Plans for the RHIC Spin Physics Program

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Abstract

This report gives a RHIC spin plan for the next 5 years. The proposed program would significantly advance our understanding of the spin structure of the proton. Major advances are expected toward an understanding of the gluon polarization in the proton, the W boson parity-violating measurements would greatly impact our detailed understanding of particularly the anti-up and anti-down quark polarizations in the proton, and the transverse spin program will enter a precision stage studying asymmetries connected to orbital angular momentum and to quark transversity.

The entire plan rests on running. The plan assumes an average of ten weeks per year. Sustained running is necessary to build the required peak and average luminosity gains anticipated, to build the level of polarization anticipated, and to accumulate the required integrated luminosity recorded by the experiments, both at $\sqrt{s} = 200$ GeV and at $\sqrt{s} = 500$ GeV, through 2013. Support for development of higher proton-proton luminosity is very important for the exciting program envisioned for beyond 2013.

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Appendices C–E are at http://spin.riken.bnl.gov/rsc/report/spinplan_2008/Appendix/

1 Executive Summary

The following RHIC Spin Plan is based on measurements in hand and on achieved RHIC polarization and integrated luminosity. The plan was requested by Steven Vigdor, Brookhaven Associate Laboratory Director, and was developed by the RHIC Spin Collaboration. Appendix A presents the charge. Polarized proton collisions at RHIC probe the spin structure of the proton using strongly interacting probes in hard scattering where the collisions are described by perturbative Quantum Chromodynamics (pQCD).

We now have measurements of cross sections for unpolarized proton-proton collisions at $\sqrt{s} = 200$ GeV, for inclusive production of pions at mid-rapidity and forward rapidity and for jets and direct photons at mid-rapidity. These cross sections are predicted by next-to-leading order pQCD, and pQCD is the basis for describing the spin dependence of the underlying parton interactions in the study of the spin structure of the proton.

Measurements at RHIC have significantly constrained the possible gluon spin contribution to the proton's spin. RHIC helicity asymmetry measurements have been used in a new global analysis of the proton's spin structure. This analysis combines the asymmetries measured in p+p collisions at RHIC with results from inclusive and semi-inclusive deep-inelastic scattering (DIS) to obtain the spin distributions for quarks, anti-quarks, and gluons in the proton. The main conclusion: the spin contribution by gluons with momentum fractions from 0.05 to 0.2, the range presently accessible at RHIC, is not large.

The following are the main points from this spin plan:

- An increase in peak and average luminosity of a factor of 2 to 3 is anticipated. Increased polarization from 60% to 70% is also anticipated.

- The original goal to determine the beam polarization to $\Delta P/P < 5\%$ has been achieved. Further improvements are envisioned to improve the efficiency of the polarization measurements and to handle the higher rates that are expected.

- Sensitivity to the gluon spin contribution to the proton spin will improve significantly, by about a factor of four in uncertainty, with additional measurements of inclusive π^0 and jets planned for 2009. Asymmetry correlations of di-jets in 2009 will provide information regarding the momentum dependence of the gluon polarization and significant improvement in sensitivity over the inclusive data. These measurements will make a major contribution to the world's quest to understand the proton's structure. Further measurements using very forward direct photon production and measurements at $\sqrt{s} = 500$ GeV are expected to significantly expand the sampled gluon momentum range. Measurements in later years, with even higher luminosity, will add the direct photon and γ+jet probes. The direct photon measurements provide direct access to the gluon polarization and the gluon momentum fraction. Overall, this program will provide direct constraints on the gluon polarization over the momentum range from a few times 10^{-3} to 0.3.

- Parity-violating production of the W boson with longitudinally polarized protons at RHIC provides a direct measure of the individual polarizations of the quarks and anti-quarks in the colliding protons. This program will break new ground in our detailed understanding of the proton's structure. In the following, we respond to specific questions included in the charge from S. Vigdor, with the numbering used in the charge (Appendix A).

1. Luminosity recorded by the experiments of 300 pb^{-1}, accumulated over the next five years, will provide precise, direct measurements of anti-quark polarizations separated by flavor at the weak scale of real-W production.
2. The upgrades that are required for these measurements are underway for the PHENIX μ trigger system and the STAR forward tracking capabilities.
3. Signal to background levels of better than 1:1 are expected in the forward/backward region for both PHENIX and STAR, based on realistic simulations that include full QCD backgrounds. The expected background levels have been included in the sensitivity estimates that are presented. Central rapidity backgrounds have been estimated, with simulation studies not yet done. A short 500 GeV run is proposed for either 2009 or 2010 to measure these levels directly.
4. Tracking provides an estimated $>$97% correct identification of the charge of the measured muon from W decay, for PHENIX. The STAR upgrade will provide 80 to 95% estimated correct identification for W decay electrons and positrons in the endcap calorimeter.
5. Final extraction of the sea quark polarized distribution functions will use a global fit, as has been recently presented.
6. The program is proposed to begin in 2010, through 2013. If the program runs an average of 10 weeks per year, 300 pb^{-1} would be expected to be accumulated by the experiments. Results by the DOE milestone in 2013 will include significant direct measurements of the sea quark polarizations and the sea quark asymmetry, $\Delta\bar{u} - \Delta\bar{d}$.

W asymmetry measurements will remain statistics-limited after 300 pb^{-1}. Future RHIC luminosity and polarization improvements would make it practical to obtain significantly more data in later years, leading to very precise determinations of the sea quark polarizations.

