THE RHIC SPIN PROGRAM: SNAPSHOTS OF PROGRESS

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I review progress toward the experimental study of polarized proton collisions at RHIC, at center-of-mass energies of several hundred GeV. The tools under development for these experiments are summarized, with emphasis on the complementarity for the spin program of the two major detectors, PHENIX and STAR. The proposed research program includes measurements of the spin structure of hadrons, tests of QCD predictions for spin observables, and polarization searches for interactions beyond the Standard Model. I argue, in particular, that RHIC should provide the best determination of the gluonic contribution to proton spin foreseen for the coming decade.

1 Introduction

About one year from today, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven will commence operation, primarily to study the formation and decay of strongly interacting matter at extremely high energy densities. The availability of polarized proton beams at RHIC will facilitate a complementary program of hadronic spin studies at unprecedentedly high energies ($\sqrt{s} = 50 - 500$ GeV) and momentum transfers ($p_T \gtrsim 10$ GeV/c), where low-order perturbative QCD (pQCD) should be viable. The projected luminosities for colliding polarized beams are sufficiently high (up to 2×10^{32} cm^{-2}s^{-1}) to permit investigation of relatively rare processes. This new capability will enable a program of unique and definitive experiments to: (1) measure the spin structure of hadrons, especially the contributions from gluons and sea antiquarks; (2) search for physics beyond the Standard Model, *e.g.*, via anomalous parity violation in very hard hadronic collisions; and (3) test pQCD predictions for polarization observables. The RIKEN institute in Japan has provided much of the foresight and generous funding contributions that make this entire spin program possible.

Overviews of the projected RHIC spin program have been provided in talks at previous symposia in this series.[1,2] In the present talk, I would therefore like to highlight recent progress. Since RHIC has not operated yet, progress is confined to construction, advances in carrying out realistic simulations, and theoretical support. I will emphasize what I view as the likely flagship experiments with polarized beams at RHIC.

2 The Tools

2.1 Acceleration and Monitoring of Polarized Beams

The schematic layout of the RHIC accelerator complex, including the specific additions needed to produce colliding polarized beams, is shown in Fig. 1. The existing AGS polarized ion source will be replaced before RHIC startup with an optically pumped source that was originally built at KEK, and has now been substantially revitalized at TRIUMF. The new source has already delivered 500 μA of pulsed beam in bench tests at TRIUMF,[3] as will be needed to attain the "enhanced" luminosities assumed later in this talk: 8×10^{31} cm^{-2}s^{-1} for $\vec{\mathrm{p}}$-$\vec{\mathrm{p}}$ collisions at $\sqrt{s}$=200 GeV and 2×10^{32} at $\sqrt{s}$=500 GeV. With the partial Siberian Snake and rf dipole indicated in Fig. 1, beam polarizations of 40–50% have been attained to date in the AGS, at energies suitable for injection into RHIC. A plan to reach the desired 70% has been developed, requiring installation of a new partial helical snake in the AGS.

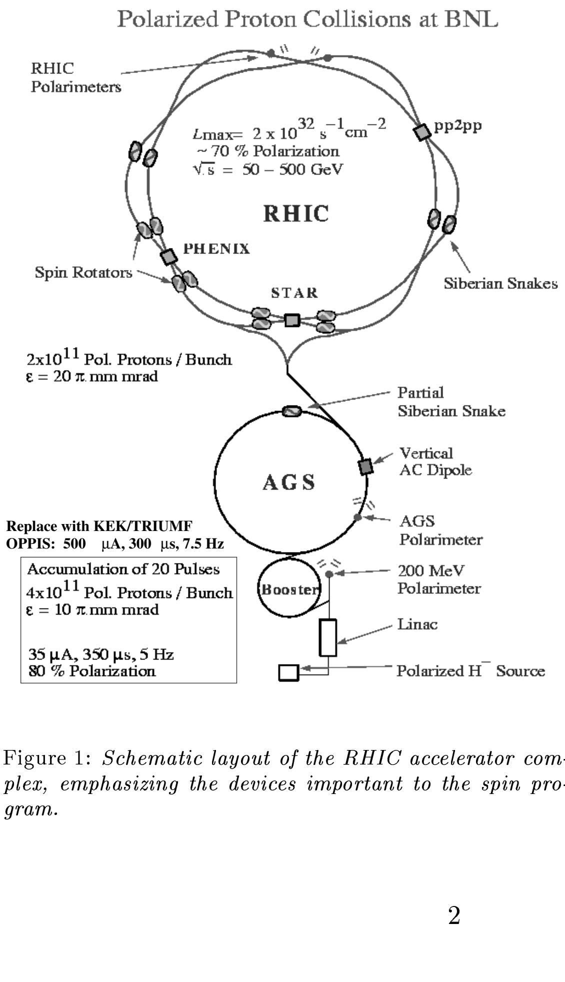

Figure 1: *Schematic layout of the RHIC accelerator complex, emphasizing the devices important to the spin program.*

