Internal-target polarized Drell-Yan Experiment at RHIC

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Abstract.
We present physics motivations and experimental considerations for an internal-target polarized Drell-Yan dimuon experiment at RHIC. Dimuons from the Drell-Yan process are detected using a spectrometer based on the existing Fermilab-E906/SeaQuest spectrometer. The primary goal of the proposed experiment is to extract the Sivers parton distribution function in the valence-quark region from the measurement of the single transverse-spin asymmetry. The sensitivity of the proposed internal-target experiment will provide a stringent test of the QCD prediction that the Sivers function in the Drell-Yan process has an opposite sign with respect to that in deep-inelastic scattering. Results of some initial studies of the expected sensitivity are shown.

1. Introduction
One of the most important topics in QCD physics is the spin structure of the nucleon. The composition of the nucleon’s spin remains unclear and continues to be a very active field of research at various facilities, including RHIC. The nucleon spin should be the sum of contributions from the quark/antiquark spins, the gluon spins, and the quark/gluon orbital angular momenta. In the last two decades, novel parton distributions involving the transverse spin and transverse momentum of quarks have been identified theoretically, and they just began to be determined quantitatively in recent experiments.

Although a large part of our current knowledge on the spin-averaged and spin-dependent parton distributions of the nucleon is acquired from lepton-induced inclusive deep-inelastic scattering (DIS) or semi-inclusive DIS reactions, complementary information can also be obtained from hadronic collisions. The single-spin asymmetries of the produced hadrons have been measured in the Fermilab fixed-target E704 experiment with transversely-polarized proton beams, and at much higher energies in the RHIC collider experiments. The double-spin asymmetries have been measured in longitudinally polarized pp collisions at RHIC. Unique information on the possible origins of the single transverse-spin asymmetry, as well as the gluon helicity distributions, have been obtained from these measurements.

The Drell-Yan process, in which a pair of charged leptons is produced in a quark-antiquark annihilation, is an ideal tool for probing parton distributions. The mechanism of the Drell-Yan process is well understood, and the absence of hadronization processes in the final state eliminates the uncertainties caused by the relatively poorly known fragmentation functions.
encountered in semi-inclusive DIS or in hadron production in \( pp \) collisions. The availability of polarized proton beams at RHIC is very significant, since unique information on polarized parton distributions could be obtained from polarized Drell-Yan experiments. However, high-statistics measurements of the Drell-Yan process are experimentally challenging due to the relatively small cross sections. Indeed, the present luminosity at RHIC for polarized \( pp \) collisions has not yet allowed a feasible experimental program to study the Drell-Yan process.

In this article, we discuss a new approach with a dedicated fixed-target Drell-Yan experiment at RHIC using an internal target [1]. As discussed later, the anticipated luminosity will be adequate for a sensitive single transverse-spin asymmetry measurement of the Drell-Yan process to test the remarkable prediction on the non-universality of the Sivers parton distribution function [2]. The proposed experimental approach will also allow for a rich program addressing many important issues in spin physics using singly or doubly polarized Drell-Yan processes.

2. TMD functions and polarized Drell-Yan processes

The primary goal of the proposed experiment is to extract the Sivers function from the measurement of single-spin asymmetries in the Drell-Yan process using 250 GeV transversely polarized proton beams impinging on a proton target. Table 1 shows the leading twist distribution functions of the nucleon, including the intrinsic transverse momentum dependent (TMD) functions, based on a perturbative QCD approach specifying the different spin states of the nucleon and the partons. The diagonal elements of the table (\( f_1 \), \( g_1 \), and \( h_1 \)) show leading-twist light-cone distribution functions which survive upon integration of transverse momenta. The distribution function \( h_1 \) is known as the transversity [3]. It is the remaining leading-order polarized distribution function of the nucleon, and shows the distribution of the transverse spins of partons inside a transversely-polarized nucleon.

| Unpolarized Nucleon | Unpolarized Parton | Longitudinally-Polarized Parton | Transversely-Polarized Parton |
|---------------------|--------------------|-------------------------------|------------------------------|
| Unpolarized Nucleon | \( f_1 \)          | \( g_1 \)                     | \( h_{1L} \)                 |
| Longitudinally-Polarized Nucleon | \( f_{1T} \) | \( g_{1T} \) | \( h_{1T} \) |
| Transversely-Polarized Nucleon | \( f_{1T} \) | \( g_{1T} \) | \( h_{1T} \) |

The other elements in Table 1 correspond to TMD distribution functions which would not survive upon integration of all observed transverse momenta. The distribution functions \( f_{1T} \) and \( h_{1T} \) are known as Sivers and Boer-Mulders functions which describe unpolarized partons in a transversely-polarized nucleon and transversely-polarized partons in an unpolarized nucleon, respectively. They vanish at tree-level in a T-reversal invariant model (T-odd), and can only be non-zero when initial or final state interactions cause an interference between different helicity states.