- We propose a precision transverse spin program for RHIC exploring and exploiting large transverse asymmetries that have been measured world-wide, at RHIC and in DIS. Quark transversity, the degree of quark polarization in a transversely polarized proton, and quark orbital angular momentum are believed to generate the observed asymmetries. Quark transversity will be measured through single jet production and through di-hadron correlations. The orbital angular momentum description of the observed asymmetries leads to a pQCD prediction connecting forward direct photon production at RHIC to asymmetries observed in DIS. This measurement will test our understanding of the underlying physics and the orbital angular momentum origin of these asymmetries. A future feature of the transverse spin program requires a new step in luminosity from RHIC. A transversely polarized beam producing Drell-Yan pairs at RHIC tests a predicted direct connection between DIS and Drell-Yan asymmetries. The gauge structure of QCD leads to the prediction that the Drell-Yan and DIS asymmetries must have opposite signs. We see Drell-Yan measurements, by both the PHENIX and STAR detectors, as being a focus of the program beginning about 2015.

Evidently this entire plan rests on running. The plan assumes an average of ten physics weeks per year. Sustained running is necessary to build the required peak and average luminosity gains anticipated, to build the level of polarization anticipated, and to accumulate the required integrated luminosity recorded by the experiments, both at $\sqrt{s} = 200$ GeV and at $\sqrt{s} = 500$ GeV, through 2013. Support for development of higher proton-proton luminosity is very important for the exciting program envisioned for beyond 2013.

2 RHIC Accelerator, Polarimetry, and Experiments

2.1 Accelerator Performance

As of 2008 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% of polarization[1] at that energy. At 200 GeV center of mass energy, the average store luminosity reached 23×10^{30} cm^{-2}s^{-1}, and the average store polarization 58% (see Tab. 1). Over the next two long polarized proton runs we aim to reach the Enhanced Luminosity goals for polarized protons, consisting of an average store luminosity of

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

both with an average store polarization of 70%. Further improvements are possible thereafter. Table 1 gives a projection of the luminosity and polarization evolution through FY2013. Luminosity numbers are given for one of two interaction points. We assume 15 weeks of physics running in FY2009 and 10 weeks in the following years to allow for commissioning of the improvements and developments of the machine performance, as well as physics running. To maximize the proton polarization in RHIC, about one month of AGS tuning is needed before RHIC operation begins.

In Fig. 1 the integrated luminosity delivered to one experiment is shown through FY2013 for 15 weeks of physics operation in FY2009, and 10 weeks in the following years. For every projected period shown in Fig. 1, based on experience, 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 Tab. 1 are used as final values. The minimum projection is what had been demonstrated in the past. For Run-9 a reduction in the bunch length by some 30% is expected from the use of a new 9 MHz radio frequency system. For operation at 500 GeV center of mass energy, the bunch length is reduced by another 20% compared to operation at 200 GeV center of mass. In addition, the 200 MHz storage system can then be turned on adiabatically, which could shorten the bunches by up to another factor of 2, depending on the achieved longitudinal emittance.

The RHIC beam polarization is limited by the source, and the polarization transmission in the AGS. After proper adjustment of tune, orbit, and snake settings, no significant polarization

[1] Based on the polarimeter analyzing power at 100 GeV.

Fiscal year		2006	2008	2009E	2010E	2011E	2012E	2013E
No of bunches	...	111	111	111	111	111	111	111
Protons/bunch, initial	10^{11}	1.4	1.5	1.8	1.9	2.0	2.0	2.0
Avg. beam current/ring	mA	187	205	250	264	280	280	280
β^*	m	1.0	1.0	0.8	0.7	0.6	0.6	0.5
Beam-beam parameter/IP	10^{-3}	5.6	4.9	6.1	7.4	7.5	7.5	7.5
Peak luminosity (200 GeV)	$10^{30}\text{cm}^{-2}\text{s}^{-1}$	28	35	63	96	121	129	137
Avg./peak luminosity	%	64	65	63	62	60	60	60
Avg. store luminosity (200 GeV)	$10^{30}\text{cm}^{-2}\text{s}^{-1}$	18	23	40	60	73	77	82
Time in store	%	46	60	60	60	60	60	60
Max luminosity/week (200 GeV)	pb^{-1}	6.5	7.5	14.5	21.6	26.4	28.0	29.8
Min luminosity/week (200 GeV)	pb^{-1}			7.5	7.5	7.5	7.5	7.5
Max luminosity/run (200 GeV)	pb^{-1}	46	19	130	150	180	200	210
Min luminosity/run (200 GeV)	pb^{-1}			70	50	50	50	50
Max luminosity/run (500 GeV)	pb^{-1}				375	450	500	525
Min luminosity/run (500 GeV)	pb^{-1}				125	125	125	125
AGS polarization, extraction, min/max	%	65[1]	55[1]	55/65	55/70	55/70	55/75	55/75
RHIC avg. store polarization, min/max	%	58	45	50/60	50/65	50/70	50/70	50/70

[1] The AGS polarization may be restated in the future after the used analyzing power is calibrated in RHIC at injection in a polarization measurement with the polarized hydrogen jet.