The first of the full superconducting helical dipole Snakes, intended to allow acceleration of polarized beams through the many depolarizing resonances in RHIC, was completed this past spring. Installation by summer 1999 of the two Snakes needed for one RHIC beam, together with the first RHIC polarimeter on the same beam ring, will allow commissioning of the first polarized proton beam in RHIC to begin during its first year of operation. Installation of the Snakes and polarimeters for the second beam is planned for the summer of 2000, along with the full complement of spin rotators needed (see Fig. 1) to allow independent adjustment of the spin orientations at the sites of the two major detectors. It is then expected that the first $\vec{\mathrm{p}}+\vec{\mathrm{p}}$ collision studies will take place in year 2 of RHIC operation. In a conservative scenario, one may hope to reach "design" luminosity for polarized collisions in year 3, and the order-of-magnitude enhanced luminosity mentioned above by the start of year 4. Together with various detector upgrades described below, this schedule would permit the full RHIC spin program to be carried out starting in 2002. Present plans call for polarized proton operation of RHIC for about 10 weeks per year, beginning in Fall 2000.

The development of beam polarimeters for RHIC has been concentrated to date on the polarized beam commissioning stage. Polarimeters at first will utilize fixed internal carbon micro-ribbon targets. The primary commissioning polarimeter will exploit the sizable analyzing powers observed [4,5] for inclusive production of charged pions at moderate momentum transfer ($p_T \gtrsim 1$ GeV/c). Funding shortages limit the pion detection to a single-arm spectrometer assembled from existing magnets. A second option would utilize $\vec{\mathrm{p}}$-carbon elastic scattering in the Coulomb-nuclear interference region, where the low-energy recoil carbon nuclei can be detected inexpensively in a left-right symmetric setup,[6] but analyzing powers are limited to a few percent. It is not clear that instrumental asymmetries can be kept sufficiently small (*i.e.,* nearly two orders of magnitude below the polarization asymmetries) for either of these designs to be adapted to the long-term needs of the RHIC spin program, where eventual absolute calibration of beam polarizations to an accuracy of $\pm 5\%$ or better is needed. For this and other reasons, a number of options for long-term polarimetry are still under discussion.[7,8] The eventual absolute calibration of beam polarizations at energies $\gtrsim 100$ GeV is likely to be performed against analyzing powers measured for the p-$\vec{\mathrm{p}}$ system with a polarized internal hydrogen target, but details have yet to be worked out.

2.2 The Major Detectors

The bulk of the RHIC spin physics program will be carried out with the two major RHIC detectors, PHENIX and STAR. Both were originally designed to analyze relativistic heavy-ion collisions, where the performance demands are quite distinct from those for a p-p collider. However, both detectors are being adapted to provide cost-effective solutions for polarization measurements. Assembly of both detectors in their respective experimental halls at RHIC is actively under way at present, and parts of both will be used for heavy-ion collision studies during the first year of RHIC operation.

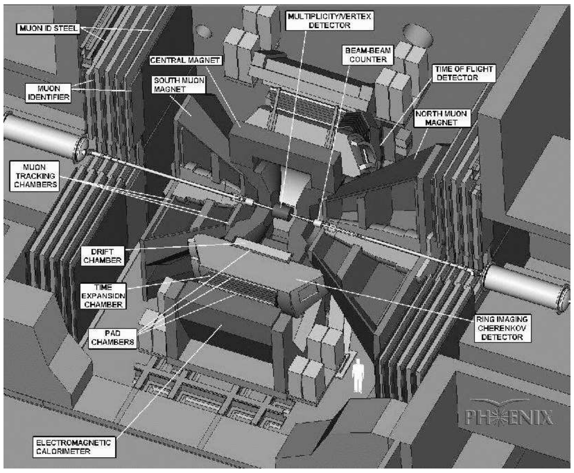

Figure 2: *Schematic of the PHENIX detector. A second muon arm has been added specifically as an upgrade aimed at the spin program.*

As shown in Fig. 2, the PHENIX detector comprises central arms and fore and aft muon detectors. The central arms provide high-resolution charged-particle tracking and electromagnetic calorimetry, but over a limited solid angle: pseudorapidities $|\eta| \leq 0.35$ and about half of the full azimuthal range. The muon arms cover the pseudorapidity range $1.2 \leq |\eta| \leq 2.4$. The primary upgrade of PHENIX aimed specifically at the spin program is the addition of the second muon arm.

The STAR detector (Fig. 3) is intended to provide a more global view of each collision. Time projection chambers are used for high-resolution tracking of many charged particles over the full azimuthal range and most of the pseudorapidity range $|\eta| \leq 3$. The major upgrades relevant to the spin program are electromagetic calorimeters (EMC) providing full azimuthal coverage over the barrel portion of the cylindrical surface ($|\eta| \leq 1.0$) and one endcap ($1.07 \leq \eta \leq 2.0$). Construction of the barrel EMC is under way, while a funding proposal for the endcap is in preparation. With suitable funding profiles, both EMC's can be completed by the summer of 2002.

