right" asymmetries were observed in hadronic reactions like $p^{\uparrow}p \to \pi X$ at forward angles of the produced pion [**?**]. It was known [**?**] that in such single-inclusive processes, A_N is suppressed by an inverse power of the pion's transverse momentum, so that simple parton-model estimates would predict nearly vanishing asymmetries. The large size of the observed asymmetries therefore posed a challenge for theorists. Among various possible explanations that were subsequently proposed and investigated, were correlations between the transverse momentum of a struck quark in the proton and the transverse proton spin, represented by novel parton distribution functions, the "Sivers functions" [**?**]. The spin asymmetries were suggested to arise from the directional preference expressed by this correlation. The Sivers functions thus extend the set of "ordinary" Feynman parton distributions which only depend on a parton's light-cone momentum fraction. While the precise role of the Sivers functions for hadronic hard processes and their factorization remained yet to be understood, it was clear that the functions would contain valuable information about the nucleon, because the correlations they represent would be closely related to orbital angular momenta of partons in the proton.

Significant theoretical progress on single-spin asymmetries and the Sivers functions has been made in recent years. A breakthrough was the realization [**?**, **?**, **?**] that there is a class of single-spin observables in QCD that are not suppressed by an inverse power of the hard scale. These asymmetries are characterized by a large momentum scale Q (for example, the virtuality of the photon in DIS) and by a much smaller, and also measured, transverse momentum $q_{\perp}$. This allows a direct probe of the partons' transverse momenta in the nucleon. For some observables, rigoros QCD factorization theorems have indeed been established [**?**, **?**, **?**] which relate the spin-dependent cross sections to parton distribution functions not integrated over the transverse momenta of the partons, among them the Sivers functions. This opened the door to clean experimental access to the Sivers functions. The "leading-twist" Sivers single-spin asymmetries emerging in this way have been studied experimentally over the past few years in DIS [**?**, **?**], and there are now quite solid indications that the Sivers effect indeed exists.

The theoretical studies have revealed an even more striking property of the Sivers functions [**?**, **?**, **?**, **?**]. Let us give a QED simple example of this that captures the essential physics. In Fig. **??**(a) we consider a "toy" DIS process. A transversely polarized charge-less "hadron", consisting of particles with electric charges $+1$ and -1, is probed by a highly virtual photon. In order not to be forced to vanish by time-reversal invariance, a single-spin asymmetry for the process requires the presence of an interaction phase. Such a phase may be generated by a rescattering of the struck "parton" in the field of the "hadron remnant", by exchange of a photon as shown in the figure. The amplitude with the additional exchanged photon interferes with that without the photon. As the electric charges of the two interacting particles are opposite, this final-state interaction is *attractive*.

Now consider a similar model for the Drell-Yan process in Fig. **??**(b). "Partons" of opposite charge annihilate to produce a highly virtual photon. The interaction generating the phase in this case is "initial-state" and is between the remnant of the transversely polarized "hadron" and the initial parton from the other, unpolarized, "hadron". These necessarily have opposite charges, and the interaction is *repulsive*. As a result, the spin-effect in this case needs to be of opposite

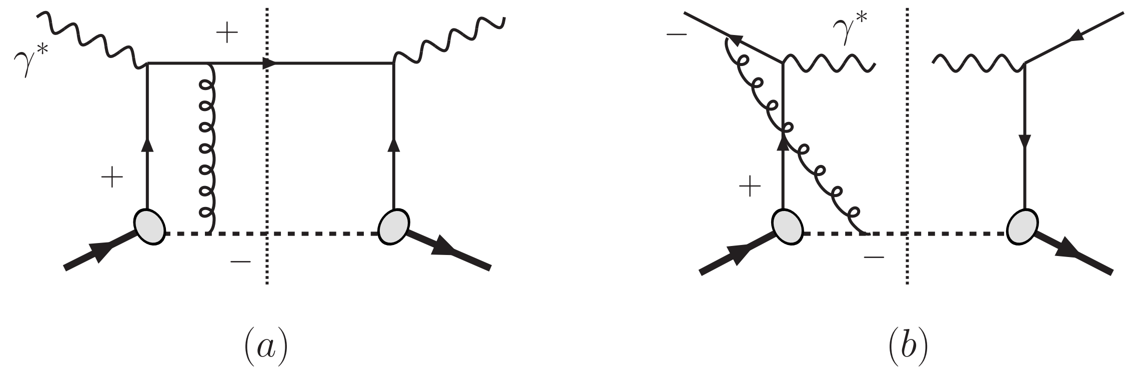

Figure 1: *Simple QED example for process-dependence of the Sivers functions.*

sign as that in DIS.

These simple models are readily generalized to true hadronic scattering in QCD. In DIS, the final-state interaction is through a gluon exchanged between the $\mathbf{3}$ and $\bar{\mathbf{3}}$ states of the struck quark and the nucleon remnant, which is attractive. In the Drell-Yan process, the interaction is between the $\mathbf{3}$ and $\mathbf{3}$ states (or $\bar{\mathbf{3}}$ and $\bar{\mathbf{3}}$) and therefore repulsive. This is the essence of the – by now famous – result that the Sivers functions contributing to DIS and to the Drell-Yan process have opposite sign [**?**, **?**, **?**, **?**]:

$$f^{\text{Sivers}}(x, k_\perp)\Big|_{\text{DY}} = -f^{\text{Sivers}}(x, k_\perp)\Big|_{\text{DIS}} . \tag{1}$$

In the full gauge theory, the phases generated by the additional (final-state or initial-state) interactions can be summed to all orders into a "gauge-link", which is a path-ordered exponential of the gluon field and makes the Sivers functions gauge-invariant. The non-universality of the Sivers functions is then reflected in a process-dependence of the space-time direction of the gauge-link. The process-dependence of the Sivers functions will also manifest itself in more complicated QCD hard-scattering, albeit in a more intricate way [**?**]. An example is the single-spin asymmetry in di-jet angular correlations [**?**, **?**, **?**], which is now under investigation at RHIC [**?**]. The verification of the predicted non-universality of the Sivers functions is an outstanding challenge in strong-interaction physics. It is most cleanly possible in the Drell-Yan process, which provides the motivation for this proposal.