Table 1: *Achieved and projected polarized proton beam parameters through FY2013. Delivered luminosities are given for one of two interaction points. Luminosities above a center of mass energy of 200 GeV increase proportionally with γ from the reduction in the transverse emittance. 15 weeks of physics operation are assumed for FY2009, and 10 weeks in the following years.*

loss is observed in RHIC up to a beam energy of 100 GeV, and no significant loss is anticipated at 250 GeV after full commissioning of ramps to that energy. Improvements in the source and the AGS are expected to increase the polarization at the AGS extraction energy from currently 60-65% to 75%. The AGS now operates routinely with two partial siberian snakes.

The luminosity can still be increased, as shown in Tab. 1, by lowering β^*, especially at 500 GeV center of mass energy. Then the main luminosity limit for the polarized proton operation is the beam-beam effect, leading to a spread in the transverse tunes. To accommodate larger beam-beam parameters other sources of transverse tune spread are minimized and different working points are evaluated. The use of electron lenses for head-on beam-beam compensation is currently studied in simulations. 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.

2.2 RHIC Polarimetry

Polarimetry is a crucial component of the RHIC Spin Program. Measurement of the absolute proton beam polarization to a precision of 5% is the goal for all high precision spin dependent measurements at RHIC. Two types of polarimeters are used at RHIC, which are based on small angle elastic scattering, with sensitivity to the proton beam polarization coming from interference between electromagnetic and hadronic amplitudes in the Coulomb-Nuclear Interference (CNI) region.

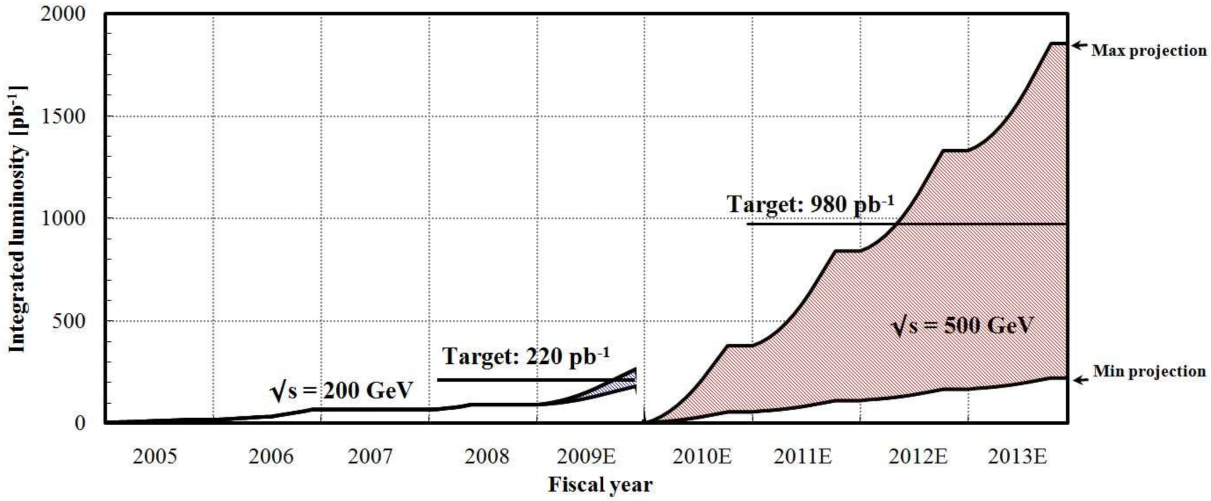

Figure 1: *Minimum and maximum projected integrated luminosity through FY2013. Delivered luminosity numbers are given for one of two interaction points, and a physics running time of 15 weeks in FY2009, and 10 weeks of physics operation per year thereafter. The assumed center of mass energy is 200 GeV until the end of FY2009, and 500 GeV thereafter.*

One type of polarimeter (p-Carbon) uses an ultra-thin (5 μg/cm^2) and 10 micron wide carbon ribbon target, and provides fast relative polarization measurements with a few percent statistical uncertainty in 20–30 sec. Repeated measurements during a fill also provide a handle on the beam polarization decay vs. time as well as measurements of beam polarization profiles in the transverse plane. The latter directly enters the average beam polarization observed in collisions at the interaction regions of the RHIC experiments.

The second polarimeter (H-Jet) uses a polarized hydrogen gas target and utilizes the analyzing power in proton-proton elastic scattering in the CNI region (Fig. 2). It accumulates data over the entire fill and provides absolute polarization measurements, with $\sim 10\%$ statistical uncertainty in a fill (6–8 hours).

H-Jet data accumulated over several fills are used for the absolute calibration of the p-Carbon polarimeters. The calibration goal of $\Delta P/P < 5\%$ was reached in the 2005 run. Fig. 3 demonstrates the normalized pC polarization measurements in fills of the 2006 run.

In addition, the two experiments STAR and PHENIX employ local polarimeters which are sensitive to transverse beam polarization, which are used to set up and to monitor the spin directions at collision.