The two detectors are complementary in their suitability to the proposed spin program. PHENIX has a distinct edge in hadron and muon particle identification and in rate capability. The muon arms considerably facilitate studies of the production of dilepton pairs, $W^{\pm}$ and J/Ψ. The fine-grained EMC in PHENIX provides very good capability to distinguish photons from π^0's over the energy range of interest near mid-rapidity. On the other hand, the expanded η coverage available in STAR for charged particles and photons

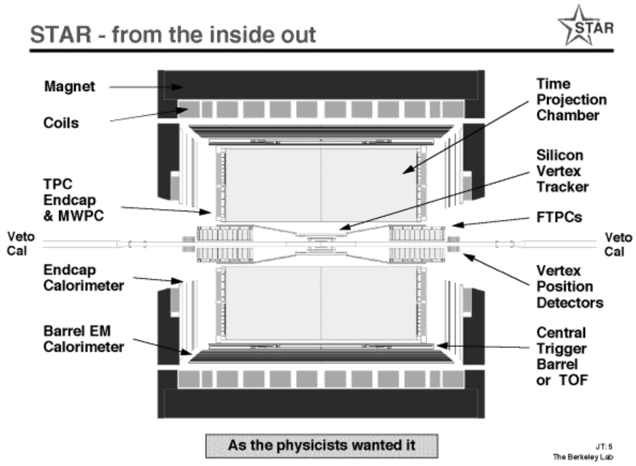

Figure 3: *Cross-section view of the subsystems of the cylindrically symmetric STAR detector. Construction has begun on the barrel portion of the electromagnetic calorimeter (EMC), while funding is still being sought for one endcap EMC.*

makes it the detector of choice for hadron jets and photon-jet coincidences. The broad coverage also considerably extends the range of Bjorken x-values that can be accessed for colliding partons, and facilitates imposition of isolation cuts to distinguish lone particles from jet fragments. Although the EMC's in STAR have generally much coarser segmentation than those in PHENIX, they include fine-grained detectors at the depth of maximum electromagnetic shower energy deposition, to aid in distinguishing between the shower profiles characteristic of single high-energy photons *vs.* daughter di-photons from neutral meson decays. The spin physics goals of the two collaborations are similar, but both detectors are needed to address these goals optimally.

2.3 Theoretical Tools

The final crucial tool for the RHIC spin physics program is perturbative QCD. The underlying assumption of the entire program is that the description of hard ($p_T \gtrsim 10$ GeV/c) proton collisions at RHIC energies can be factorized into a non-perturbative structure part, about which we seek to learn, and perturbative partonic collisions. The colliding proton beams are thus viewed as ensembles of polarized parton beams; the parton luminosities and polarizations are related to those of the protons by the spin-independent and spin-dependent parton distribution functions (PDF's) that characterize the proton's substructure. The parton-level cross sections and spin observables are given straightforwardly by leading-order (LO) pQCD [9] or, in the case of electroweak (e.g., $W^{\pm}$ production) processes, by the Standard Model. In fact, next-leading-order (NLO) calculations have already been performed for many of the processes central to the RHIC spin program: they provide important quantitative corrections, but generally do not alter the qualitative design of experiments. Nonetheless, thorny issues remain, associated, for example, with potential spin effects arising from multiple soft gluon radiation[10] preceding hard partonic collisions. A large and very active group of theorists are addressing these issues and present indications remain very encouraging for the clean interpretability of RHIC spin results. But it will clearly be wise in the early years of RHIC to test pQCD predictions for spin effects, *e.g.*, by checking that single-spin transverse asymmetries involving light quarks really do approach zero [11] at sufficiently high p_T, and by comparing spin structure results from proton collisions to those obtained with electromagnetic probes.

3 Snapshots of the RHIC Spin Physics Program

3.1 Determination of the Gluon Helicity Distribution

As we have already heard in several previous talks at this conference, the *next essential piece* of the nucleon spin puzzle is measurement of the gluon helicity preference $\Delta G(x, Q^2)$: the difference between the PDF's for gluons with spin projection along *vs.* opposite the nucleon's overall longitudinal spin projection. It is already known that gluons dominate the *mass* of the proton.[12] Do they also make crucial contributions to the spin?

By virtue of the axial anomaly of QCD,[13] there are contributions from the integral $\Delta G(Q^2) \equiv \int_0^1 \Delta G(x, Q^2)dx$, as well as from quark and antiquark helicity preferences, to the integrated asymmetry measured in polarized deep inelastic scattering (DIS) experiments. Thus, these experiments strictly determine only a correlation between the integrated quark and gluon helicity preferences, as illustrated by the SMC analysis [14] in Fig. 4. An independent measurement of ΔG is needed even to pin down the *quark* contributions to the proton spin. An experimental precision better than ± 0.5 in ΔG is required to reduce the ambiguity in quark contributions to a level comparable to the actual measurement errors in the DIS asymmetries. The quark and gluon contributions must be determined separately before we can constrain the fraction of the nucleon spin attributable to *orbital* angular momentum of the partons.

