Status and Prospects of the RHIC Spin Physics Program

January 29, 2007 (Draft)

Abstract

The following is meant to provide a summary describing the RHIC Spin program for the preparation of the 2007 Nuclear Physics Long Range Plan. This summary is based on a more extensive presentation in the 2005 Research Plan for Spin Physics at RHIC, available at

`http://spin.riken.bnl.gov/rsc/report/masterspin.pdf`

In addition to the material presented there, this summary includes new work based on the acceleration of polarized protons in RHIC in 2005 and 2006, theoretical work particularly on the developing area of the transverse spin structure of the proton, and new experimental results on both proton helicity and transverse spin structure.

Authors

Gerry Bunce and Werner Vogelsang (chairs), Alexander Bazilevsky, Les Bland, Abhay Deshpande, Wolfram Fischer, Matthias Grosse-Perdekamp, Ernst Sichtermann, Marco Stratmann, Bernd Surrow
(see also: authors of Research Plan for Spin Physics at RHIC [A1])

1 Summary

The key points for RHIC Spin are:

- Understanding the spin structure of the proton is a major goal of Nuclear Physics.
- Colliding polarized protons at RHIC probes the proton with strongly interacting probes, complementing DIS. RHIC spin is particularly sensitive to gluon, $\bar{u}$ and $\bar{d}$ polarization in the polarized proton.
- 60% average beam polarization and average luminosity $L = 2{\times}10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ were achieved in 2006, at $\sqrt{s} = 200$ GeV.
- Published results for unpolarized cross sections for π^0, jet, and direct-photon production are described well by next-to-leading order perturbative QCD. This is the basis for extracting the gluon and anti-quark polarizations from spin asymmetries.
- Published results for helicity asymmetries for π^0 and jet production rule out early theoretical predictions of a gluon contribution two or three times the proton spin. Sensitivity at the level of distinguishing between whether the gluons contribute 70% or little of the proton spin is expected from the 2006 data and future runs.
- Direct-photon measurements of the gluon polarization require running to collect 200 pb^{-1} integrated luminosity (through mid-2009 in the example schedule of 10 weeks/year in the Spin Plan [A1]), at $\sqrt{s} = 200$ GeV. This is to be followed with running at $\sqrt{s} = 500$ GeV to measure anti-quark polarization via parity violating production of W bosons, for 900 pb^{-1}, through 2012 in the Spin Plan.
- Very large single-spin asymmetries have been measured with transversely polarized protons producing $\pi^{0,\pm}$ in the kinematic region where perturbative QCD successfully describes the measured unpolarized cross sections.
- Theoretical advances have connected transverse single spin asymmetries with the orbital angular momentum of partons in the proton, although we emphasize that this is a work in progress. The issue is the extent to which the connection can be made quantitative.
- The RHIC Spin Plan,
`http://spin.riken.bnl.gov/rsc/report/masterspin.pdf`,
describes a robust initial program to explore the spin structure of the proton.

2 Introduction

Spin plays a central role in our theory of the strong interactions, *Quantum Chromodynamics* or QCD, and to understand spin phenomena in QCD will help to understand QCD itself. Nucleons, protons and neutrons, are built from quarks and the QCD force-carrier, gluons. *Unpolarized* deep inelastic scattering (DIS) experiments, scattering high energy electrons and muons from nucleons, first discovered quarks in the 1960s, and then over the next 30 years, DIS experiments exquisitely verified the QCD prediction for the energy dependence of the scattering. This was a triumph of QCD. *Polarized* deep inelastic scattering experiments then showed that the quarks and anti-quarks in the nucleon carry only a small fraction of the nucleon spin, a major surprise. Recent results set the fraction to be about 30%. The remaining $\sim 70\%$ must be carried by the gluon spin and by orbital angular momentum of the quarks and gluons in the nucleon. Experiments with polarized protons colliding at RHIC probe the proton spin in new profound ways that are complementary to DIS. A particular strength of the RHIC spin program is to measure the gluon contribution to the proton spin. A second emphasis will be a clean, elegant measurement of the quark and anti-quark polarizations, sorted by quark flavor, through parity-violating production of W bosons. RHIC is also probing the structure of transversely polarized protons, which may be related to the orbital angular momentum of the quarks and gluons in the proton. To contribute to the understanding of nucleon structure and the nature of confinement of the quarks and gluons inside the nucleons is a major goal of Nuclear Physics, and the primary objective of RHIC spin.

The key tool for for this work is polarized RHIC. We show in Fig. 1 the achieved luminosity, polarization and figure of merit ($\sqrt{LP^4}$) for our double-helicity asymmetry measurement of gluon polarization.

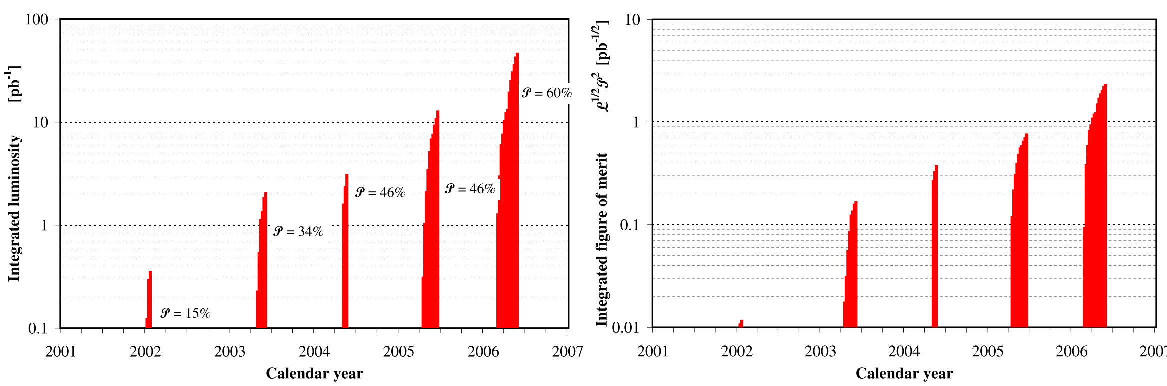


Figure 1: *Luminosity, polarization and figure of merit (*$\sqrt{LP^4}$*) for double-helicity asymmetry measurements at RHIC so far.*

3 Compelling questions in spin physics

The results from polarized inclusive DIS motivated a world-wide effort to further unravel the spin structure of the nucleon, primarily by addressing the question of how the proton's constituents carry the proton spin. There are various possibilities, related to average quark and anti-quark spins, gluon spins, and quark and gluon orbital angular momenta, as summarized by the proton spin sum rule [38,39,40]:

$$\frac{1}{2} = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle \; . \tag{1}$$

The gluon spin contribution is directly obtained from the gluon helicity distribution measurable in polarized high-energy scattering by integration over all momentum fractions:

$$\langle S_g \rangle (Q^2) = \int_0^1 \Delta g(x, Q^2) dx = \int_0^1 \left[g^+ - g^- \right] (x, Q^2) dx \; , \tag{2}$$

where g^+ (g^-) denotes the number density of gluons with the same (opposite) sign of helicity as the proton's. We have explicitly written out the dependence on the "resolution" scale Q. The most compelling current questions of QCD spin physics addressed at RHIC are:

How do gluons contribute to the proton spin? The integral of Δg could well be a major contributor to the proton spin. Section 5 will discuss in detail the first results from RHIC on observables sensitive to Δg, and the future prospects. It is worth pointing out that early theoretical predictions of a gluon contribution twice or three times as large as the proton spin are now being ruled out by the RHIC data [A2, A3] and by data from lepton-nucleon scattering at HERMES [A4] and COMPASS [A5].

What is the flavor structure of the polarized sea in the nucleon? In order to understand the proton helicity structure in detail, one needs to learn about the quark and anti-quark densities, $\Delta u, \Delta \bar{u}$, $\Delta d, \Delta \bar{d}, \Delta s, \Delta \bar{s}$, *individually*. This is also important for models of nucleon structure which generally make clear qualitative predictions about, for example, the flavor asymmetry $\Delta \bar{u} - \Delta \bar{d}$ in the proton sea [43,44]. These predictions are often related to fundamental concepts such as the Pauli principle and are all the more interesting due to the fact that rather large *unpolarized* asymmetries $\bar{u} - \bar{d} \neq 0$ have been observed in DIS and Drell-Yan measurements [45,46,47]. Further fundamental questions concern the strange quark polarization. The polarized inclusive-DIS measurements point to a sizable negative polarization of strange quarks. Dedicated measurements of strange quark polarization in semi-inclusive DIS have so far not been sufficiently sensitive. In Section 6 we briefly summarize the possibilities RHIC will offer for disentangling the various flavor polarizations in the nucleon.