For the near term, we have embarked on an upgrade program to replace the current p-Carbon polarimeter vacuum vessels with longer ones that accommodate two polarimeter set-ups and associated targets in each ring. This a) doubles the number of targets and minimizes the need to open the vessels during a long run, b) reduces the time required for successive measurements of the horizontal and vertical polarization profiles and thus experiment downtime, c) allows installation and testing of in situ new photo-diode detectors with higher rate capabilities, and d) improves the pumping and vacuum system. We are also investigating the possibility of using nano technology to produce carbon targets for the RHIC polarimeters. While promising work

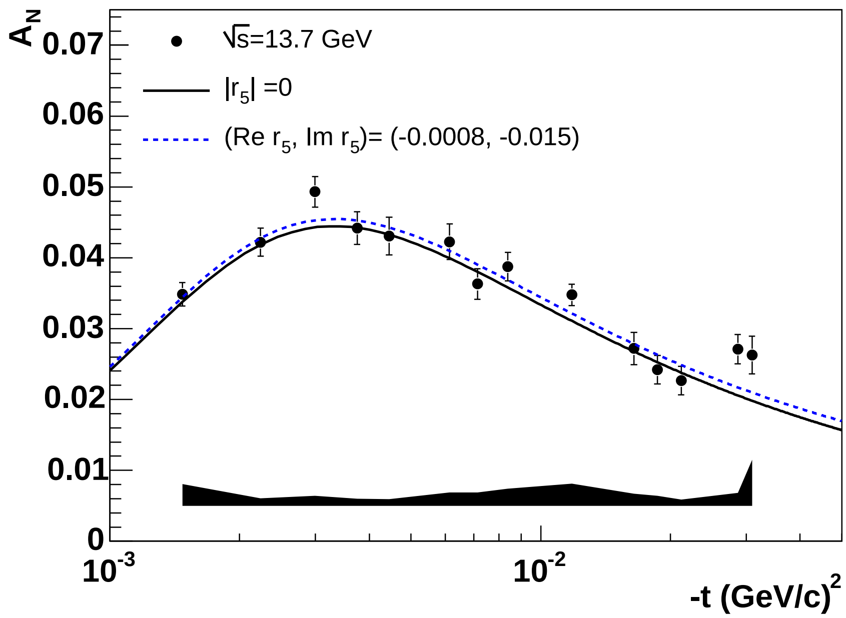

Figure 2: *Analyzing power, A_N, in proton-proton elastic scattering as a function of four-momentum transfer squared, $-t$, measured by the H-Jet polarimeter with 100 GeV/c RHIC proton beam [1]. The errors on the data points are statistical. The lower band represents the total systematic error. Theoretical prediction (solid line) and fit to the data (dashed line) are shown for comparison.*

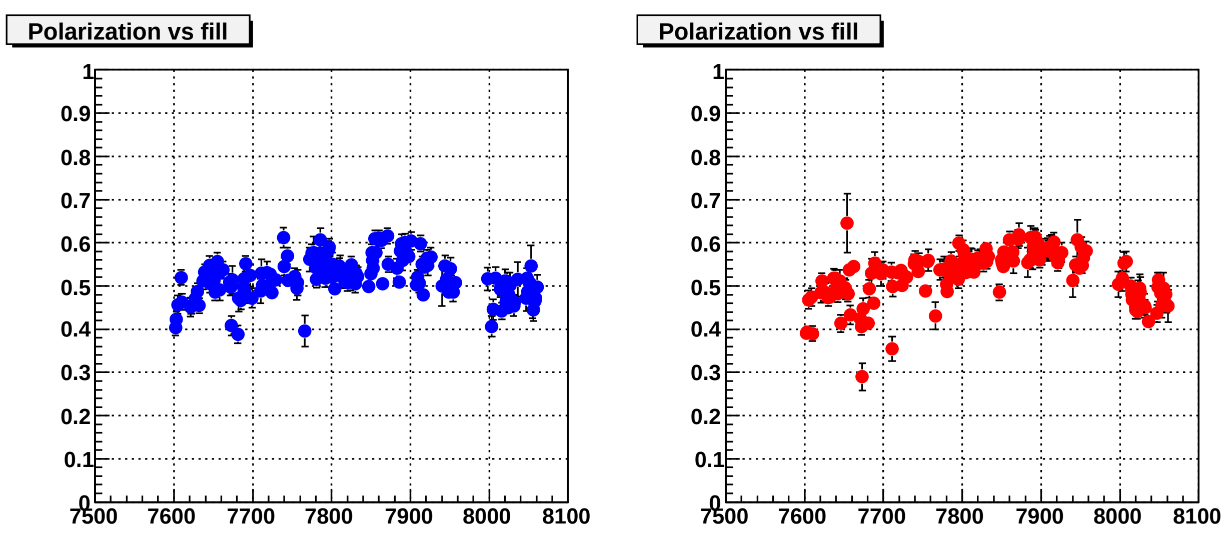

Figure 3: *Fill-by-fill polarizations for "blue" (left) and "yellow" (right) beams in RHIC run 2006, measured by the pC polarimeters. Fill numbers < 8000 are for 100 GeV/c beams. Fill numbers > 8000 are for 31.2 GeV/c beams.*

has been done, the challenge is to produce 30 mm long filaments or strands to be tested to assess durability and heat dissipation under realistic beam conditions.

In addition we plan a testing program using carbon beams from the Tandem spanning the carbon recoil energies, to better calibrate the silicon and photo-diode detectors' response.

In Run 2008, the polarized jet target was tested running with the Blue and Yellow beams separated by 5 mm vertically and both incident on the jet. Data analysis is in progress while initial results are encouraging. If deemed successful, this mode would allow the jet to continuously monitor the polarization of both beams in all physics fills, instead of alternating between the two beams.