At present there are only coarse constraints on $\Delta G(x, Q^2)$ available from observed scaling violations in polarized DIS. The three quite different distributions for $\Delta G(x, Q^2)$ shown in Fig. 5, resulting from NLO fits of the DIS data by Gehrmann and Stirling,[15] give some indication of the range of values consistent with the data. In all models for the gluon spin distribution suggested to date, the dominant contributions to the integral $\Delta G(Q^2)$ arise from Bjorken x-values below 0.1, simply because that is where most of the gluons reside. RHIC spin experiments can probe the range $0.01 \lesssim x_{gluon} \lesssim 0.3$, sufficient to deduce the integral with the desired precision.

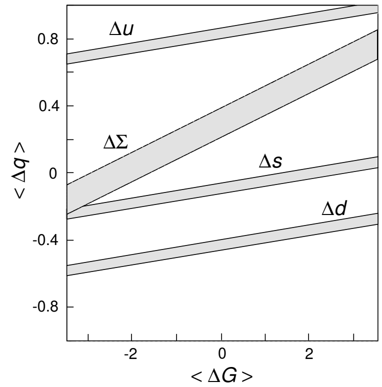

Figure 4: *The correlation of quark and gluon contributions to the longitudinal polarization of a proton, introduced by the effect of the QCD axial anomaly on the interpretation of polarized DIS asymmetries.*[14] *The separation of quark and gluon contributions to polarized DIS is scheme-dependent, and is shown here for one particular QCD factorization scheme. The bands in each case represent $\pm 1\sigma$ limits on the quark contributions deduced* [14] *from DIS results.*

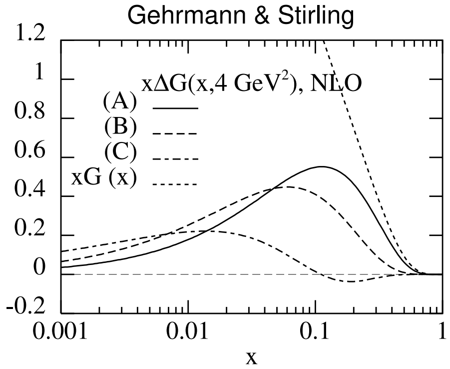

Figure 5: *Three models of the gluon helicity distribution used in next-leading-order global analyses of polarized DIS results by Gehrmann and Stirling.*[15] *All three are consistent with observed scaling violations in DIS. The solid curve (A), corresponding to an integral $\Delta G(4\ GeV^2)$=1.71, is used in simulations presented here.*

Many processes in $\vec{\rm p}$+$\vec{\rm p}$ collisions offer sensitivity to $\Delta G(x, Q^2)$: *e.g.*, direct photon production via gluon Compton scattering ($q + g \to q + \gamma$); dijet or di-hadron production via quark-gluon or gluon-gluon elastic scattering; open heavy quark (c or b) production via gluon-gluon fusion. All of these examples will be measured by the PHENIX and/or STAR collaborations, and the results from several such processes are likely to be included in eventual NLO analyses of polarization data to extract $\Delta G(x, Q^2)$. However, one should keep in mind that such analyses are subject to many intertwined theoretical ambiguities: competing LO partonic processes contributing to the measured channels; non-negligible NLO corrections; several relevant, and poorly delineated, polarized PDF's; pQCD scale ambiguities; uncertain treatments of experimental isolation cuts and of poorly known aspects of fragmentation functions; the effects of multiple soft gluon radiation, and of the transverse initial parton momentum components ("k_T-smearing") they introduce.[16] In light of these ambiguities, *the best constraints on the extracted polarized gluon PDF should be expected from those experiments that approach most closely the ideal of a direct LO measurement of the gluon helicity preference at experimentally determined values of x_{gluon}.* Based on this criterion, I concentrate below on one particular RHIC experiment: the measurement of the longitudinal spin correlation A_{LL} for $\vec{\mathrm{p}} + \vec{\mathrm{p}} \rightarrow \gamma$ + jet + X with the STAR detector.

The advantages of direct photon production and of γ-jet coincidence detection can be summarized as follows:

1) There is a single dominant LO pQCD process: $q + g \rightarrow q + \gamma$. The main LO background, from annihilation $q + \overline{q} \rightarrow \gamma + g$, contributes at the $\sim 10\%$ level. NLO calculations have been performed,[17] and indicate no qualitative changes from the LO expectations (except for a slightly *enhanced* sensitivity to ΔG). Higher-twist corrections are expected to remain negligible at $p_T \gtrsim 10$ GeV/c.