The Sivers asymmetry has been determined in semi-inclusive DIS in the HERMES [4] and COMPASS [5] experiments by decomposing the Sivers asymmetry and the Collins asymmetry (transversity with the Collins fragmentation function) using their different azimuthal angular dependencies. Both experiments have already measured a number of data points of the Sivers asymmetry in the momentum fraction region of \( 0.005 < x < 0.3 \) with error bars below the 1% level. The Sivers function has been obtained from a global fit of the Sivers asymmetry, measured at HERMES (proton target) and COMPASS (deuteron target), carried out by several theory groups [6, 7].
One important property of the Sivers function found in the theoretical studies is its “non-universality”. The Sivers function contributes with opposite sign to the transverse-spin asymmetries in the DIS process and the Drell-Yan process [8]:

\[ f_{\text{Sivers}}(x, k_{\perp})|_{\text{DY}} = - f_{\text{Sivers}}(x, k_{\perp})|_{\text{DIS}}. \]

This is a fundamental QCD prediction based on gauge invariance and its verification constitutes an important milestone for the field of hadron physics. It allows one to test non-perturbative aspects of QCD and the concept of factorization, including transverse-momentum dependence in the analysis of hard-scattering reactions.

It is now crucial to investigate the Sivers transverse-spin asymmetry in the Drell-Yan process in order to compare it with that from the DIS process and to test the “non-universality” of Eq.(1). This aspect has become one of the top priorities for the world-wide hadron physics community. In order to measure the asymmetry in the Drell-Yan process, we need to collect a significant amount of statistics to be comparable with the precision of the DIS data.

In the Drell-Yan process, the Sivers function is measured in single transverse-spin asymmetries where only one of the initial nucleons is transversely polarized. Similar to the case of DIS where the two single-spin asymmetries, Sivers and Collins, have to be disentangled, the same is true for the Drell-Yan process [9, 10]. However, these two asymmetries also can be separated using their different dependencies on the azimuthal angles of the lepton production plane (\( \phi \)) and the nucleon’s spin vector relative to the two hadron planes (\( \phi_S \)). Following [9], the Sivers asymmetry is proportional to a \( \sin(\phi - \phi_S) \) modulation, while transversity with the Boer-Mulders function is proportional to a \( \sin(\phi + \phi_S) \) modulation:

\[
\frac{d\sigma}{d\Omega d\phi_S dx_1 dx_2 d^2q_T} \propto \frac{\alpha^2}{12Q^2} \sum_q \hat{q}_q^2 \times \left\{ \ldots + (1 + \cos^2 \theta) \sin(\phi - \phi_S) \mathcal{F} \left[ \ldots f_q f_q^{\perp T} \right] \right. \\
+ \left. (\sin^2 \theta) \sin(\phi + \phi_S) \mathcal{F} \left[ \ldots h_1^{\perp T} h_1^{\perp} \right] \right\},
\]

where \( \mathcal{F}[\ldots] \) corresponds to the convolution integrals over functions of the corresponding transverse momenta, which were omitted here.

3. Proposed experimental approach

The experimental apparatus is similar to the one used in a series of experiment at Fermilab with extracted beams (E605, E772, E789, E866, and E906). The Fermilab-E906/SeaQuest spectrometer comprises a solid iron focusing dipole magnet containing the beam dump, followed by a large open aperture dipole for precise momentum determination. Multi-wire proportional and drift chambers between the first two magnets, as well as after the second dipole provide tracking information, supplemented by scintillation hodoscopes used primarily for fast triggering. A final large iron absorber instrumented with proportional tubes provides muon identification. We expect to use as many of the detector elements and electronic components as possible from the E906 experiment, which will become available after the completion of the experiment in 2013.

The IP2 area, where the BRAHMS experiment was located previously, is the candidate experimental site. It has an available space of ±7 m up and downstream of the nominal interaction point (or 14 m in total). We expect that the target position can be chosen anywhere in this space. There is about 1.7 m space from the floor to the beam pipe which may needs minor civil engineering work to fit the Fermilab-E906/SeaQuest detector, especially for the downstream large detectors.
We plan to have two phases of the beam-time request, parasitic beam time with collider experiments as a phase-1, and dedicated beam time as a phase-2. There are two possibilities for parasitic running of this experiment. Each presents different constraints.

In the first option, we request a beam intensity of \(2 \times 10^{11}\) per bunch, with 112 stored bunches this leads to a bunch repetition frequency at the target of \(\sim 10\) MHz, which corresponds to \(2 \times 10^{18}/s\). We will use a cluster-jet or a pellet target with a thickness of \(10^{15}\) atoms/cm\(^2\). The target thickness is about 50 times smaller than the RHIC CNI carbon target, and we hope that this is acceptable and qualifies as a parasitic experiment to be carried concurrently with the collider experiments. The luminosity corresponds to \(2 \times 10^{33}\) cm\(^{-2}\)s\(^{-1}\). We will be able to accumulate an integrated luminosity of \(10,000\) pb\(^{-1}\) during a period of \(5 \times 10^6\) seconds, approximately 8 weeks, or 3 years of 10-week beam time per year by considering efficiency and live time. One beam store continues for about 6 hours, and we will consume about 10% of the beam particles in each store by hadronic reactions in the target. The beam lifetime can be naively estimated to be about 15 hours, and is dominated by small-angle scattering.