Finally, while the polarized Jet target has calibrated the RHIC polarimeters for the physics runs, primarily at 100 GeV and once at 31 GeV, we have yet to provide a good calibration at RHIC injection. The only such measurement was carried out in a 15-hour run in 2004 which resulted in a meager 12% absolute beam calibration. Since then, the RHIC beam intensity and polarization have increased dramatically to allow a much more accurate calibration. This will serve several goals: a) cross calibrate the AGS and RHIC p-Carbon polarimeters at the same energy, b) provide a good RHIC injection measurement to discern polarization losses, if any, during RHIC ramps.

2.3 Experiments

Since the BRAHMS experiment successfully accomplished its physics program in 2006, the RHIC Spin program is being carried out by two principal experiments, PHENIX and STAR. Both experiments have been improving their capabilities for spin measurements. Extended electromagnetic calorimetry acceptance, including the Nose Cone Calorimeters and Muon Piston Calorimeters in PHENIX and the Forward Meson Spectrometer in STAR, will allow not only to improve kinematic coverage for well utilized probes in spin measurements, such as π^0, photon, jet and di-jet, but also will add the ability for γ+jet measurements over a wide kinematic range. Silicon vertex trackers, including the VTX and FVTX in PHENIX and the HFT in STAR, will open an opportunity to study charm and bottom quark production by measuring the displaced decay vertex. These trackers will also considerably extend the kinematic coverage for γ+jet measurements in PHENIX. Two detector upgrades are necessary for measurements of the flavor-separated quark and anti-quark polarizations through parity-violating W production. They are the muon trigger upgrade for the PHENIX muon arms and the Forward GEM Tracker (FGT) in STAR, and are discussed in detail in Sec. 5. In addition, an upgrade to the STAR TPC front-end readout electronics and data acquisition system will be accomplished by Run 9. It will increase the STAR event rate capability by an order of magnitude to $\sim$1 kHz, which will extend measurements to lower p_T and provide considerably better sensitivity for lower x measurements.

Only part of the RHIC delivered luminosity is sampled by the experiments, due to data acquisition live time, experiment uptime, and vertex acceptance. In PHENIX, this fraction, $\epsilon_{\mathrm{sample}}$ is approximately 30%. It is mainly limited by the fraction of collisions within the PHENIX interaction region, about 50%. It will be improved by a factor of 1.2–1.3 after the new 9 MHz rf system is installed in the RHIC rings, which will lead to a reduction of bunch length. Bunch length dynamic reduction at higher beam energies will lead to additional increase in the PHENIX

$\epsilon_{\rm sample}$ by a factor of 1.3–1.4 for the $\sqrt{s} = 500$ GeV program. In STAR, $\epsilon_{\rm sample}$ historically has been about 25%, due to the combined effects of experiment uptime and data acquisition live time. Beginning in Run 2009, this fraction is expected to increase to 50% for measurements such as jets and photons, which do not require a tight constraint on the collision vertex. This fraction will be ∼45% for W asymmetry measurements, because a moderate vertex constraint will be needed in order to obtain good charge-sign discrimination with the FGT.

The achieved $\epsilon_{\rm sample}$ along with expected improvements in the next runs are summarized in Table 2.

	Achieved (Run 2008)	Projected for $\sqrt{s} = 200$ GeV	Projected for $\sqrt{s} = 500$ GeV
PHENIX	0.30	0.35–0.40	0.50–0.55
STAR	0.25	∼0.50	∼0.45

Table 2: *Fraction $\epsilon_{\rm sample}$ of luminosity sampled by RHIC experiments over delivered luminosity.*

For physics sensitivities in this document we assume 50 pb^{-1} for $\sqrt{s} = 200$ GeV, and 300 pb^{-1} for $\sqrt{s} = 500$ GeV, for the luminosities used by the experiments. These correspond to a ratio of sampled luminosity to delivered luminosity of $\sim 1/3$, using a midpoint estimate for delivered luminosity (see Fig. 1). The sampled to delivered ratio could improve significantly if expected improvements in the vertex length are achieved.

3 Physics Introduction

The exploration of the inner structure of the nucleon is of fundamental importance. Two decades have passed since the European Muon Collaboration (EMC) at CERN discovered that the spins of the quarks and anti-quarks in the proton provide only an unexpectedly small fraction of the proton's spin [2, 3]. This finding, which became famously known as the "proton spin crisis", implies that the spins of the gluons or orbital angular momenta of the partons must contribute significantly to the proton spin, or both. To advance our understanding of the spin structure of the nucleon is the primary objective of the RHIC spin physics program. Its major goals are to measure the spin-dependent gluon distribution and constrain the gluon spin contribution to the proton spin, to elucidate the flavor structure of the valence and sea quark polarizations in the proton, and to explore high-energy spin phenomena arising for transverse proton polarization. As this report will show in detail, significant achievements have been made at RHIC toward these goals. Commensurate with these, there have been major advances in theory. In the following, we introduce the key objectives of the RHIC spin program, highlighting the progress that has been made, at RHIC and on the associated theory.