2) The sensitivity to gluon polarization is guaranteed to be large in an experiment with appropriate kinematic coverage. The pQCD spin correlation for gluon Compton scattering approaches unity when the γ is detected in the direction of the incident quark (where the cross section for the process is also maximized). Large quark polarizations ($\gtrsim 30\%$) are available at momentum fractions $x_{quark} \gtrsim 0.2$ to probe ΔG. It is then highly desirable to sample very asymmetric partonic collisions ($x_q \geq 0.2$ with $x_g \leq 0.1$), in which both products will be boosted forward in the lab frame. Coverage for such asymmetric collisions requires the endcap EMC proposed for STAR, which then also spans the appropriate range of partonic c.m. angles, where the spin correlation is large.

3) Detection of γ-jet coincidences allows event-by-event kinematic reconstruction of the momentum fractions $x_{1,2}$ for the colliding partons. It is this coincidence detection involving jets that requires the large acceptance of STAR, and that facilitates the *direct* extraction of $\Delta G(x, Q^2)$ from the data. The combination of coincidence and polarization measurements also turns out to yield considerably reduced sensitivity (in comparison to cross section measurements aimed at determining the *unpolarized* gluon PDF) to the kinematic uncertainties arising from k_T-smearing.[18]

4) Measurements with STAR will cover a suitably broad range of momentum fractions, $0.01 \lesssim x_g \lesssim 0.3$, to determine the integral contribution of gluons to the proton helicity with a precision better than ± 0.5. This coverage requires runs at two bombarding energies, $\sqrt{s} = 200$ and 500

GeV. Adequate statistical precision can be obtained with 10-week runs at each energy, at "enhanced" $\vec{p}+\vec{p}$ luminosities. In an optimistic scenario, these runs could take place in 2002-3.

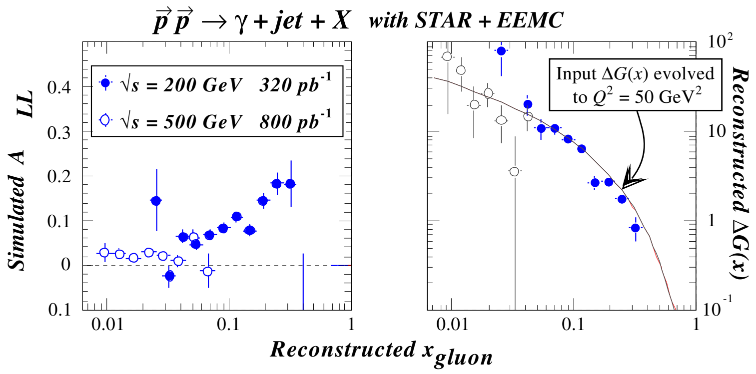

Figure 6: *Simulation results for the pp spin correlation A_{LL} and the gluon helicity distribution $\Delta G(x)$ extracted therefrom, for photon-jet coincidence events detected in STAR (including its planned endcap EMC) at $\sqrt{s}$=200 GeV (closed symbols) and 500 GeV (open symbols). The events analyzed [18] have been subjected to cuts foreseen for the real data. The error bars reflect counting statistics for 10-week runs at each energy, assuming $\vec{p}+\vec{p}$ luminosities $\sim 10^{32}$ $cm^{-2}s^{-1}$. The solid curve in the right-hand frame represents the theoretical input for $\Delta G(x, Q^2 = 50 (GeV/c)^2)$. The small systematic deviations between the input and extracted gluon helicity distributions arise from simplifying assumptions in the data analysis, and are correctable via simulations, as discussed in the text.*

Simulation results that demonstrate the quality of data attainable for the extracted $\Delta G(x)$ are shown in Fig. 6. Events were generated with the code PYTHIA,[19] version 5.7, incorporating all LO photon production processes, plus initial-state gluon radiation and splitting that give rise to k_T-smearing, plus final-state parton fragmentation. LO spin effects for all the hard partonic processes were included [18] as appropriate for proton beam polarizations of 0.7 and Gehrmann-Stirling spin-dependent PDF's[15] evolved with Q^2 (chosen equal to $p_T^2/2$). The gluon helicity distribution used as input to the simulations was set A from Ref. [15], as represented by the solid curve in Fig. 6, after evolution to a value of Q^2 corresponding to the minimum – and most probable – transverse momentum transfer included in the simulations, p_T=10 GeV/c. Although $\Delta G(x, Q^2)$ continues to rise rapidly down to the lowest x_g values covered in the proposed experiment, the gluon *polarization* $\Delta G(x)/G(x)$ decreases with decreasing x_g, producing the decrease in simulated A_{LL} values seen in the left-hand frame.

