Opportunities with Polarized Hadron Beams

Wolfgang Lorenzon

*Randall Laboratory of Physics, University of Michigan, 450 Church Street,
Ann Arbor, Michigan 48109-1040, USA
lorenzonz@umich.edu*

Published 29 February 2016

Spin physics at future hadron facilities provide unique opportunities for the study of QCD well beyond those available at existing facilities. Opportunities with polarized protons in the Fermilab Main Injector are discussed that encompass polarized Drell-Yan scattering of unprecedented precision and also enable measurements of transversity, helicity and other transverse momentum dependent distributions. Forthcoming measurements at COMPASS-II that aim to test fundamental predictions of non-perturbative QCD, and complementary studies at RHIC-Spin that address, among others, open puzzles such as the sharing of the nucleon spin among its constituents are also discussed.

1. Introduction

Tremendous progress has been made over the past few years in understanding the structure and dynamics of the nucleon. Nevertheless, after decades of study, the origin of nucleon spin and the distributions of quarks and gluons in nuclei remain mysteries. Questions such as “how much do the quarks and gluons contribute to the nucleon spin?” and “is there significant orbital angular momentum?” are central in hadronic physics. Measurements performed in Deep Inelastic Scattering (DIS) have taught us that the contribution of the quarks to the nucleon spin, $\Delta\Sigma$ is about 30%. Although the Q^2 evolution in polarized DIS gives us information on the contribution of the gluons to the nucleon spin, Δg , it provides relatively weak constraints. A spin physics program such as STAR or PHENIX at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is therefore needed to map out $\Delta g(x)$. And indeed, 2009 RHIC measurements from PHENIX on π^0 production and from STAR on jet production in A_{LL} have provided the first significant non-zero results on $\Delta g(x)$. These results suggest that the gluons may contribute as much as 60% to the proton spin when $\Delta g(x, Q^2)$ is integrated in the x -range of 0.001 and 1, although with large uncertainties. Data from 2011 & 2012 on $W^\pm$ production from

This is an Open Access article published by World Scientific Publishing Company. It is distributed under the terms of the Creative Commons Attribution 3.0 (CC-BY) License. Further distribution of this work is permitted, provided the original work is properly cited.

STAR and PHENIX indicated a flavor asymmetry in the polarized light quark sea, $\Delta\bar{u} - \Delta\bar{d} > 0$, that is opposite to the flavor asymmetry in the unpolarized light quark sea, $\bar{u} - \bar{d} < 0$, as measured in Drell-Yan scattering at Fermilab.¹

In order to improve the current measurements, new instrumentation is needed in forward direction to push the data to higher rapidity, η , therefore pushing x_{beam} (x_{target}) to higher (lower) values. Extensive detector and spectrometer upgrades at STAR and PHENIX are planned over the next decade to enable low- x measurements of $\Delta g(x, Q^2)$ (as part of the longitudinal spin program) as well as *jet* and Drell-Yan measurements (as part of the transverse spin program). These upgrades are coordinated in such a way that they can lead to EIC detectors.

While the RHIC spin physics program is in full swing, the SeaQuest experiment at Fermilab is pursuing a high- x Drell-Yan program with the 120 GeV proton beam from the Main Injector to determine the light antiquark flavor distributions in the nucleon sea, and how they are modified in nuclei. Science data collection started in March 2014 and is expected to last until the summer of 2016. At that time the development of a high-luminosity facility for polarized Drell-Yan with polarized beam and/or polarized target using the SeaQuest spectrometer is planned. Two experiments have been approved so far. E-1027 will use a polarized beam on an unpolarized liquid H_2 target to perform a precise measurement of the Sivers function for valence quarks (*i.e.* Sivers sign change), and E-1039 will use an unpolarized beam on a polarized frozen NH_3 target to probe sea quark distributions.

The COMPASS-II experiment at CERN is however expected to take the first polarized Drell-Yan data. It is scheduled to start the science run in spring 2015, employing the 190 GeV π^- beam on a transversely polarized hydrogen target, with the aim to measure the sign change in the Sivers function.

2. The Missing Spin Program: Drell-Yan

As with semi-inclusive DIS (SIDIS) or deep-inelastic jet production, Drell-Yan is purely leptonic in one half of the hard-scattering diagram, which facilitates clean interpretation and enables the event-level determination of the parton kinematics. Unlike SIDIS, however, Drell-Yan does not suffer from QCD final state effects, is free from fragmentation functions, and provides clean access to sea quarks. Furthermore, it offers the unique possibility to test the transverse momentum-dependent distribution (TMD) formalism, *i.e.* the sign change of T-odd distribution functions.