Precision measurement of the polarized gluon distribution $\Delta g(x)$ over a large range of momentum fraction x, to constrain the gluon spin contribution to the proton spin.
The spin-dependent gluon distribution $\Delta g(x, Q^2)$ is a fundamental component of nucleon structure. It measures the difference of number densities g^+, g^- of gluons with the same (opposite)

sign of helicity as the proton's:

$$\Delta g(x, Q^2) \equiv g^+(x, Q^2) - g^-(x, Q^2) \ , \tag{1}$$

where x is the momentum fraction of the gluon. We have indicated the dependence on the hard "resolution" scale Q at which the gluon is probed. QCD quantitatively predicts the variation of Δg with that scale. The integral of Δg over all momentum fractions $0 \leq x \leq 1$ gives the gluon spin contribution to the proton spin,

$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx \ . \tag{2}$$

Processes in polarized pp scattering at RHIC with final states produced at large transverse momentum provide unique access to $\Delta g(x, Q^2)$. As we described in the 2005 and 2007 RHIC Spin Plans [4, 5], spin asymmetries for such inelastic reactions may be interpreted in terms of the polarized parton distribution functions, among them Δg, and short-distance interactions of the partons. Thanks to the asymptotic freedom of QCD, the latter can be calculated in QCD perturbation theory. Using these calculated partonic cross sections, Δg can be extracted from the experimental measurements of spin asymmetries, over a range in x that is determined by the experimental kinematics.

Large efforts have been made over the past few years to obtain the first-order (or, "next-to-leading order (NLO)") QCD corrections to the spin-dependent partonic scattering cross sections relevant for the RHIC spin program, and for the measurement of Δg in particular [6]. This program is very advanced. The calculations for single-inclusive reactions such as $pp \to \pi X$ and $pp \to \mathrm{jet} X$, which have so far been used by the RHIC experiments to constrain Δg, have been completed. The attention is now shifting to less inclusive final states, such as di-jets or hadron pairs, concurrent with the path taken by the RHIC experiments. The viability of the perturbative-QCD approach has been established at RHIC by the successful quantitative comparison of measurements for the spin-averaged cross sections with the theoretical NLO predictions.

Published RHIC results [7, 8] indicate that the gluons in the proton are relatively little polarized in the range $0.02 \lesssim x \lesssim 0.3$ so far accessible at RHIC. Complementary results from lepton scattering made by the HERMES and COMPASS experiments [9, 10, 11] are consistent with this finding. Recent RHIC data collected during Run 6 [12, 13] close in on the spin-dependent gluon distribution Δg with higher precision.

A new "global analysis" of the RHIC and inclusive and semi-inclusive DIS asymmetry data has recently been introduced [14]. This analysis is an important theoretical advance. It treats all measured data simultaneously, which allows to extract the set of spin-dependent parton distribution functions that provides the optimal description of the combined data. All theoretical calculations in the analysis are performed at NLO of QCD perturbation theory. Quark, antiquark, and gluon polarized distributions in the proton have been obtained. The combined data set places a strong constraint on Δg. The gluon spin distribution turns out to be small in the region of momentum fraction $0.05 \lesssim x \lesssim 0.2$, but with still relatively large uncertainty. It is not yet possible to make a statement about the full integral over all $0 < x < 1$, the gluon spin contribution ΔG to the proton spin.

The results of the global analysis emphasize the two directions in which further experimental information will be of crucial importance. The first is to provide precision determinations of

$\Delta g(x, Q^2)$ over the presently accessible range in momentum fraction, $0.02 \lesssim x \lesssim 0.3$. This will allow definitive determinations of the gluon spin contribution arising from this region. The second is to constrain $\Delta g(x, Q^2)$ at lower and, possibly, higher x than so far accessible. It is not ruled out that there are significant contributions to ΔG from $x < 0.02$ or so, and reaching to lower x will improve the extrapolations needed to obtain the full integral. While large contributions to the integral are not expected from the high-x region, it is predicted by some models that $\Delta g/g$ becomes sizable there [15]. As we will describe in this document, planned measurements at RHIC should well allow to fulfill these goals. Studies of di-jet and jet-photon coincidences, at central and forward angles, allow precision mapping of $\Delta g(x, Q^2)$ over a broad range in x. Both channels have tremendous assets: di-jets will be produced with very large statistics, while direct-photon events generally have a favorable analyzing power. Measurements at RHIC's higher pp center-of-mass energy of 500 GeV, both for inclusive channels and for coincidences, will also be important for reaching lower x.

Measurements of the polarized quark and anti-quark flavor structure in the proton. Parity violation is a fundamental phenomenon in nature. Even though very well established and tested, its very observation in polarized pp scattering at RHIC would be a qualitatively new and beautiful measurement. Up quarks in the proton are known from the DIS measurements to be highly polarized along the proton spin, at momentum fraction $x \gtrsim 0.1$. Thus, a beam of polarized protons of negative helicity essentially provides a beam of left-handed up quarks. As a manifestation of the maximal parity violation of the W bosons, they precisely couple only to left-handed particles. Therefore, when the up quarks collide with a $\bar{d}$ anti-quark from an unpolarized proton to produce a W^+ boson, a very large and negative single-spin asymmetry should be seen when the decay positrons are in the forward direction of the polarized proton. Never before has parity violation in the quark sector been studied in such a direct way. We also note in this context that the valence region $x \gtrsim 0.1$ probes the presence of non-vanishing orbital angular momentum components in the nucleon wave function [15, 16]. This has become a particularly interesting topic recently for the case of the down valence quarks, where DIS measurements performed at the Jefferson Laboratory [17] indicate the importance of such components in nucleon structure. The measurements at RHIC for W^- production with forward negative leptons will offer exciting independent information, at a much higher scale set by the large W mass, $Q^2 \approx 6400$ GeV^2, vs. $Q^2 \sim 1 - 10$ GeV^2 in present polarized DIS.