The projected results for $\Delta G(x)$ shown in the right-hand frame of Fig. 6 were extracted from the simulated asymmetries with a simple-minded reconstruction algorithm, which assumed that *only* the gluon Compton scattering process contributed to the events, and then always with $k_T = 0$ and with $x_g = \min[x_1, x_2]$. The neglect of other contributions included in the generated events leads to the small systematic deviations of the extracted $\Delta G(x)$ from the input curve at the larger x_g-values seen in Fig. 6. These deviations can eventually be compensated in an experiment by using simulations to introduce appropriate corrections, but in any case they have little effect on the integral gluon spin contribution deduced from the results. A *fit* to the data points in the right-hand frame with the functional form used for $\Delta G(x)$ by Gehrmann and Stirling [15] gives an extracted integral $\Delta G_{recon} = 1.62 \pm 0.23$. The error bar on the fitted value, which includes the uncertainty in extrapolating the data to $x_g = 0$, is reduced by a factor of 6 by the inclusion of the 500 GeV data. It does not include other systematic errors, associated, for example, with subtraction of background from π^0 and η^0 production and with beam polarization absolute calibration uncertainties. When such other systematic errors are included the error bar on the integral is likely to increase to about ± 0.4. The quality of these projected results is thus comparable to that contemplated with an $\vec{e}$-$\vec{p}$ collider at HERA[20] and is distinctly superior to that of other measurements planned for the coming decade.

3.2 Antiquark Polarizations from $W^{\pm}$ Production

Polarized DIS experiments have suggested that the sea in a polarized proton is significantly polarized.[14] It is important for our understanding of the structure of the sea to know if this polarization is shared by antiquarks as well as quarks, and if it is flavor-dependent. The study of intermediate vector boson production in RHIC $\vec{p}+\vec{p}$ collisions provides a very clean way to address these questions. Since the production processes are weak, one can measure parity-violating *single* spin asymmetries A_L^{PV} associated with spin-flip of *each* of the two polarized proton beams (referred to below as beams a and b). In kinematic regimes ($|\eta| > 1$) sampling quite asymmetric parton collisions (*e.g.,* $x_a >> x_b$), this allows one to separate the contributions from polarized (predominantly valence) quarks *vs.* polarized antiquarks.

This separation is most easily illustrated for $W^{\pm}$ production, where there is, in each case, a single dominant partonic process: $u + \overline{d} \to W^+$; $d + \overline{u} \to W^-$. The parity-violating analyzing powers can be written straightforwardly in terms of the relevant PDF's;[21] *e.g.*,

$$A_L^{PV}(\mathrm{W}^+, \mathrm{beam}\ a) \;=\; \frac{\Delta u(x_a)\overline{d}(x_b) - \Delta\overline{d}(x_a)u(x_b)}{u(x_a)\overline{d}(x_b) + \overline{d}(x_a)u(x_b) + hfc}, \tag{1}$$

where hfc refers to small contributions from heavier quark flavors. In the limit $x_a >> x_b$, these general results tend toward direct measurements of the quark and antiquark polarizations:

$$x_a >> x_b \Rightarrow A_L^{PV}(\mathrm{W}^+, \mathrm{beam}\ a) \to \frac{\Delta u}{u}(x_a);\quad A_L^{PV}(\mathrm{W}^+, \mathrm{beam}\ b) \to \frac{\Delta\overline{d}}{\overline{d}}(x_b); \tag{2}$$

$$x_a >> x_b \Rightarrow A_L^{PV}(\mathrm{W}^-, \mathrm{beam}\ a) \to \frac{\Delta d}{d}(x_a);\quad A_L^{PV}(\mathrm{W}^-, \mathrm{beam}\ b) \to \frac{\Delta\overline{u}}{\overline{u}}(x_b). \tag{3}$$

One thus has, in principle, the capability to calibrate the extraction of antiquark polarizations by comparing the quark polarizations measured simultaneously (via spin-flip of the *other* beam) to results already known from DIS. This calibration is crucial for the entire RHIC spin program, because it represents one of the few points of direct confrontation of results obtained via hadronic probes with those from electromagnetic probes.

Figure 7 illustrates the range of x-values over which quark and antiquark polarizations could be sampled, and the statistical sensitivity attainable for $\vec{\mathrm{p}}+\vec{\mathrm{p}}\to \mathrm{W}^\pm+\mathrm{X}$ processes measured at $\sqrt{s}$ = 500 GeV with the PHENIX detector. (STAR will measure these processes with comparable sensitivity.) The predicted analyzing powers[21] are large and strongly sensitive to the antiquark polarizations over the range $0.05 \lesssim x_{\overline{q}} \lesssim 0.1$. The separation of quark from antiquark contributions is not quite so clean as suggested by Fig. 7. The W's are detected in practice via single, isolated hard leptons ($\mathrm{e}^\pm$ or $\mu^\pm$ at $p_T \gtrsim 25$ GeV/c) from their decay, and this complicates the identification of events where $x_a >> x_b$. Such events completely dominate the W^- sample at $|\eta|_e \geq 1.0$, but the W^+ sample always contains sizable contributions from both $u_a + \overline{d}_b \to \mathrm{W}^+$ and $u_b + \overline{d}_a \to \mathrm{W}^+$ processes.[18] The difference arises between the two cases because both $\mathrm{W}^\pm$ are produced left-handed, so that the daughter leptons are emitted preferentially *along* the W^- momentum direction, but *opposite* the W^+ direction. Thus, it is the measurement of down quark polarizations from W^- production that will afford the best comparison of RHIC results with those from (semi-inclusive) polarized DIS.