What are the origins of transverse-spin phenomena in QCD? It has been known for a long time that very interesting QCD spin effects are associated with scattering of transversely polarized protons. Very large single-transverse spin asymmetries in fixed-target pp scattering were observed [29,30, 31], where none had been expected. The last few years have seen a renaissance in both theory and the experimental studies of single-spin asymmetries. They were investigated in semi-inclusive hadron production $eN^\uparrow \to e\pi X$ in deep-inelastic scattering [A6], and for proton targets remarkably large asymmetries were found also here. RHIC has opened new possibilities for extending the studies of single-spin asymmetries in hadronic scattering into a regime where, unlike the fixed-target case, the use of perturbative QCD in the analysis of the data is justified. The STAR [A7], PHENIX [A8] and BRAHMS [A9] collaborations have presented data for single-inclusive hadron production, to be discussed in Sec. 7. Large single-spin effects at forward rapidities persist to RHIC energies, a finding that has been a milestone for this field. The value of single-spin asymmetries lies in what they may tell us about QCD and the structure of the proton. They probe parton orbital angular momenta and spatial distribution [56,117,A10,A11], transverse polarization of partons, known as “transversity” [51,52], correlations of quarks and gluons inside the nucleon [57], and also the color Lorentz forces exerted by the nucleon remnant on a a struck parton [A12].

4 High-energy pp scattering as a probe of nucleon structure

At RHIC, beams of spin-polarized protons are collided. One primarily looks for relatively rare inelastic events, in which a final state is produced at very large transverse momentum or with large invariant mass, implying an underlying short-distance interaction. For the theoretical description of such processes, there are often very powerful QCD factorization theorems [24] that state that the corresponding cross sections are essentially products of separate long-distance and short-distance contributions. The long-distance pieces contain information on the structure of the nucleon in terms of its distributions of constituents, “partons”. The short-distance parts describe the hard interactions of these partons and can be calculated from first principles in QCD perturbation theory. While the parton distributions describe universal properties of the nucleon, that is, are the same in each reaction, the short-distance parts carry the process-dependence and have to be calculated for each reaction considered. The idea at RHIC is therefore to learn about nucleon spin structure by extracting the universal parton distribution from experimental measurements, using precise theoretical calculations of the short-distance parts.

As an explicit example, we consider a reaction that has been of great importance for the RHIC program so far, $pp \to \pi(p_T)X$. The pion is assumed to be at large transverse momentum p_T, and X denotes an arbitrary hadronic final state. Schematically, the factorized cross sections then is:

$$d\sigma \;=\; \sum_{a,b,c} f_a \,\otimes\, f_b \,\otimes\, D_c^{\pi} \,\otimes\, \left[d\hat{\sigma}_{ab}^{c,(0)} + \frac{\alpha_s}{\pi} d\hat{\sigma}_{ab}^{c,(1)} + \ldots \right] \,, \tag{3}$$

where the sum is over all contributing partonic channels $a + b \to c + X$, with $d\hat{\sigma}_{ab}^{c}$ the associated partonic cross section written as a perturbative series. The $f_{a,b}$ are the parton distributions, and the D_c^{π} denote the parton-to-pion fragmentation functions D_c^{π}. The symbols $\otimes$ denote appropriate convolutions in the partons’ momentum fractions. Corrections to Eq. (3) as such are suppressed by inverse powers of p_T.

The measured quantities in spin physics experiments at RHIC are *spin asymmetries*. For collisions of longitudinally polarized proton beams, one for example defines a double-spin asymmetry for a given process by

$$A_{LL} = \frac{d\sigma(++) - d\sigma(+-)}{d\sigma(++) + d\sigma(+-)} \equiv \frac{d\Delta\sigma}{d\sigma} \,, \tag{4}$$

where the signs indicate the helicities of the incident protons. The basic concepts laid out above carry over to the case of polarized collisions as well: spin-dependent inelastic pp cross sections factorize into “products” of polarized parton distribution functions of the proton and hard-scattering cross sections describing spin-dependent interactions of partons. As in the unpolarized case, the latter are calculable in QCD perturbation theory since they are characterized by large momentum transfer. Schematically, one has for the numerator of the spin asymmetry in

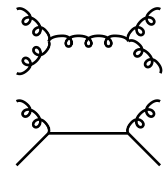
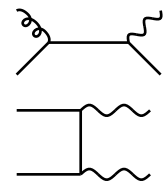
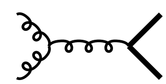
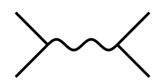
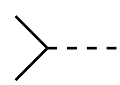
Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$ [61,62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \mathrm{jet(s)} + X$ $[71, 72,$A13$]$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \mathrm{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$ $[67, 73, 74, 75, 76]$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$ $[77]$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan) $[78, 79, 80]$	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$ $[78]$	$\vec{q}\vec{\bar{q}} \to Z^0,\ \vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm, q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	

Table 1: *Key processes at RHIC for the determination of the parton distributions of the longitudinally polarized proton, along with the dominant contributing subprocesses, the parton distribution predominantly probed, and representative leading-order Feynman diagrams. The references given in the left column are for the corresponding next-to-leading order calculations.*

$pp \to \pi(p_T)X$:

$$d\Delta\sigma \;=\; \sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes D_c^\pi \otimes \left[d\Delta\hat{\sigma}_{ab}^{c,(0)} + \frac{\alpha_s}{\pi} d\Delta\hat{\sigma}_{ab}^{c,(1)} + \ldots \right] , \tag{5}$$

where the parton distribution functions and partonic short-distance cross sections are now spin-dependent. Measurement of spin asymmetries will therefore give direct information on the spin-dependent parton distributions, among them for example Δg.

Knowledge of higher-order corrections in the perturbative expansion of the partonic cross sections is generally important, because in hadronic scattering these are often sizable, and because they also reduce the dependence of the cross section on the choice of the factorization/renormalization scale. The $d\hat{\sigma}_{ab}^{c,(0)}$ $[d\hat{\sigma}_{ab}^{c,(1)}]$ (or their spin-dependent counterparts) in Eqs. (3) and (5) are known as the leading-order (LO) ["next-to-leading order" (NLO)] contributions to the partonic cross sections. For essentially all reactions relevant at RHIC, the NLO corrections are available, also for the spin-dependent case. The key processes, some of which will be discussed in detail in the following, are listed in Table 1, where we also give the dominant underlying partonic reactions and the aspect of nucleon spin structure they probe. We give reference to the corresponding NLO calculations in the first column of Table 1. For each of the processes in Table 1 the parton densities enter with different weights, so that each has its own role in helping to determine the polarized parton distributions. Some will allow a clean determination of gluon polarizations, others are more sensitive to quarks and anti-quarks. Eventually, when data from RHIC will become available for most or all processes, a "global" analysis of the data, along with information from lepton scattering, will be performed which then determines the $\Delta q, \Delta \bar{q}, \Delta g$. Efforts toward global analyses are now underway [86,A14].

In the spin-averaged case, the parton distribution functions are known with rather good accuracy. This has allowed quantitative tests at RHIC itself of the theoretical NLO framework that we have just outlined. A remarkable agreement between experimental data for a variety of processes at RHIC and the theoretical predictions was found, within the uncertainties. This is shown by Fig. 2 which presents comparisons of data from PHENIX and STAR for mid-rapidity π^0 [59] and jet [A15], forward π^0 [A16], and mid-rapidity direct-photon [A17] production with NLO calculations [61,62,63,67,68,A13]. It provides the basis for extending this type of analysis to polarized reactions. In addition, each of the cross sections just shown are strongly dominated by partonic scatterings with initial gluons [A1], which makes them very promising probes of gluon polarization in the spin-dependent case.

5 The gluon contribution to the proton spin

The PHENIX and STAR experiments have made considerable progress since the Spin Plan [A1] was written on measurements that will lead to understanding the contribution of gluons to the spin of the proton. As presented in Table 1, several probes are used at RHIC for determining the gluon polarization, and each has been computed in perturbative QCD (pQCD) at NLO. Furthermore, cross section measurements at RHIC are well described by pQCD for each of the gluon probes, as presented in Fig. 2. This establishes a solid theoretical foundation for the interpretation of spin asymmetries measured at RHIC. Here we will present recent spin measurements by PHENIX and STAR, and discuss the approach to a robust understanding of the gluon polarization in the proton.

The upper part of Figure 3 shows measurements of the double-beam-helicity asymmetry A_{LL} for production of pions and jets at mid-rapidity, presented to the Spin2006 conference at Kyoto [A2, A3], which update earlier, published results [A15, A18]. The upper left panel shows the π^0 asymmetry for $\sqrt{s}$=200 GeV versus p_T, from the RHIC 2005 and 2006 data runs, from the PHENIX experiment. The 2006 results presented here include only higher p_T data that were selected for fast analysis. The upper right panel of Figure 3 shows the inclusive-jet A_{LL} from STAR obtained for runs through 2005. The systematic uncertainty for the raw asymmetry measurements is $< 10^{-3}$ for each measurement. The systematic scale uncertainty for the polarization normalization for these and future measurements, shown as 40%, is expected to be reduced to ≈10% from the polarized jet polarimeter calibration, as discussed in Section 10.