It has long been recognized that $W^\pm$ boson production at RHIC provides unique and clean access to the individual polarizations of anti-quarks in the colliding protons [18]. When the decay lepton is produced more to the backward region of the polarized proton, first direct probes of $\bar{u}$ and $\bar{d}$ anti-quark polarization at medium momentum fraction, $0.04 \lesssim x \lesssim 0.15$ become possible. Here the goal is to explore the details behind the small total quark and anti-quark spin contribution to the proton spin measured by DIS. Do anti-quarks play a decisive role in this? Do $\bar{u}$ and $\bar{d}$ carry similar polarization? This question becomes all the more interesting in view of the large difference between the spin-averaged $\bar{u}$ and $\bar{d}$ found in DIS and Drell-Yan measurements. It is well known that such questions relate to fundamental aspects of strong-interaction dynamics. Models of nucleon structure generally make clear predictions about the flavor asymmetry in the sea [19, 20, 21]. For example, since u quarks in the proton are primarily aligned with the proton spin while d quarks carry opposite polarization, one finds from considerations based on the Pauli principle the qualitative expectations $\Delta\bar{u} \geq 0$, $\Delta\bar{d} \leq 0$ [19], and there are arguments that the flavor asymmetry in the nucleon should be even larger in the polarized than in the spin-averaged case, $|\Delta\bar{u} - \Delta\bar{d}| > |\bar{u} - \bar{d}|$.

Dedicated measurements of the quark and anti-quark polarizations can also be performed in semi-inclusive DIS by tagging definite hadrons in the final state. Data have been obtained by the SMC, HERMES, and COMPASS collaborations [22]. They are included in the new global analysis [14] discussed above, and indeed the results give a first hint at a flavor asymmetry in the polarized sea. However, the uncertainties are still large, and it is in particular difficult to quantify the systematic uncertainty of the results related to the fragmentation mechanism at the relatively modest energies available. We emphasize again that the $W^{\pm}$-boson measurements at RHIC are entirely free of this ambiguity, at much higher scales, and have little theoretical uncertainty. Ultimately, all RHIC data for the spin asymmetry in W production will be included in the global analysis, so that the best possible information can be extracted and comparison to the information from semi-inclusive DIS can be made.

We will discuss W production at RHIC in detail in this document, and also the challenges that are involved in the measurements.

Studies of transverse-spin phenomena in QCD.
At the same time that we observe small or zero helicity asymmetries in our measurements sensitive to the gluon polarization, large spin asymmetries are observed at RHIC for production of pions and other hadrons in the forward direction of the polarized beam, for transversely polarized protons colliding with unpolarized protons. The RHIC results [23, 24, 25], demonstratively in the hard scattering regime, along with results from DIS [26, 27] and e^+e^- annihilation [28], have led to a renaissance of transverse spin, with many new experimental results, and major advances in the theoretical treatment, based on perturbative QCD.

The value of single-spin asymmetries lies in what they may tell us about QCD and the structure of the proton. Much progress has been made in our conceptual understanding of single-spin phenomena in recent years. Particular focus has been on a class of parton distribution functions known as “Sivers functions” [29], which express a correlation between a parton’s transverse momentum, and the proton spin vector. They therefore contain information on orbital motion of partons in the proton. Theoretical studies have found that the Sivers functions are not universal in hard-scattering reactions [30, 31, 32]. Their non-universality has a clear physical origin that may be viewed as a rescattering of the struck parton in the color field of the remnant of the polarized proton. Depending on the process, the associated color Lorentz forces are predicted to act in different ways on the parton. In deep-inelastic scattering (DIS), the final-state interaction between the struck parton and the nucleon remnant is attractive. In contrast, for the Drell-Yan process it becomes an initial-state interaction and is repulsive. As a result, the Sivers functions contribute with opposite signs to the single-spin asymmetries for these two reactions [30, 31, 32, 33]. Beyond color-singlet processes, the non-universality manifests itself in more complex, but calculable, ways. It has been predicted [34] that the sign change with respect to DIS also occurs in $pp \to \gamma\, \mathrm{jet}\, X$ through the dominant Compton process. For “pure-QCD” processes such as $pp \to \mathrm{jet}\, \mathrm{jet}\, X$, initial-state and final-state interactions tend to counteract [35, 36].

The prediction of non-universality of the Sivers functions is fundamental and rooted in the gauge structure of the interactions. It tests all our concepts for analyzing hard-scattering reactions, and its verification is an outstanding challenge in strong-interaction physics that has become a top priority for the world-wide hadronic physics community. Given that Sivers-type single-spin asymmetries have been observed in semi-inclusive DIS [26, 27], the challenge is on now for pp scattering at RHIC to provide definitive tests.

Another important focus of transverse-spin physics is "transversity". The transversity parton distributions, introduced in [37, 38], measure the transverse polarization of partons along or opposite to the transverse proton spin. Differences between transversity and the helicity distributions discussed earlier give information about relativistic effects in the nucleon [38]. The transversity densities also determine the fundamental tensor charge of the nucleon [38, 39]. The peculiar chiral-odd nature of transversity, which is responsible for much of its physics, has made experimental determinations elusive so far. Only recently has it become possible to combine measurements of Collins-type single-spin asymmetries in lepton scattering [26] with dedicated determinations of the Collins fragmentation functions in e^+e^- annihilation [28], to obtain a first glimpse at the valence transversity distributions [40]. Transversely polarized pp scattering at RHIC offers access to the transversity distributions. Two fragmentation effects, the Collins mechanism [41] and "Interference Fragmentation" [42], provide excellent probes. We will discuss these planned measurements in this document.