2.1. The Sivers Sign Change

The measurement of polarized Drell-Yan interactions is a major milestone in the hadronic physics community, motivated by a fundamental prediction of QCD that postulates that a naïvely time-reversal-odd distribution function, such as the Sivers function, measured in Drell-Yan (or $W^\pm$ production) must have the opposite sign if measured in SIDIS. The Sivers function is a transverse-momentum dependent

distribution function that captures non-perturbative spin-orbit effects inside a polarized proton. The experimental verification of the sign change goes to the heart of the gauge formulation of QCD and would fundamentally test the factorization approach to the description of processes sensitive to transverse parton momenta (*i.e.* test the TMD formalism).

The HERMES² and COMPASS³ experiments have measured single transverse spin asymmetries to high precision, and global fits to the Sivers asymmetries have been performed.^{4,5} In order to make a meaningful comparison of sign and shape, comparable measurements are needed for single spin asymmetries in the Drell-Yan process. There are plans for a variety of experiments around the globe that aim to measure polarized Drell-Yan either with a polarized beam or a polarized target (see Table 1). But at present, only the COMPASS-II experiment is scheduled to run in the near future. COMPASS-II is scheduled to start taking π^- beam in May 2015 for 140 days and expects to measure the sign of the Sivers function in the same kinematics as SIDIS with a statistical precision δA_N of 0.014 (in a single x_f -bin centered at $x_f = 0.2$ assuming 2 years of data taking). A very high luminosity polarized Drell-Yan experiment is therefore needed to not only measure the sign, but also the magnitude and shape of the Sivers function with sub-percent precision.

Table 1. Planned polarized Drell-Yan experiments. For comparison, the unpolarized SeaQuest experiment at Fermilab is listed as well. Here, x_b and x_t are the parton momentum fractions in the beam and target, respectively. The relative figure of merit (rFOM) is the luminosity times beam or target polarization squared times the dilution factor squared, relative to E-1027.

experiment	particles	energy (GeV)	x_b or x_t	rFOM	timeline
COMPASS-II (CERN)	$\pi^- + p^\uparrow$	190 $\sqrt{s} = 17.4$	$x_t = 0.1 - 0.3$	1.1×10^{-3}	2015, 2018
PAX (GSI)	$p^\uparrow + \bar{p}$	collider $\sqrt{s} = 14$	$x_b = 0.1 - 0.9$	2.3×10^{-5}	>2020
PANDA (GSI)	$\bar{p} + p^\uparrow$	15 $\sqrt{s} = 5.5$	$x_t = 0.2 - 0.4$	1.1×10^{-4}	>2018
NICA (JINR)	$p^\uparrow + p$	collider $\sqrt{s} = 20$	$x_b = 0.1 - 0.8$	6.8×10^{-5}	>2018
PHENIX/STAR (RHIC)	$p^\uparrow + p^\uparrow$	collider $\sqrt{s} = 510$	$x_b = 0.05 - 0.1$	1.0×10^{-3}	>2018
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 - 0.5$ $x_b = 0.05 - 0.6$	4.0×10^{-4} 2.1×10^{-3}	>2021
SeaQuest (unpol.) (FNAL E-906)	$p + p$	120 $\sqrt{s} = 15$	$x_t = 0.1 - 0.45$ $x_b = 0.35 - 0.85$	--	2012-2016
pol tgt DY (FNAL E-1039)	$p + p^\uparrow$	120 $\sqrt{s} = 15$	$x_t = 0.1 - 0.45$	0.09	2017-2018
pol beam DY (FNAL E-1027)	$p^\uparrow + p$	120 $\sqrt{s} = 15$	$x_b = 0.35 - 0.85$	1	>2018

2.1.1. Opportunities at RHIC: $W^\pm$ production at STAR and PHENIX

Recent theoretical developments suggest⁶ that applying proper TMD Q^2 evolution may significantly suppress the Sivers asymmetries with increasing Q^2 . Effects in SIDIS measurements from HERMES and COMPASS are modest, since their Q^2 -ranges only cover $1.3 - 6 \text{ GeV}^2$ and $1.3 - 21 \text{ GeV}^2$, respectively. But predictions for $W^\pm$ boson asymmetries, at Q^2 values of roughly $6,400 \text{ GeV}^2$, are much more dramatic. While the W^- asymmetry can be quite large (*i.e.* of order 30%) if calculated in a naïve parton model without TMD Q^2 evolution,⁷ once QCD evolution is taken into account,⁸ the asymmetry is only about $2 - 3\%$, following a roughly $1/\sqrt{Q^{0.7}}$ suppression for the peak of the Sivers asymmetry as a function of Q^2 . This suppression is much stronger than any other known evolution effects, but needs input from data to constrain the non-perturbative portion in the evolution. The only place where Sivers asymmetries in $W^\pm$ production can currently be measured is RHIC. Plans exist for a 2% measurement in 2015 with the hope to measure the sign-change in the Sivers asymmetry in $W^\pm$ production. This may be possible if the Q^2 suppression is weaker than expected.