The curves shown in Fig. 3 represent the resulting A_{LL} values calculated for a range of gluon polarization models [2], from a suggested very large positive gluon polarization, "GRSV-max", with an integrated gluon contribution to the proton spin, see Eqs. (1) and (2), of $\langle S_g \rangle = 1.9$ at scale $Q = 1$ GeV, to "maximally" negative gluon polarization, "$\Delta g = -g$", where

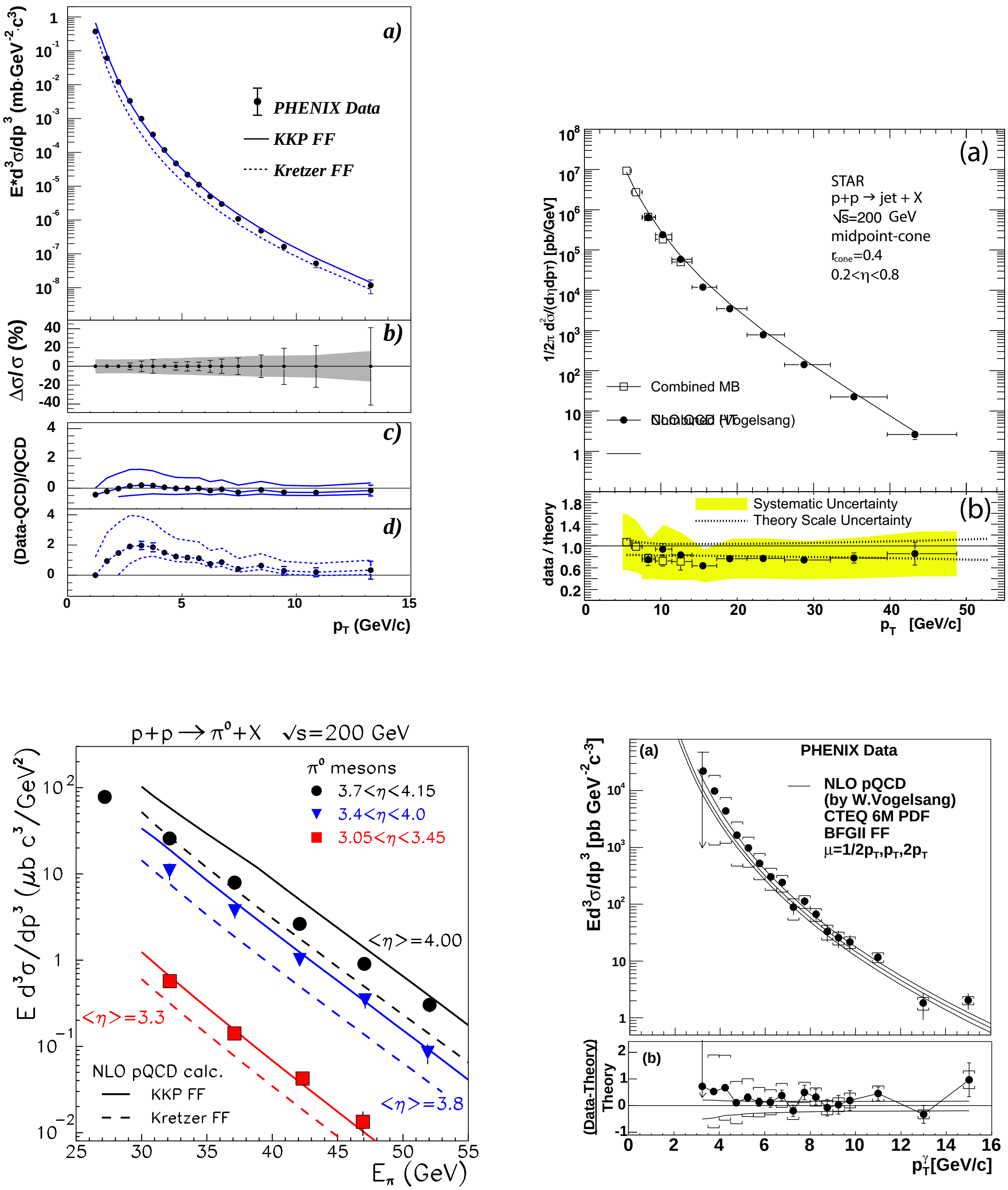


Figure 2: *Data for the cross section for single-inclusive π^0 production $pp \to \pi^0 X$ at $\sqrt{s} = 200$ GeV at mid-rapidity from PHENIX (upper left, [59]) and at forward rapidities from STAR (lower left, [A16]), for mid-rapidity jet production from STAR (upper right, [A15]), and for mid-rapidity prompt-photon production from PHENIX (lower right, [A17]). The lines show the results of the corresponding next-to-leading order calculations [61,62,63,67,68,A13].*

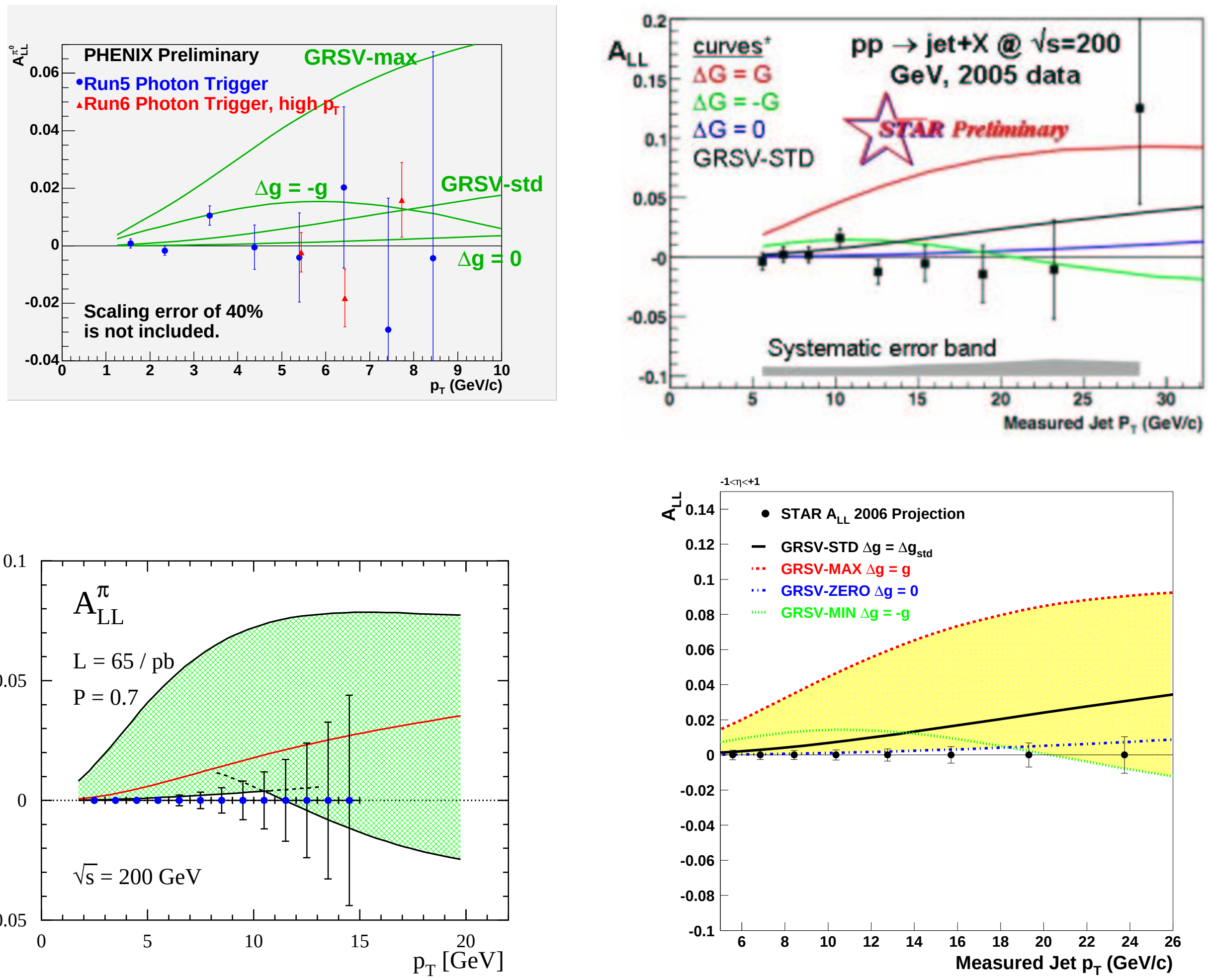


Figure 3: *Data for the double-spin asymmetry for mid-rapidity single-inclusive π^0 production at $\sqrt{s} = 200$ GeV from PHENIX in runs 5 and 6 (upper left, [A2]) and for jet production from STAR in run 5 (upper right, [A3]). The lower figures show sensitivities for these measurements for PHENIX with 65 pb^{-1} luminosity (left), and for STAR from the 2006 run (right).*

$\langle S_g\rangle(1\,\mathrm{GeV}^2) = -1.8$. Curves labeled "$\Delta g = 0$" correspond to very little gluon polarization, $\langle S_g\rangle(1\,\mathrm{GeV}^2) = 0.1$, and results for "GRSV-std" represent the best fit to deep inelastic scattering (DIS) data [2], with $\langle S_g\rangle(1\,\mathrm{GeV}^2)$ of about 0.4. In each case the input gluon polarization vs. gluon momentum fraction x_g is specified at a resolution scale of Q^2=0.4 GeV^2, and then evolved to a scale $Q = \mathcal{O}(p_T)$ relevant for comparison with data. It should be mentioned that the study in [2] is only limited to gluon polarizations without nodes, i.e., without a change of sign at some x_g. All calculations of A_{LL} shown in Fig. 3 use NLO pQCD, cf. Eqs. (3) and (5), and the unpolarized parton distributions and fragmentation functions, are taken from [58,64].