3.3 Theoretical Predictions for Other RHIC Spin Measurements

In addition to the very substantial recent progress made on machine and detector design and construction, as well as on experiment simulations, for the RHIC spin program, there has been a steady flow of new ideas for experiments supplied by interested theorists. I briefly review a few recent highlights here.

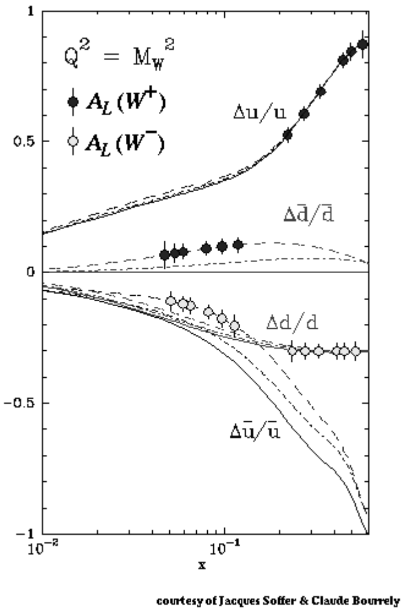

Figure 7: *The Bjorken x ranges and statistical precision goals for PHENIX measurements of u and d quark and antiquark polarizations, via single-spin parity-violating asymmetries for inclusive $W^{\pm}$ production at $\sqrt{s} = 500$ GeV. Only those events in which a daughter muon from the W decay is detected in one of the muon arms are included. The curves represent various model predictions [21] for the spin-dependent structure functions.*

There continues to be strong interest in the distributions of *transversely* polarized quarks in a transversely polarized proton. These transversity distributions $\Delta_T q(x, Q^2)$ are expected to differ from the helicity distributions $\Delta q(x, Q^2)$ by virtue of relativistic quark behavior, and they provide new and independent information about nucleon spin structure.[22] In particular, when expressed in a helicity basis, the transversity measures the chiral-odd probability that a polarized nucleon may undergo a fluctuation in which it emits a quark of one helicity, and then absorbs a quark of the opposite helicity.[22] Transversity can be measured, in principle, via transverse spin correlations (A_{TT}) in hard $\vec{p}$-$\vec{p}$ collisions. Drell-Yan dilepton or Z^0 production represents a cleanly interpretable case, except for the fact that unknown quark transversities will be folded there with unknown, and perhaps very small, antiquark transversities. Martin *et al.*[23] have recently estimated the largest effects that might be expected from transversities in Drell-Yan production, by exploiting an inequality first suggested by Soffer [24]: $2|\Delta_T q(x, Q^2)| \leq q(x, Q^2) + \Delta q(x, Q^2)$. The predicted effects are small, but measurable. For example, at $\sqrt{s} = 150$ GeV, they predict maximal A_{TT} values of plus several percent in the dilepton mass range from 10–20 GeV, to be compared to the small negative values expected in the absence of relativistic effects (*i.e.,* for $\Delta_T q = \Delta q$).[23] Alternative reactions for exploring transversity, without the sensitivity to antiquarks, are also under active consideration.[22]

Tests of spin substructure models can be extended, in principle, beyond nucleons to hyperons, if one can measure the polarization of such hadrons (via their weak decay) when they appear as substantial fragments of a partonic jet. Measurements of this sort by the OPAL [25] and ALEPH [26] collaborations, for e^+e^- collisions at the Z^0 resonance, seem consistent with the simplest model of Λ spin structure, in which the spin is carried completely by the strange valence quark. However, de Florian *et al.* have pointed out [27] that the contrast with the complexity of the nucleon spin structure is not necessarily so striking, since the LEP results can also accommodate quite different models of the Λ's spin/flavor structure. As illustrated in Fig. 8, these models could be very clearly distinguished by RHIC measurements of longitudinal polarization transfer (D_{LL}) in inclusive Λ production: $\vec{p}+p\rightarrow \vec{\Lambda}+X$. The inferred polarized fragmentation functions will be sensitive not only to the Λ structure, but also to its parentage: one should expect quite different results for Λ's that are direct fragments and for decay daughters of heavier hyperons (*e.g.,* $\vec{\Sigma}^0 \rightarrow \vec{\Lambda}\gamma$ or $\vec{\Xi}^0 \rightarrow \vec{\Lambda}\pi^0$) with very different internal spin coupling. From this viewpoint, it would be desirable to detect photons or π^0 correlated with the Λ, along with its daughter proton and π^-, requiring a large acceptance detector with good charged-particle tracking and electromagnetic calorimetry. STAR appears to fill this bill, but relevant simulations have yet to be performed.