We consider the single-transverse-spin asymmetry (SSA) for the Drell-Yan prcess in pp scattering at RHIC: $p(S_\perp) + p \to \gamma^* + X$, where the virtual photon decays into the lepton pair. The three momenta P_A, P_B and q form the so-called reaction plane, see Fig. **??**. After integrating out the lepton angles in the rest frame of the virtual photon, we obtain the following differential cross section for the Drell-Yan process:

$$\frac{d\sigma}{dM^2 dy d^2q_\perp} = \frac{4\alpha^2\pi}{3sM^2}\left[W_{UU}(x_1, x_2, M^2, q_\perp) + \sin\phi W_{TU}(x_1, x_2, M^2, q_\perp)\right] , \tag{2}$$

where M is the invariant mass of the lepton pair, $q_\perp$ the virtual photon's transverse momentum, and y its rapidity. ϕ is the azimuthal angle between the virtual photon and the transverse polarization vector in a frame where the polarized hadron is moving in the $+z$ direction as shown in Fig. **??**. At low transverse momentum, x_1 and x_2 are related to the mass and rapidity through $x_1 = M/\sqrt{s}\, e^y$ and $x_2 = M/\sqrt{s}\, e^{-y}$ where s is the hadronic center-of-mass energy squared. The hadronic tensors W_{UU} and W_{TU} depend on the unpolarized quark distribution and the quark

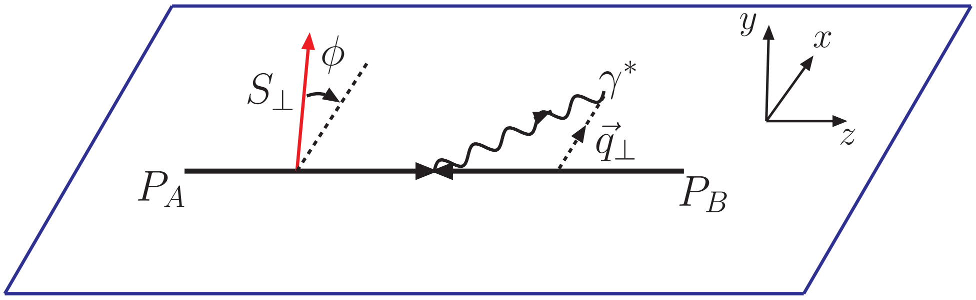

Figure 2: *Definition of momenta and angles for the Drell-Yan process.*

Sivers function, respectively. One interesting azimuthal asymmetry can be calculated from the above equation, by integrating over the transverse momentum of the virtual photon $|q_\perp|$ but keeping the azimuthal angle dependence of $\sin\phi$. This asymmetry depends on the "$1/2$-moment" of the Sivers function [**?**]:

$$f_T^{(1/2)}(x) = \int d^2k_\perp \frac{|\vec{k}_\perp|}{M} f^{\rm Sivers}(x, k_\perp) \quad (3)$$

(defined for each flavor). As we discussed above, the nontrivial universality property for the Sivers function allows us to predict the SSA for Drell-Yan process at RHIC by using the constraints from the SIDIS process studied by the HERMES and COMPASS collaborations. In Ref. [**?**], the valence quark Sivers functions were fitted to the HERMES data, and the following parameterizations were obtained:

$$u_T^{(1/2)}(x)|_{\rm DIS} = -0.75x(1-x)u(x), \quad d_T^{(1/2)}(x)|_{\rm DIS} = 2.76x(1-x)d(x)\ , \quad (4)$$

where $u(x), d(x)$ denote the unpolarized quark distributions. We notice that the $(1-x)$ suppression for the Sivers function relative to the unpolarized quark distribution is consistent with a power counting analysis for the quark distribution at large-x [**?**]. To predict the SSA for the Drell-Yan process, we will have to reverse the signs for the Sivers functions in (**??**). With these results, we show in Fig. **??** the prediction at RHIC as function of the pair rapidity. The asymmetry is found to be sizable over a wide range of rapidities.

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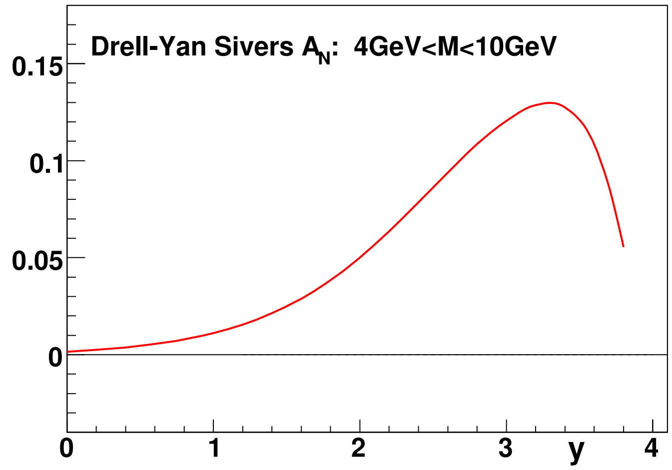

Figure 3: *Sivers asymmetry for the Drell-Yan process at RHIC, as functions of virtual-photon rapidity y.*

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