Other important results related to gluon polarization were reported at the Spin2006 conference by both PHENIX and STAR [A2, A3]: an analysis of A_{LL} for π^0 based on RHIC run-5 data taken at pseudo-rapidity intervals $0.2 \leq \eta \leq 0.8$ (using the STAR BEMC) and $1.086 \leq \eta \leq 2$ (using the STAR EEMC – an important baseline measurement for future prompt photon measurements at STAR); first results for A_{LL} for charged pions from PHENIX and STAR; an A_{LL} measurement for π^0's at mid-rapidity from a few days of data taking at $\sqrt{s} = 62\,\mathrm{GeV}$ during RHIC run-6, and $A_{LL}(\eta^0)$ at $\sqrt{s} = 200$ GeV, both from PHENIX.

RHIC data, for each of the channels studied so far, rule out a very large gluon polarization, with either positive or (to a lesser extent) negative gluon polarization. A large positive gluon polarization was suggested when the DIS experiments first discovered that the quarks (and anti-quarks) carry only very little of the proton spin. A large positive gluon polarization could mask a ”bare” quark polarization [41]. However, at this point we cannot distinguish between the gluon carrying 70% of the proton spin or carrying none of the proton spin, or determine the sign of the gluon polarization. The lower panels of Figures 3 show that RHIC will soon be able to address this central question to the proton spin puzzle. (Note that the luminosity shown for PHENIX, 65/pb, corresponds to expected recorded luminosity within the vertex acceptance of the experiment for the delivered luminosity of 275/pb indicated in Fig. 8.)

Our goal is to measure the gluon polarization versus the gluon momentum fraction in the proton, x_g. The single-inclusive measurements shown in Fig. 3 have the great virtue of large cross sections and significant sensitivity to the gluon polarization through their subprocesses (Table 1). However, these measurements do not provide an x_g distribution directly. One major complication is that at lower p_T and mid-rapidity, gluon-gluon scattering is most important, and for this subprocess the asymmetry A_{LL} is roughly “quadratic” in the gluon density. This explains why the curves in Fig. 3 assuming a large and negative gluon polarization yield a positive A_{LL} at lower p_T and only turn negative at higher p_T when quark-gluon scattering becomes more important. These probes cannot distinguish well the sign of the gluon polarization unless one accesses transverse momenta in excess of about $10\,\mathrm{GeV}$ or measures at forward rapidities.

The other major complication is common to all probes and relates to the question of how to extract information about gluon polarization, or parton distributions in general, from experimental data. For a given data point in p_T the gluon polarization is probed in a significant range in x_g as expressed by the convolutions inherent to the theoretical description of hard scattering cross sections, see Eqs. (3) and (5). Therefore each measured A_{LL} point versus p_T has significant overlap with its neighbors in x_g. It is straightforward to use a model for $\Delta g(x_g)$ to predict $A_{LL}(p_T)$. However, we cannot directly go the other way, to map the points in p_T onto gluon polarization values versus x_g. This is also the situation for semi-inclusive DIS measurements of the gluon polarization. In addition, each probe covers only a limited range in x_g, so that in order to arrive at an integrated gluon contribution to the proton spin, one must assume a certain behavior of the gluon polarization in the unmeasured regions in x_g. The goal must be to push measurements to the smallest possible x_g to reduce extrapolation uncertainties to a minimum.

We will now discuss our approach to deal with each of these complications and to arrive at a robust understanding of the gluon polarization in the proton:

(1) Direct-photon production is dominated by the gluon-Compton contribution, $q\,g \to \gamma\,q$. Its spin asymmetry is therefore linear in gluon polarization. Further, due to the electromagnetic vertex for the photon, the quark polarization contribution enters A_{LL} weighted by the quark charge squared and, to lowest order, is directly related to the already measured DIS asymmetry A_1^p, which is large at large quark momentum fraction x_q. Therefore, a direct-photon measurement directly measures the sign and size of the gluon polarization with excellent sensitivity. However, the figure of merit is low due to the small cross section. As shown in the Spin Plan [A1], the expected sensitivity for the gluon polarization from direct-photon production distinguishes the sign of the gluon polarization, for the curves shown in Fig. 3.

(2) An important part of the RHIC spin program, a feature of the large aperture STAR experiment and part of the PHENIX upgrade plan with vertex and nose cone calorimeter detectors, will be two-particle, jet-jet (or hadron-hadron) and photon-jet correlations. At leading order approximation, the hard-scattering subprocess kinematics can be calculated directly for these correlations on an event-by-event basis, giving an estimate of x_g for each measurement. This idea is presented in the Spin Plan [A1]. Theoretical work is in progress that will provide all relevant cross sections and spin asymmetries to next-to-leading order accuracy, so that spin asymmetries for two-particle correlations will provide results on gluon polarization at much better constrained values of x_g than all single-inclusive measurement done so far.

(3) As mentioned before, it is important to measure the gluon polarization over the widest possible range in x_g, in order to reduce the uncertainty to the gluon contribution to the proton spin from unmeasured regions. The RHIC program will use three approaches to extend gluon polarization measurements to lower x_g. The first is to collide at higher energy, $\sqrt{s}$=500 GeV, the energy that is planned for 2009-12 to measure the parity-violation for W boson production (Section 6). Running at 500 GeV extends the x_g range to lower values by the factor 2.5 for fixed minimum p_T, compared to 200 GeV running. The second approach is to measure A_{LL} for heavy quark production, using the vertex detectors being built (Section 8). The heavy quark mass sets the hard scale so that pQCD applies, and heavy-quark production at lower p_T is mainly described by gluon-gluon fusion (Table 1). These measurements will then access lower x_g. However, like for other single-particle inclusive processes, no information about the sign of the gluon polarization can be obtained from measurements at small p_T. The photon-jet (or photon-pion) two-particle correlation at large rapidity is dominated by quark-gluon scattering. These measurements, using existing and new forward electromagnetic calorimeters that will be in place for 2007 for both STAR and PHENIX, offer access to low x_g and large x_q, with large subprocess analyzing power. The process has a large quark polarization due to the large x_q. Indeed, STAR will have electromagnetic calorimeter coverage from η from $+4$ to -1, including the new FMS (Section 8) and the existing end cap and barrel calorimeters.

(4) Finally, the determination of the gluon polarization requires consideration of all existing data through a "global analysis" by making use of results from all probes, from RHIC and from DIS. Examples of early work on this are [86,A14]. An important advantage of a global analysis is to consider each measurement directly in its experimental variables, rather than attempting to use derived or unmeasurable variables such as x_g. Also, the global analysis can be consistently carried out at next-to-leading order accuracy.

To summarize, we anticipate measurements of the gluon polarization using many probes at RHIC, and also with two collision energies, and that these measurements will, together, produce a robust understanding of the gluon contribution to the proton's spin.

6 W physics

We intend to use the parity-violating production of W bosons to measure the anti-quark and quark polarizations identified by flavor. This will be a clean, elegant, direct measurement which is a central focus of the RHIC Spin program. This program requires $\sqrt{s} = 500$ GeV. W-bosons are identified as high p_T leptons, typically requiring $p_T > 20$ GeV/c. They are produced at

RHIC with both beams longitudinally polarized. Single-helicity parity violating asymmetries are obtained for each polarized beam by summing over the spins of the other beam:

$$A_L = \frac{1}{P} \times \frac{(N/L)_- - (N/L)_+}{(N/L)_- + (N/L)_+} \tag{6}$$

with P the measured polarization of the polarized beam, and $(N/L)_-$ the number of observed W bosons, normalized by the relative luminosity, for collisions with beam helicity $-$.