The second option, which we call “beam dump mode”, is feasible if we can use an internal-target with a thickness of \(10^{17}\) atoms/cm\(^2\). In this case, we will request our beam time at the end of every store after the collider experiments have stopped taking data, and dump the beam which is not used by us. Assuming a beam intensity of \(10^{11}\) per bunch with 112 bunches, the luminosity given under these conditions is \(10^{35}\) cm\(^{-2}\)s\(^{-1}\). We expect to use about 20% of the beam particles by hadronic reactions in the target, which corresponds to 40 pb\(^{-1}\). Each data taking period will take about 1,000 seconds, depending on how fast the beam dumps. We request 250 stores to accumulate 10,000 pb\(^{-1}\).

After the parasitic runs in phase-1, we request dedicated beam time in phase-2. A beam intensity of \(2 \times 10^{11}\) per bunch with 168 stored bunches (as assumed at eRHIC) provides a bunch repetition frequency of \(\sim 15\) MHz, and corresponds to \(3 \times 10^{18}/s\). We will use a pellet target or a solid target with a thickness of \(10^{16}\) atoms/cm\(^2\). It corresponds to a luminosity of \(3 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\). We can accumulate 30,000 pb\(^{-1}\) luminosity during \(10^6\) seconds, approximately 2 weeks, or 8 weeks of beam time by considering efficiency and live time. We expect to consume about 10% of the stored beam particles by hadronic reactions during 30 minutes. Under these conditions, the beam lifetime can be estimated to be 1.5 hours, again dominated by small-angle scattering. Special short-interval operation will be necessary. Even higher luminosity may become possible with the “beam dump mode”, if target of \(10^{17}\) atoms/cm\(^2\) thickness would be available.

4. Experimental sensitivities

A fast Monte Carlo simulation with an experimental apparatus fitted in the IP2 area has been performed to evaluate the kinematic acceptance and yield of the experiment. The assumptions of the experimental components and detector elements are based on the Fermilab-E906/SeaQuest experiment apparatus, but the restriction of the length of the IP2 area in beam direction must be considered. The total length of the E906 apparatus is about 25 m, while the length of the IP2 area is about 14 m in beam direction. In order to accommodate the detector apparatus in this area, the length of the first dipole magnet is assumed to be 3.9 m with a momentum kick of 2.1 GeV/c; the first magnet of the E906 apparatus had a length of about 5 m and providing a momentum kick of 2.5 GeV/c. The second dipole magnet for the momentum analysis is assumed to have a length of 2.4 m with a momentum kick of 0.55 GeV/c. The geometrical momentum resolution of the spectrometer is \(6 \times 10^{-4} \times p\) (GeV/c).

Results of the fast Monte Carlo simulation with PYTHIA for the internal-target experiment at \(E_{\text{beam}} = 250\) GeV or \(\sqrt{s} = 22\) GeV have been performed. By assuming an integrated luminosity of 10,000 pb\(^{-1}\), we estimate that about 50,000 Drell-Yan events will be collected at the dimuon invariant mass region \(4.5 < M_{\mu^+\mu^-} < 8\) GeV.

Figure 1 shows the experimental coverage of \(x_1\) and \(x_2\), the momentum fractions of the
polarized proton beams and the target protons. The sensitive $x$ region of the Sivers function $f_{T1}^g(x)$ measurement is 0.2 - 0.5 which has an overlap with the measured region by the DIS experiments ($x < 0.3$), and the higher-$x$ region is covered with a better sensitivity.

By using a transversely-polarized beam, measurement of single-spin asymmetry:

$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R},$$

yields the Sivers function. Figure 2 shows the $A_N$ integrated over transverse momenta in the region $0 < q_T < 1$ GeV/c of the virtual photon and dimuon mass range $4.5 < M_{\mu^+\mu^-} < 8$ GeV calculated with the Sivers function [11, 12]. The expected statistical sensitivities are calculated for 10,000 pb$^{-1}$ in phase-1 and 40,000 pb$^{-1}$ in phase-1 + phase-2, assuming a beam polarization of 0.7. By these measurements, we will be able to study not only the sign of the Sivers function but also the shape of the function.

![Figure 1.](image1.png)  
**Figure 1.** Experimental coverage of $x_1$ and $x_2$, the momentum fraction of the polarized proton beams and the target protons.

![Figure 2.](image2.png)  
**Figure 2.** Drell-Yan $A_N$ integrated over $0 < q_T < 1$ GeV/c and $4.5 < M_{\mu^+\mu^-} < 8$ GeV. Indicated are the expected statistical sensitivities for 10,000 pb$^{-1}$ (red circles) and 40,000 pb$^{-1}$ (blue squares).

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