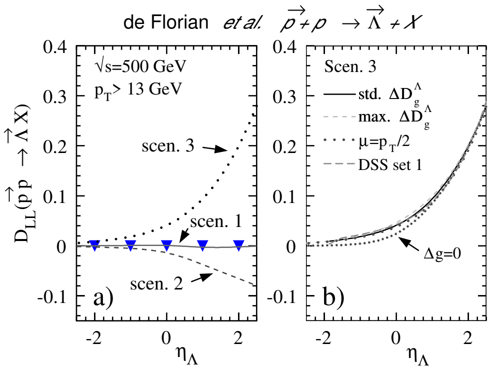

Figure 8: *Predictions* [27] *for helicity transfer from a polarized proton beam to a Λ jet fragment, based on various model scenarios of the Λ spin structure and the fragmentation process, all consistent with polarized fragmentation measurements at LEP. RHIC measurements for Λ's produced at pseudorapidity $\eta \gtrsim 1$ could easily distinguish among the scenarios.*

An exciting possibility at RHIC is to use parity violation in hard jet production to probe potential new interactions of very short range, beyond the Standard Model. Parity violation does arise within the Standard Model for quark-quark scattering, from interference between gluon- and Z^0-exchange.

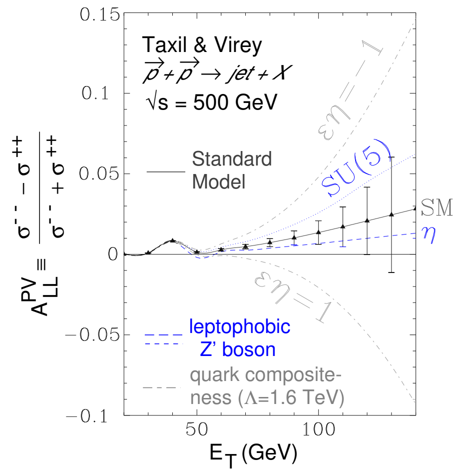

Figure 9: *Predictions [28] for two-spin parity-violating asymmetries in hard jet production, based on mechanisms within and beyond the Standard Model. The error bars reflect estimates of the statistical uncertainties attainable with STAR in one standard year of $\vec{p}+\vec{p}$ running.*

Predictions [28] for the resulting two-spin asymmetries (measuring sensitivity of the cross section to the simultaneous flip of both beam helicities) for jet production at $p_T \sim 100$ GeV/c are shown in Fig. 9. Such hard collisions may also be sensitive to interference with amplitudes associated with new phenomena at a mass scale $\gtrsim$1 TeV. The calculations in Fig. 9 include consideration [28] of two such classes of phenomena, associated either with quark compositeness or with a new heavy "leptophobic" Z$'$ boson. The present limits on such new phenomena still allow modifications to the parity-violating asymmetries that are large in comparison to the uncertainties contributed by PDF errors to the Standard Model predictions. With realistic measurement uncertainties, RHIC $\vec{p}+\vec{p}$ experiments should attain sensitivities at $\sqrt{s} = 500$ GeV comparable to those that can be reached in 2 TeV unpolarized $\overline{p}p$ collisions at the Tevatron.[28]

4 Conclusions

There can no longer be any doubt that a productive program of polarization measurements in $\vec{p}+\vec{p}$ collisions at several hundred GeV c.m. energies will take place at RHIC in the first years of the next century. Strong spin subgroups have formed within both the PHENIX and STAR collaborations. Upgrades to facilitate the spin research program are well under way for the accelerator complex and for both major detectors. Though many details remain to be addressed, I envision forefront research with this polarized collider for at least a 10-year period, with emphasis on: (1) the best measurement accessible in the coming decade of the gluon contribution to the proton spin; (2) separation of flavor-dependent antiquark helicity preferences within a polarized proton, via $W^{\pm}$ production; and (3) searches for new ultrashort-ranged parity-violating interactions in hard quark-quark scattering at $p_T \sim 100$ GeV/c. Prospects for other groundbreaking results are very encouraging: theorists are proposing new ideas for RHIC spin experiments faster than we can simulate them. Very recent examples include suggestions to determine polarized fragmentation functions in Λ production [27] and to search for intrinsic charm in the proton.[29]

The RHIC spin program will blossom fully after $\vec{\mathrm{p}}+\vec{\mathrm{p}}$ luminosities $\approx 10^{32}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ are reached. But even before that, in the second and third years of RHIC operation, PHENIX and STAR will gather important information on polarization systematics in hadronic processes and first indications of the gluonic contribution to the proton spin. Strong spin physics is also accessible beyond STAR and PHENIX, including a proposed experiment [30] to map out polarization observables for $\vec{\mathrm{p}}$-$\vec{\mathrm{p}}$ elastic scattering over a broad range of momentum transfers, at unprecedentedly high energies.

In short, as RHIC spin rapidly approaches the "real axis," there is a great deal of work to do!

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