2.1.2. Opportunities at Fermilab: Polarized Beam Drell-Yan – E-1027

There is a great opportunity at Fermilab to set up a polarized Drell-Yan experiment at a relatively modest cost to conclusively perform this fundamental test of the gauge structure of QCD. The primary motivation for a polarized Drell-Yan program at the Fermilab Main Injector is the combination of very high luminosity and large coverage in parton momentum fraction x , and a spectrometer that is already set up, well-understood, and optimized for Drell-Yan. The SeaQuest spectrometer covers both the valence quark ($x_{\text{Beam}} = 0.35 - 0.85$) and the sea quark ($x_{\text{Target}} = 0.1 - 0.45$) regions. It therefore accommodates polarized Drell-Yan scattering with either a polarized beam or a polarized target. Although the Sivers function can be measured for both the valence quarks or the sea quarks, the SIDIS data from HERMES and COMPASS are much more constrained by valence quarks than by sea quarks. In fact, there are currently no transverse single spin asymmetry SIDIS data that are constrained by sea quarks. Thus, using a polarized beam promises to be a substantial advantage over a polarized target. Projections for the transverse single-spin asymmetry⁴ in Drell-Yan production for the E-1027 polarized beam experiment at Fermilab⁹ are shown in Fig. 1 assuming the same nominal running conditions as the present, unpolarized Drell-Yan program.

This demonstrates that the combination of high luminosity and large x -coverage makes Fermilab arguably the best place to measure single-spin asymmetries in polarized Drell-Yan scattering with high precision. It would allow a measurement of the sign, the magnitude, and the shape of the Sivers function with sufficient precision to verify this fundamental prediction of QCD conclusively.

Fig. 1. Projections for the Siverts asymmetry (red solid circles) for E-1027 at Fermilab as a function of x_f . The blue solid curve indicates a prediction for the Siverts asymmetry based on the SIDIS results of HERMES and COMPASS, and the yellow band represents the $\sqrt{20}$ -sigma error band. The experimental asymmetry A_N is related to the Siverts amplitude given in Table 2 by $A_N = \frac{2}{\pi} A_T^{\sin \phi_S}$.

2.1.3. Polarized proton polarization scheme

Initial studies of polarizing the Main Injector proton beam¹⁰ were based on the RHIC dual Siberian snake design; however, space constraints rendered this approach no longer feasible. Instead, within the space constraints of the Main Injector, a novel, compact solution was found that suggested that a single Siberian snake could be as efficient as a Siberian snake-pair to provide polarized proton beams to experiments resulting in substantial cost savings. The new approach would cost approximately \$10 M, including M&S, effort, overhead and 50% contingency (based on estimates from the initial dual snake design). This solution led to the Stage I approval by Fermilab in November 2012.

2.1.4. Opportunities at Fermilab: Polarized Target Drell-Yan – E-1039

Polarized fixed target Drell-Yan production has gained considerable attention in recent years due to its particular sensitivity to antiquarks and its close connection to orbital angular momentum (OAM) of sea quarks. If we are to resolve the proton spin puzzle in general and the quark OAM in particular, it is vital to make a Drell-Yan measurement of the Siverts function for sea quarks. Although the connection between the Siverts distribution and quark OAM is still model-dependent,^{5,11} it is clear that the existence of a non-zero Siverts function requires non-zero quark OAM.¹²

To enable these measurements, E-1039, which assumes Drell-Yan production on a polarized target at SeaQuest using the present unpolarized beam from the Main Injector, was approved by Fermilab in July 2013 to probe the sea quark Siverts asymmetry.¹³ Projections for the sea quark Siverts asymmetry as a function

Fig. 2. Projections for the Siverts asymmetry (red solid circles) for E-1039 at Fermilab as a function of x_f . The yellow band shows the prediction with uncertainties based on SIDIS data, while the green band shows the prediction with uncertainties based on a pion cloud model.

of x_f are shown in Fig. 2, assuming 2.8×10^{18} protons on target (POT) and an 88% target polarization. Existing SIDIS data poorly constrain⁴ the sea quark Siverts function, while a significant Siverts asymmetry is expected from a pion-cloud model.¹⁴ Measuring a non-zero Siverts asymmetry would be a significant discovery and present strong evidence for $L_{\bar{u}} \neq 0$.