Drell-Yan production of, for example W^+, $\vec{p} + p \to u + \bar{d} \to W^+ \to l^+ + \nu$, can be considered for three kinematic regions: W produced forward, central, and backward from the polarized beam. Forward W^+ production is dominated by a contribution with the u-quark from the polarized proton, and the $\bar{d}$ anti-quark from the unpolarized proton, due to the much larger quark density vs. anti-quark density at large momentum fraction. In this case, $A_L(\text{forward } W^+) \approx \Delta u/u$. That is, the parity violation signal, due to the maximal violation of parity in the production of the W, directly measures the u-quark polarization at that momentum fraction in the polarized proton. Similarly, $A_L(\text{backward } W^+) \approx \Delta\bar{d}/\bar{d}$. For centrally produced W, the parity violating asymmetry combines contributions from both the u and $\bar{d}$ polarizations, as discussed in the Spin Plan [A1]. Our expected sensitivity is indicated in Fig. 4 (Fig. 23 of the Spin Plan [A1]), and the PHENIX muon data sensitivity is shown; STAR electron data will be similarly very sensitive to the quark and anti-quark polarizations.

There are several complications, however. The rapidity of the W is not directly measured, but rather the rapidity of the lepton. This is addressed by the program RHICBOS [96]. We intend, in a later draft, to replace Fig. 4 with a RHICBOS simulation to indicate more directly the sensitivity for different quark and anti-quark polarizations. A second complication is triggering. The

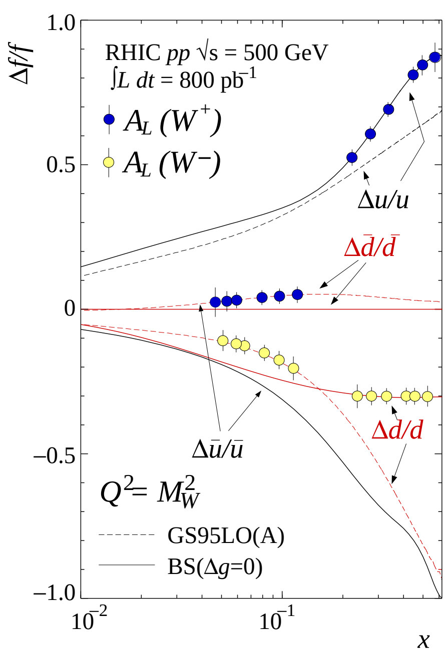


Figure 4: *Expected sensitivity for the flavor-decomposed quark and anti-quark polarization overlayed on the parton densities of Refs. [7] (BS) and [8] (GS95LO(A)). Darker points and error bars refer to the sensitivity from $A_L(W^+)$ measurements, and lighter ones correspond to $A_L(W^-)$.*

STAR experiment will use an existing high-tower electromagnetic calorimeter trigger, which has been commissioned. The PHENIX experiment requires additional triggering capability, and is developing new hardware for this, discussed in the upgrade section of this report (and in the Spin Plan [A1]). A third complication is to identify the lepton charge sign. The STAR experiment requires additional forward tracking, discussed in the upgrade section; the PHENIX experiment can identify the charge sign for muons. A fourth complication is background from several processes: Z bosons, heavy quark decay, and from punch-through of hadrons that then decay (in the PHENIX muons arms for example), faking high-p_T leptons. Background issues are still under study.

7 Transverse-spin results

The motivations and goals for transverse spin measurements at RHIC were described in the *Research Plan for Spin Physics at RHIC* [A1]. This section provides updates on the many theoretical and experimental advances since the writing of that document.

Within the leading-twist collinear formalism of QCD, vanishingly small transverse single spin asymmetries (SSA) are expected. Consequently, transverse SSA provide a window on physics beyond the standard parton model. The large asymmetries observed experimentally have stimulated theoretical developments aimed at understanding the transverse spin structure of the proton. One important objective is to elucidate the role of parton orbital angular momentum. The Sivers effect [56], which involves a correlation between the parton intrinsic transverse momentum k_T and the proton spin in the initial state, may provide this opportunity. A further key objective is to access the transversity distributions through the Collins-Heppelmann effect [108,118], where the Collins function correlates transverse momentum of hadrons relative to the thrust axis with the transverse spin of the parton in the fragmentation process.

The Sivers effect has witnessed particularly interesting theoretical developments recently. It was realized that for the associated Sivers functions to exist, final- or initial-state interactions are required. In the absence of these, the Sivers functions would vanish by time-reversal invariance of QCD. In DIS, the interaction may be viewed as a rescattering (gauge-link [A12]) of the parton in the color field of the nucleon remnant. Depending on the process, the associated color Lorentz forces will act in different ways on the parton. In DIS, the rescattering is an attractive interaction. In contrast, for the Drell-Yan process it is repulsive. Therefore, the Sivers functions contribute with opposite signs to the single-spin asymmetries for these two processes [A12]. This remarkable physical prediction of “non-universality” of the Sivers functions really tests all concepts for analyzing hard-scattering reactions that we know of, and awaits experimental scrutiny. The process-dependence of the Sivers functions will also manifest itself in more complicated QCD hard-scattering. An example is the single-spin asymmetry in di-jet angular correlations [A19, A20], which is now under investigation at RHIC and will be discussed below. Another important recent development is the relation between moments of the Sivers distribution and quark-gluon correlators that enter in a collinear, twist-3 QCD calculation [A21].

Experimental work on transverse spin physics is a world-wide effort. Recent experimental progress includes direct observation of the Collins function in e^+e^- collisions by the Belle collaboration [A22]. The large Collins asymmetry observed promises to provide a window onto

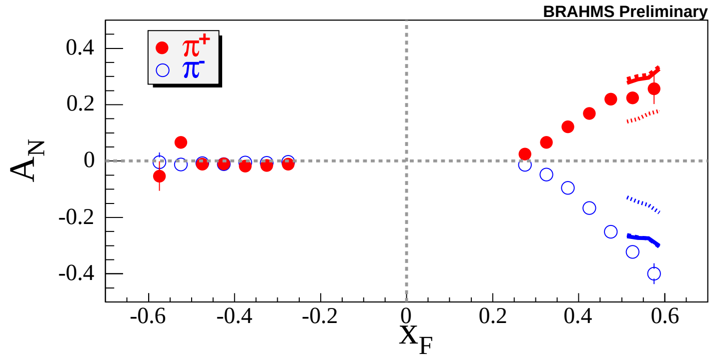


Figure 5: *Measured transverse single-spin asymmetries for forward $\pi^\pm$ production at $\sqrt{s}$=62 GeV as a function of x_F [A9]. Data are compared to twist-3 [A23] and Sivers model [A24] calculations for p_T >1 GeV/c.*

transversity at RHIC. Both Collins and Sivers type asymmetries have been observed by the HERMES collaboration in semi-inclusive deep inelastic scattering (SIDIS) from a transversely polarized hydrogen target [A6]. No transverse spin asymmetries have been observed by COMPASS in SIDIS from a polarized deuterium target, consistent with theoretical expectations of cancellations between up quark and down quark contributions, which are averaged over in their measurements. Experimental observation of these spin effects in other hard scattering processes is an important step to bolster our understanding of these phenomena. RHIC has begun such measurements and is poised for more complete studies in future runs.

RHIC Run 6 demonstrated polarized proton operation at $\sqrt{s}$=200 GeV at very high luminosity and polarization. Interaction rates approaching 1 MHz were repeatedly delivered in this run with average beam polarization of 60%. Transversely polarized proton collisions were observed at both PHENIX and STAR. For the latter, a data sample with integrated luminosity of 6.8 pb^{-1} was recorded for forward pion production and a data sample of 1.1 pb^{-1} was recorded for dijet studies near midrapidity. Results for transverse single spin asymmetries in forward $\pi^\pm$ and $K^\pm$ production from polarized proton collisions at $\sqrt{s}$=62 GeV were reported by the BRAHMS collaboration.

The Run-6 transverse spin results are striking. Results [A9] for A_N for forward $\pi^\pm$ production in polarized proton collisions at $\sqrt{s}$=62 GeV (Fig. 5) show flavor-dependent mirror asymmetries that increase with x_F, for positive values of x_F. At the highest π^+ x_F probed the ratio of spin dependent cross sections, $\sigma(\uparrow)/\sigma(\downarrow)$, is greater than a factor of two, comparable to analogously large spin effects observed at lower collision energy [29]. Similarly, both K^+ and K^- are produced with large (positive) asymmetries. This striking spin dependence, even at collision energies that permit production of hundreds of particles, demands a simple explanation.

Dijet production near midrapidity in polarized proton collisions at $\sqrt{s}$=200 GeV was expected to be sensitive to Sivers type asymmetries through spin dependence of the jet-pair momentum imbalance, responsible for the observed azimuthal angle difference distribution [A19, A20, A25]. The large SSA expected in dijet production near midrapidity are in contrast to observations by STAR [A26] that find the dijet SSA to be consistent with zero (Fig. 6). This discrepancy may reflect delicate subprocess-dependent cancellations in the theory [A25].