E-1039 is scheduled to run for a 2-year period shortly after SeaQuest has finished data collection in 2016. It will determine the sign and value of the anti- u quark Siverts distribution function.

2.1.5. Opportunities at Fermilab: Double-Spin Drell-Yan

Having both a polarized beam and a polarized target would allow measurement of a variety of double-spin observables, such as transversity, helicity and other transverse momentum dependent distributions, thus opening up opportunities for a very rich, high-luminosity spin physics program at Fermilab complementary to that at RHIC and Jefferson Laboratory. Complementarity is emphasized by the fact that in SIDIS there is, at leading twist, one structure function per TMD, while in Drell-Yan, there are at least two structure functions per TMD.¹⁵ This means that the same TMDs can be measured in different structure functions, allowing to perform cross checks of the TMD extraction and even of the underlying formalism. A systematic study of quark TMDs in Drell-Yan requires double-polarization. Only in that case can all eight leading-twist TMDs be measured.^{15, 16}

3. Conclusions

There are many exiting opportunities with polarized hadron beams in the coming decade. COMPASS, RHIC, and Fermilab offer complementary probes and processes

to study the hadronic landscape, each with its particular strengths and weaknesses. COMPASS can access TMDs from SIDIS and Drell-Yan processes with an essentially identical apparatus, and will perform the first polarized Drell-Yan measurements. But COMPASS' secondary beam (*i.e.* π^- beam) cannot reach luminosities that are large enough to also measure the magnitude and shape of the Siverson asymmetry with sufficient precision. RHIC has the unique capability to measure $W^\pm$ production and therefore study TMD evolution in great detail, but since it is running in collider mode can also not reach high enough luminosities to perform high precision Drell-Yan measurements. The three orders of magnitude higher FOM afforded by a primary beam (*i.e.* polarized p beam) on a fixed target make Fermilab the best place to perform Drell-Yan studies with sufficient precision to verify this fundamental prediction of QCD conclusively. Only if we focus on the particular strengths of each facility can we hope to answer some of the burning questions: “how much do the quarks and gluons contribute to the nucleon spin?”, “is there significant orbital angular momentum?”, or “does the TMD formalism work? Does the Siverson function change sign?”.

Acknowledgments

The author wishes to thank Oleg Denisov, John Lajoie and Paul Reimer for helpful contributions and useful comments. This work was supported by the U.S. National Science Foundation under grant 1204942.

References

1. E866/NuSea Collab. (R.S. Towell *et al.*), *Phys. Rev. D* **64**, 052002 (2001).
2. HERMES Collab. (A. Airapetian *et al.*), *Phys. Rev. Lett.* **103**, 152002 (2009).
3. COMPASS Collab. (M. Alekseev *et al.*), *Phys. Lett. B* **673**, 127 (2009).
4. M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia, A. Prokudin and C. Turk, *Eur. J. Phys. C* **39**, 89 (2009).
5. A. Bacchetta and M. Radici, *Phys. Lett. B* **107**, 212001 (2011).
6. S.M. Aybat, A. Prokudin and T.C. Rogers, *Phys. Rev. Lett.* **108**, 242003 (2012).
7. Z.-B. Kang and J.-W. Qiu, *Phys. Rev. Lett.* **103**, 172001 (2009).
8. M. G. Echevarria, A. Idilbi, Z. B. Kang and I. Vitev, *Phys. Rev. D* **89**, 074013 (2014).
9. E-1027 Collab. (L.D. Isenhower *et al.*), (2012)
<http://lss.fnal.gov/archive/test-proposal/1000/fermilab-proposal-1027.pdf>.
10. Spin@Fermi Collab. (E.D. Courant, *et al.*), [arXiv:1110.3042 [physics.acc-ph]].
11. S.J. Brodsky D.S. Hwang, and I. Schmidt, *Nucl. Phys. B* **642**, 344 (2002).
12. D. Boer *et al.*, [arXiv:1108.1713 [nucl-th]].
13. E-1039 Collab. (D. Geesaman *et al.*), (2013)
<http://lss.fnal.gov/archive/test-proposal/1000/fermilab-proposal-1039.pdf>.
14. P. Sun and F. Yuan, *Phys. Rev. D* **88**, 034016 (2013).
15. S. Arnold, A. Metz and M. Schlegel, *Phys. Rev. D* **79**, 034005 (2009).
16. P.J. Mulder and R.D. Tangerman, *Nucl. Phys. B* **461**, 197 (1996).