Precise results for SSA in forward neutral pion production were made possible by the Run-

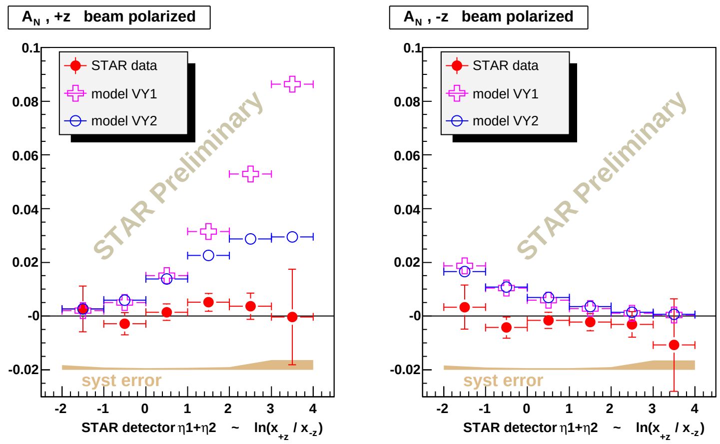


Figure 6: *Measured transverse single-spin asymmetries for dijet production at $\sqrt{s}$=200 GeV as a function of $\eta_1 + \eta_2$ for the jet pair [A26] compared to theoretical expectations [A20].*

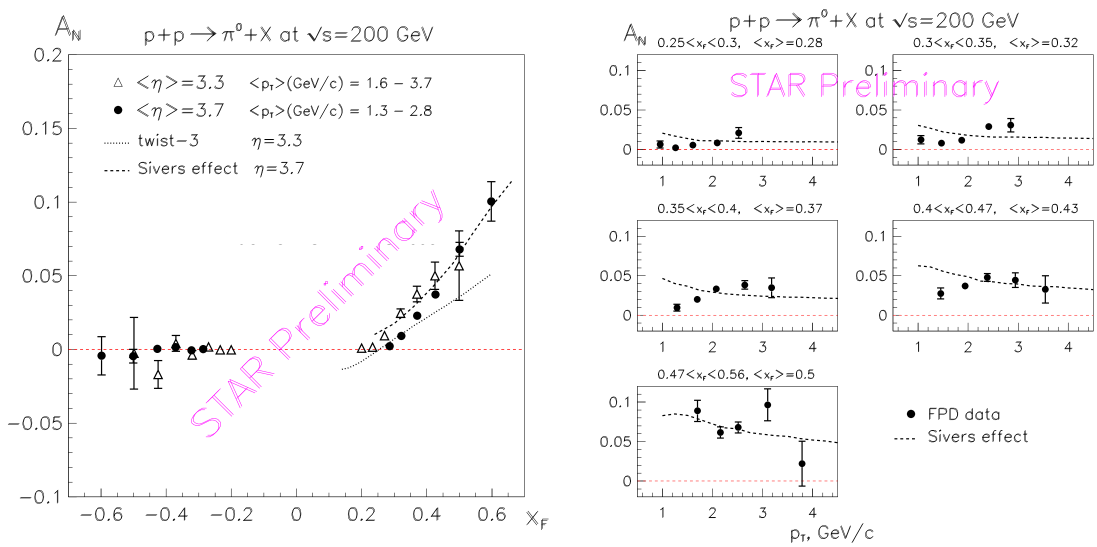


Figure 7: *Measured transverse single-spin asymmetries for forward π^0 production at $\sqrt{s}$=200 GeV (left) showing the x_F dependence at two different η values in comparison to theory [A23, A24]; and (right) showing the p_T dependence in x_F bins in comparison to theory [A24].*

6 performance of RHIC. Figure 7 shows the Feynman-x dependence of the forward π^0 SSA at two different angles in comparison to theoretical expectations [A7]. A_N is found to be larger at the larger angle where, for the same π^0 energy, the p_T of the neutral pion is greater. This is contrary to the theoretical expectation of a $1/p_T$ dependence for A_N at fixed x_F at an appropriate scale. Partial mapping of A_N in the $x_F - p_T$ plane demonstrates that SSA do not follow simple expectations from theory, possibly reflecting the unknown scale dependence of spin-correlated transverse momentum dependent (Sivers) distribution functions or the quark-gluon correlators that enter in twist-3 descriptions. But, unpolarized cross sections are generally reproduced by next-to-leading-order perturbative QCD calculations at $\sqrt{s}$=200 GeV in these kinematics [A16] (see Fig. 2), unlike the situation at lower collision energies [A27], promising that a more complete understanding of transverse spin dynamics can be attained at RHIC energies.

Future prospects for understanding the origin of these striking transverse phenomena at RHIC are bright. Both STAR and PHENIX have implemented large-acceptance forward electromagnetic calorimeters. These devices will permit the measurement of transverse SSA in multi-photon (jet-like) final states, near-side π^0-π^0 correlations and direct photon production. Such measurements can isolate contributions from the Sivers and Collins effects, and can elucidate the dynamical origin of the forward pion transverse SSA.

8 PHENIX and STAR upgrades

Several upgrade projects have been developed by the STAR and PHENIX collaborations to introduce new or enhanced experimental capabilities for their detectors in the areas of precision vertex reconstruction, tracking at high momenta, fast event selection, particle identification and increased acceptance for measurements at forward rapidity. The suite of detector upgrades is designed to provide access to new physics and to make best use of increased luminosity in heavy ion, polarized proton and nucleon-nucleus collisions at RHIC.

To accomplish the W measurements described in Section 6, the PHENIX and STAR experiments need:

- extended data collection periods with longitudinally polarized protons colliding at $\sqrt{s} = 500\,\mathrm{GeV}$,
- charge identification for highly energetic leptons from W decay, and
- efficient lepton triggers with high background rejection.

At present the experiments have the necessary capabilities only in the central rapidity region, where the measurement sensitivities are limited. In the forward rapidity region, where the sensitivity of the measurements is largest, PHENIX requires upgraded trigger capability to select $W \rightarrow \mu^{\pm} + \nu$ in its muon arms. The charge discrimination with the muon arms is sufficient.

STAR requires an upgrade to its forward tracking capabilities to be able to discriminate highly energetic electrons from positrons in $W \rightarrow e^{\pm} + \nu$. Triggering will be provided by the fully commissioned endcap electromagnetic calorimeter.

The experiment upgrade schedules are consistent with RHIC polarized proton physics operation at $\sqrt{s} = 500\,\mathrm{GeV}$, which in a technically driven schedule (cf. Section 5 of the Spin Plan [A1]) is expected to start in the year 2009 and continue through the year 2012.

Both the PHENIX and the STAR collaborations are pursuing upgrades that serve other goals in spin and in heavy ion physics.

A Hadron Blind Detector (HBD) in PHENIX is being installed for measurements of low-mass e^+e^- pairs from the decay of light vector mesons and the low-mass continuum in Au-Au collisions. It is also planned to use the HBD to trigger on high momentum charged hadrons in polarized proton-proton collisions.

The PHENIX collaboration is constructing a Silicon Vertex Tracker (VTX) covering the central rapidity. R&D work is underway for a forward silicon detector covering the muon spectrometer acceptance. A prime motivation is to study the production of charm and beauty quarks in AA, dA, and (polarized) pp collisions using the technique of measuring the displaced decay vertex. In addition the barrel vertex tracker will improve PHENIX's capability to study jet production.

For the spin physics program, the principal physics goals with the VTX are thus to measure $\Delta g/g$ via charm and beauty production, and to resolve the kinematic dependence of $\Delta g/g$ on Bjorken-x via coincident γ+jet production.

Finally, a forward tungsten-silicon sampling calorimeter, the NoseCone Calorimeter (NCC), is being developed in PHENIX to increase the acceptance for jet-photon physics in pp, dA and AA collisions. The NCC will cover the pseudo-rapidity range $1.0 < \eta < 3.0$. A small $PbWO_4$ electromagnetic calorimeter in the PHENIX muon magnet piston is presently being commissioned and will have an acceptance of $3.1 < |\eta| < 3.9$.

The STAR collaboration is extending its forward electromagnetic calorimetry coverage to cover pseudo-rapidities in the range of 2.5 to 4.0. A prime motivation is to probe the contributions of gluons to nuclear structure at small values of Bjorken-x, $x \sim 0.001$, in dA collisions. The longitudinal spin physics program in STAR benefits from the extended kinematic coverage in the determination of Δg, as do the studies of transverse spin phenomena described in Sections 3 and 7. An upgrade to the Time-Projection-Chamber front-end readout electronics and to the Data Acquisition system will increase the STAR event rate capability by an order of magnitude to $\sim 1000\,\mathrm{Hz}$ by the year 2008.

Particle identification will be improved for momenta up to $\sim 3\,\mathrm{GeV}/c$ with a barrel Time-Of-Flight detector. A Heavy Flavor Tracker has been proposed to study the unique matter produced in AA collisions at RHIC. When combined with upgraded inner pointing detectors, it will aid the study of charm and beauty production in polarized pp collisions.

9 New results from COMPASS, HERMES and JLab

The fundamental nature of the nucleon spin puzzle and the high interest and need to understand it is evident from the number of experimental programs presently underway to study aspects of the nucleon's spin structure. This section comments on experiments complementary to the RHIC Spin program, and updates their status since the RHIC Spin Plan was submitted in 2005 [A1].

9.1 COMPASS experiment at CERN

This is a fixed target polarized DIS experiment at CERN which uses a longitudinally polarized 160 GeV/c secondary muon beam on solid polarized targets made up predominantly of ^{6}LiD. Both longitudinal and transverse target polarization orientations are possible. A newly designed wide acceptance target magnet coupled with a extensive particle ID capabilities distinguishes COMPASS from the EMC and SMC experiments which occupied the same beam line in the last two decades. The physics measurement goals of this experiment are: 1) polarization of the gluon within polarized nucleons, 2) light quark helicity distribution by flavor, 3) lambda and anti-lambda polarization, 4) transverse spin distributions. Lepto-production of open charm and of hadron pairs from photon-gluon fusion reaction are considered most promising towards COMPASS's measurements of $\Delta g/g$. Only a limited range in gluon momentum fractions is accessible.

The most recent data sets released by the experiment [A5] included physics topics such as $\Delta g/g$ from photon gluon fusion, an improved measurement of g_1^d and of the quark spin contribution $\Delta\Sigma \sim 0.3$, and Sivers' physics distributions from the deuteron target. In contrast to non-zero asymmetries measured on proton targets at the HERMES experiment at DESY, COMPASS has seen zero asymmetries, which may be understood from cancellations between contributions by u and d quarks in this case [A28]. For 2007, the COMPASS experiment is expecting to take data with a transversely polarized proton target. This will be followed by two years of dedicated operations of the experiment to study physics of the Primakov effect, which involves unpolarized meson/hadron beams impinging on unpolarized targets. The next spin run is hence expected to to be around 2009/10 and will be focused on physics associated with Deeply Virtual Compton Scattering (DVCS) and Generalized Parton Distributions (GPDs).

9.2 HERMES experiment at DESY

The HERMES experiment [A4] at DESY allows studies of nucleon spin structure by scattering the 27 GeV/c electron/positron beam in HERA off internal gaseous targets that are polarized longitudinally or transversely. The main focus of the physics program has been the semi-inclusive DIS physics with extensive particle identification in the detector, which has afforded us new insight into the flavor separated quark distributions. In the last years HERMES has delivered new and exciting results in transverse spin, gluon polarization, and nuclear effects. These will allow us to understand various aspects of nucleon structure, including transversity and the Sivers and Collins effects.

Despite such exciting input in the recent past on different aspects of nucleon spin, the HERMES program will end in the summer of 2007, when the HERA collider is planned to be decommissioned, as its injector (PETRA) will be used for a different purpose.

9.3 Spin experiments at Jefferson Laboratory

The CEBAF accelerator at Jefferson Laboratory is a superconducting radio frequency electron accelerator facility. It provides high polarizations (85%) and high currents (several $\sim 100\ \mu$A in some of its experimental halls) . There are three experimental halls. Most experiments use electron beams with 5.5 GeV energy. The machine consists of a race track layout of circulating beam lines with two linear accelerators joined by two 180^o arcs.

The low electron beam energy available from CEBAF, and the fixed target nature of the experimentation in three experimental halls, makes for the very different focus of the physic program [A29]: nucleon structure in the transition region from the non-perturbative to perturbative QCD. This is also the region where physics of higher twist plays an important role, which becomes an important topic of investigations for the Jlab experiments. The high intensity beams and solid and gaseous targets allow high luminosities, and lead naturally to the physics of exclusive reactions using high acceptance detectors. Highlights of the physics program at Jlab so far have been: precise measurement of GDH sum rule, high precision measurements of spin structure functions at high x, azimuthal spin asymmetries, and results on DVCS (Deeply Virtual Compton Scattering) which are now considered to be the most promising towards future experimental efforts to measure the partonic orbital angular momenta.

A major upgrade of the CEBAF facility is being proposed. The 12 GeV upgrade of the CEBAF, along with some upgrade of the three experimental halls, and a new Hall D to study exotic states in QCD, together is called the *Jlab 12 GeV upgrade*. The project has received a CD 1 from DOE, and is expected to start construction in the next years to be completed around 2012 for beginning of physics.

10 RHIC accelerator performance

As of 2006, polarized proton beams have been accelerated, stored, and collided in RHIC at a center of mass energy of 200 GeV. A single proton beam was accelerated to 250 GeV beam energy, with 45% measured polarization at that energy, where we use the polarimeter analyzing power from 100 GeV. At 200 GeV center of mass energy, the average store luminosity reached $20 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and the average store polarization 60% (see Table 2). Over the next two years we aim to reach the Enhanced Luminosity goal for polarized protons, consisting of an average store luminosity of

- $60 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for 200 GeV center of mass energy, and
- $150 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for 500 GeV center of mass energy,

both with an average store polarization of 70%. Table 2 gives a projection of the luminosity and polarization evolution through FY2008. Luminosity numbers are given for 200 GeV center of mass energy and for each of two interaction points. For each year the maximum achievable luminosity and polarization is projected. Projections over several years are not very reliable and should only be seen as guidance for the average annual machine improvements needed to reach the goal. We assume 10 weeks of physics running in FY2007 and FY2008 to allow for commissioning of the improvements and developments of the machine performance.

In Figure 8 the integrated luminosity delivered to each experiment is shown through FY2012 for 10 weeks of physics operation per year. For every projected period shown in Figure 8 the weekly luminosity starts at 25% of the final value, and increases linearly in time to the final value in 8 weeks. During the remaining weeks the weekly luminosity is assumed to be constant. For the maximum projection the values in Table 2 are used as final values until FY2008. For later years the FY2008 values are assumed with no further improvement. The minimum projection is one third of the maximum projection, based on past experience in projecting luminosities. For operation at 500 GeV center of mass energy, the luminosity projections in Table 2 need to be multiplied by 2.5 because of the smaller beam size at 250 GeV. We expect no significant reduction in the average store polarization at this energy.

Fiscal year		2002A	2003A	2004A	2005A	2006A	2007E	2008E
No of bunches		55	55	56	106	111	111	111
Protons/bunch, initial	10^{11}	0.7	0.7	0.7	0.9	1.4	1.7	2.0
β^*	m	3	1	1	1	1	0.9	0.9
Peak luminosity	$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2	6	6	10	35	60	90
Average store luminosity	$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.5	3	4	6	20	40	60
Time in store	%	30	41	41	56	46	58	60
Max luminosity/week	pb^{-1}	0.2	0.6	0.9	1.9	7.0	14.1	21.9
Max integrated luminosity	pb^{-1}	0.5	1.6	3	13	46	132	197
Average store polarization	%	15	35	46	47	60	65	70
Max LP^4/week	nb^{-1}	0	9	40	90	945	2520	5250

Table 2: *Achieved and projected polarized proton beam parameters through FY2008. Delivered luminosities are given for 200 GeV center of mass energy and one of two interaction points. 10 weeks of physics operation per year are assumed. The designation 2002A refers to achieved, and 2008E refers to expected.*

The RHIC beam polarization is limited by the source, and the polarization transmission in the AGS. No significant polarization loss in RHIC is observed. Small improvements in the source, and a new working point in the AGS are expected to increase the polarization at the AGS extraction energy from currently 65% to 75%. The AGS now operates routinely with both the warm and cold Siberian snakes. The main luminosity limit for the polarized proton operation is the beam-beam effect, leading to a spread in the transverse tunes. Other sources of transverse tune spread are minimized, to accommodate larger beam-beam parameters. Dynamic pressure rises have been largely eliminated through modifications in the vacuum system. However, operation with short bunches can still lead to emittance growth from electron clouds. We expect a polarized proton luminosity improvement by a factor 2-5 with the RHIC II upgrade. This improvement is expected from pre-cooling protons at injection, and a further reduction in β^*.

RHIC polarimetry uses two techniques: scattering from a micro-ribbon carbon target to obtain several measurements of the beam polarization during the typical 6 hour RHIC fill; and scattering from a polarized atomic hydrogen jet target which accumulates data over the entire fill (and over several fills) to precisely calibrate the carbon target polarimeter. Both polarimeters use elastic scattering in the Coulomb-nuclear-interference (CNI) region, where the dominant spin-dependent scattering amplitude is the electromagnetic spin flip term that generates the proton's anomalous magnetic moment. The polarimeters were described in the Spin Plan [A1]. New since then is the first publication from the jet data [A30], on the analyzing power which observes the CNI peak predicted first by Schwinger in 1946 [A31]. This is the first measurement where the peak structure can be observed (see Fig. 33, right panel, of the Spin Plan [A1] where we presented early data from the jet). From these data (taken in 2004), a 7% uncertainty was obtained on A_N. We anticipate that the uncertainties for the beam polarization for each of the 2005, 2006, and future runs will be $\Delta P/P < 5\%$.

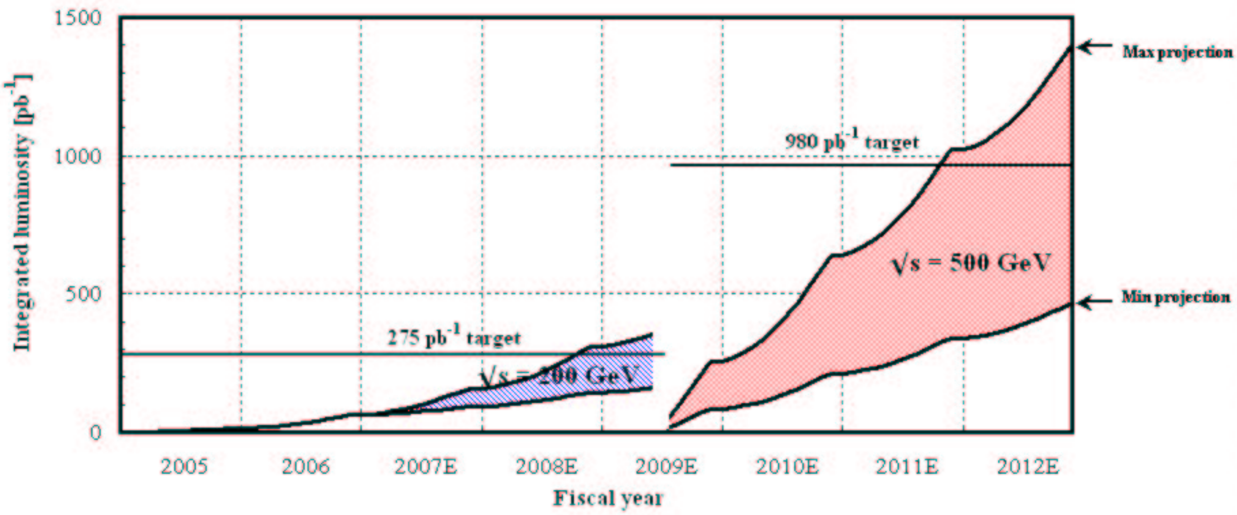


Figure 8: *Minimum and maximum projected integrated luminosity through FY2012. Delivered luminosity numbers are given for each of two interaction points, and 10 weeks of physics operation per year. It is assumed that the center of mass energy is 200 GeV until mid-FY2009, and 500 GeV thereafter. This is an example plan and the target luminosities are used for physics sensitivities discussed here and in the Spin Plan [A1].*

11 Outlook

The RHIC spin program studies the nucleon spin structure in a qualitatively new way, using strongly interacting probes and at collider energy. The program is underway, with great success in preparing the proton beams at high energy with high polarization and high luminosity at $\sqrt{s} = 200$ GeV and anticipated also for planned running at $\sqrt{s} = 500$ GeV. Proposed RHIC spin running through 2012, at 10 weeks/year, is expected to greatly expand our knowledge of the gluon and anti-quark contributions to the proton helicity, and explore the transverse spin structure of the proton. These results should be robust, with overlapping sensitivities of various probes, each well described by perturbative QCD. Also through this period and beyond, important new detectors are expected to become available, expanding our capabilities to study the spin structure of the proton, exploiting the expected increased luminosity of RHIC II. The next proposed step in our study of the structure of the nucleon is a polarized electron-polarized proton collider, which would bring in qualitatively new methods of probing nucleon structure and of studying spin phenomena in QCD. We see each of these steps, the ongoing third generation fixed target DIS experiments at DESY, CERN, and the Jefferson Laboratory, RHIC spin, and a polarized e-p collider, leading to a robust understanding of nucleon structure and the nature of confinement of the quarks and gluons inside the nucleons, and to a deeper understanding of QCD itself.

References

[References [1-210] correspond to those in the RHIC spin plan.]

[A1] C. Aidala *et al. Research Plan for Spin Physics at RHIC*, available at http://spin.riken.bnl.gov/rsc/report/masterspin.pdf

[A2] K. Barish, for the PHENIX collaboration, Proceedings of the Spin 2006 Symposium, Kyoto, Japan, to be published.

[A3] B. Surrow, for the STAR collaboration, Proceedings of the Spin 2006 Symposium, Kyoto, Japan, to be published.

[A4] D. Hasch, Overview of HERMES experiment at DESY, Proceedings of Spin2006 Symposium, Kyoto, Japan, to be published.

[A5] A. Magnon, Overview of COMPASS expeirment at CERN, Proceedings of Spin2006 Symposium, Kyoto, Japan, to be published.

[A6] A. Airapetian *et al.* (HERMES collaboration), Phys. Rev. Lett. **94** (2005) 012002.

[A7] L. Nogach, for the STAR collaboration, Proceedings of the Spin 2006 Symposium, Kyoto, Japan, to be published [hep-ex/0612030].

[A8] S. S. Adler (PHENIX collaboration), Phys. Rev. Lett. **95** (2005) 202001.

[A9] J.H. Lee and F. Videbaek, for the BRAHMS collaboration, Proceedings of the Spin 2006 Symposium, Kyoto, Japan, to be published.

[A10] M. Burkardt, Nucl. Phys. A **735** (2004) 185; Phys. Rev. D **72** (2005) 094020; M. Burkardt and G. Schnell, Phys. Rev. D **74** (2006) 013002.

[A11] D. Sivers, Phys. Rev. D **74** (2006) 094008.

[A12] S. J. Brodsky, D. S. Hwang and I. Schmidt, Phys. Lett. B **530** (2002) 99; Nucl. Phys. B **642** (2002) 344; J. C. Collins, Phys. Lett. B **536** (2002) 43; X. Ji and F. Yuan, Phys. Lett. B **543** (2002) 66; A. V. Belitsky, X. Ji and F. Yuan, Nucl. Phys. B **656** (2003) 165; D. Boer, P. J. Mulders and F. Pijlman, Nucl. Phys. B **667** (2003) 201.

[A13] B. Jäger, M. Stratmann and W. Vogelsang, Phys. Rev. D **70** (2004) 034010.

[A14] M. Hirai, S. Kumano and N. Saito, Phys. Rev. D **74** (2006) 014015; D. de Florian, G. A. Navarro and R. Sassot, Phys. Rev. D **71** (2005) 094018; G. A. Navarro and R. Sassot, Phys. Rev. D **74** (2006) 011502; M. Stratmann, Proceedings of the 14th International Workshop on Deep Inelastic Scattering (DIS2006), Tsukuba, April 2006.

[A15] B.I. Abelev *et al.* (STAR collaboration), Phys. Rev. Lett. **97** (2006) 252001.

[A16] J. Adams *et al.* (STAR collaboration), Phys. Rev. Lett. **97** (2006) 152302.

[A17] S.S. Adler *et al.* (PHENIX collaboration), Phys. Rev. Lett. **98** (2007) 012002.

[A18] S. S. Adler *et al.* (PHENIX collaboration), Phys. Rev. D **73** (2006) 091102.

[A19] D. Boer and W. Vogelsang, Phys. Rev. D **69** (2004) 094025.

[A20] W. Vogelsang and F. Yuan, Phys. Rev. D **72** (2005) 054028.

[A21] X. Ji, J.W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. Lett. **97** (2006) 082002.

[A22] R. Seidl *et al.* (Belle collaboration), Phys. Rev. Lett. **96** (2006) 232002.

[A23] C. Kouvaris, J.W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. D **74** (2006) 114013.

[A24] U. D'Alesio and F. Murgia, Phys. Rev. D **70** (2004) 074009.

[A25] A. Bacchetta, C.J. Bomhof, P.J. Mulders and F. Piljman, Phys. Rev. D **72** (2005) 034030.

[A26] J. Balewski, for the STAR collaboration, Proceedings of the Spin 2006 Symposium, Kyoto, Japan, to be published [hep-ex/0612036].

[A27] C. Bourrely and J. Soffer, Eur. Phys. J. **C36** (2004) 371.

[A28] W. Vogelsang and F. Yuan, Phys. Rev. D **72** (2005) 054028; M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia and A. Prokudin, Phys. Rev. D **72** (2005) 094007 [E: D **72** (2005) 099903]; J. C. Collins, A. V. Efremov, K. Goeke, S. Menzel, A. Metz and P. Schweitzer, Phys. Rev. D **73** (2006) 014021.

[A29] Z-E. Meziani, Overview of J-Lab Experimental program on nucleon spin structure, Proceedings of Spin2006 Symposium, Kyoto, Japan, to be published.

[A30] H. Okada *et al.*, Phys. Lett. **B638** (2006) 450.

[A31] J. Schwinger, Phys. Rev. **69** (1946) 681.