4 Measurements of the Polarized Gluon Distribution at RHIC

One of the main goals of the RHIC spin program is to precisely determine the spin-dependent gluon distribution $\Delta g(x)$ over a wide range in gluon momentum fraction x. As we discussed in the Introduction, the integral of $\Delta g(x)$ over all x gives the gluon spin contribution ΔG to the proton spin. In view of the proton "Spin Crisis" or "Puzzle" presented by determinations from DIS [2, 3] that the spins of the quarks and anti-quarks contribute at most about a third of the proton's spin, ΔG could well be key to understanding the proton spin in QCD. RHIC exploits high transverse momentum (p_T) final states originating from collisions of polarized protons that directly involve the gluons. The spin dependence in the partonic subprocesses is often large, providing good sensitivity to the gluon spin distribution, and the large acceptance of the detectors offers access to a wide range of the gluon momentum fraction x.

Since the last update [5], the impact of our data to date has become much more clear. Many earlier fits solely to DIS data with moderate to large gluon contributions are incompatible with RHIC and new DIS data. This is best demonstrated in a recently released NLO global fit [14] to all data, DIS, SIDIS and RHIC inclusive π^0 and jet data, on an equal footing. The best fit in this analysis has a gluon distribution with a node in the x region addressed by the RHIC measurements to date (at the initial scale of $Q^2 = 1$ GeV^2), pointing toward the need for improved sensitivity to the x dependence of $\Delta g(x)$. Moreover, substantial contributions to the integral ΔG are still possible at lower x, indicating the need to extend measurements in that direction as well.

RHIC is uniquely situated in the next five years to address these issues. Basing our plans on realistic assumptions that would give 50 pb^{-1} recorded at 200 GeV in the early portion of the coming five years, with opportunities for additional data near the end of the term, and significant integrated luminosity at 500 GeV for the W program, very important contributions can be made to our understanding of $\Delta g(x)$. The statistics on the inclusive jet and π^0 channels will be improved by about a factor of 4. These data integrate over broad ranges in x. New in the coming five years will be the opportunity to perform measurements sensitive to the shape of $\Delta g(x)$. This will provide important constraints on the functional form assumed in global analyses, thereby reducing the theoretical uncertainty in extracting the gluon polarization and reducing the uncertainty in the determination of the integral contribution, ΔG, that arises from extrapolation outside the measured region. For $0.02 < x < 0.3$, our best information will come from di-jet correlations. These will be backed up by important independent information from γ-jet correlations, albeit with lower statistical precision. To reach $x \simeq 0.01$ and below, we will exploit new calorimetry at forward rapidity, using γ correlations with mid-rapidity jets in addition to measurements at center-of-mass energy 500 GeV. Thus, over the next five years we expect to be able to map out $\Delta g(x)$ with relevant precision in the x-range of a few times 10^{-3} to ~ 0.3.

To achieve this goal, we require progress with polarized beams consistent with improvements described in Sec. 2. With the completion of the FMS and DAQ1000 at STAR, no further upgrades are required, although it is expected that addition of the Forward GEM Tracker will be beneficial to detecting jets and photons in the covered region. PHENIX will greatly improve its capabilities with the VTX tracking and Nose Cone Calorimeter upgrades.

In the following we expand on the above by presenting the most recent data, demonstrating their important impact on the first global (hadronic plus (SI)DIS) fits, and describing how our future measurements will provide important qualitative improvements in our understanding of the role of the gluon spin in the proton. Note that additional details of the planned measurements of Δg are presented in Appendix C.

4.1 Recent Results

4.1.1 Inclusive π^0s and jets

The 200 GeV run in 2006 produced 8 pb^{-1} of recorded integrated luminosity with longitudinal polarization, resulting in large improvement on the inclusive measurements made by the two experiments in previous years. Shown in Fig. 4 are the double spin asymmetries A_{LL} for inclusive jets at STAR and inclusive π^0s at PHENIX. The curves correspond to theoretical NLO calculations [43, 44] of A_{LL} for a range of polarized gluon distribution functions [45, 46], as described in the figure caption.

The first full-fledged global analysis at next-to-leading order (NLO) accuracy of all currently available spin-dependent data, including the 2006 RHIC preliminary results for inclusive jets and π^0s, was completed very recently by DSSV [14]. The resulting polarized gluon density is depicted in the upper left panel of Fig. 5 together with estimates of the typical uncertainties involved in the analysis procedure based on a common approach using “Lagrange multipliers”. The DSSV result is compared to previous fits of GRSV [45] and DNS [47], which are now outside the uncertainties estimated by DSSV. The impact RHIC data have on the determination of $\Delta g(x)$ is clearly visible in the upper right panel where the partial contributions $\Delta\chi_i^2$ of the individual data sets for variation of the truncated integral of Δg over the range $0.05 < x < 0.2$ are shown. RHIC data currently provide the best limit on negative values of this integral and are comparable to DIS for positive values. For $x \lesssim 0.05$ the uncertainties in $\Delta g(x)$ are still sizable, and the full integral, $\Delta G = \int_0^1 \Delta g(x) dx$, which represents the contribution of gluons to the spin of the nucleon, is still not determined. Additional constraints from measurements over an extended x range, especially at lower x where the spin-averaged distribution $g(x)$ is large, in addition to

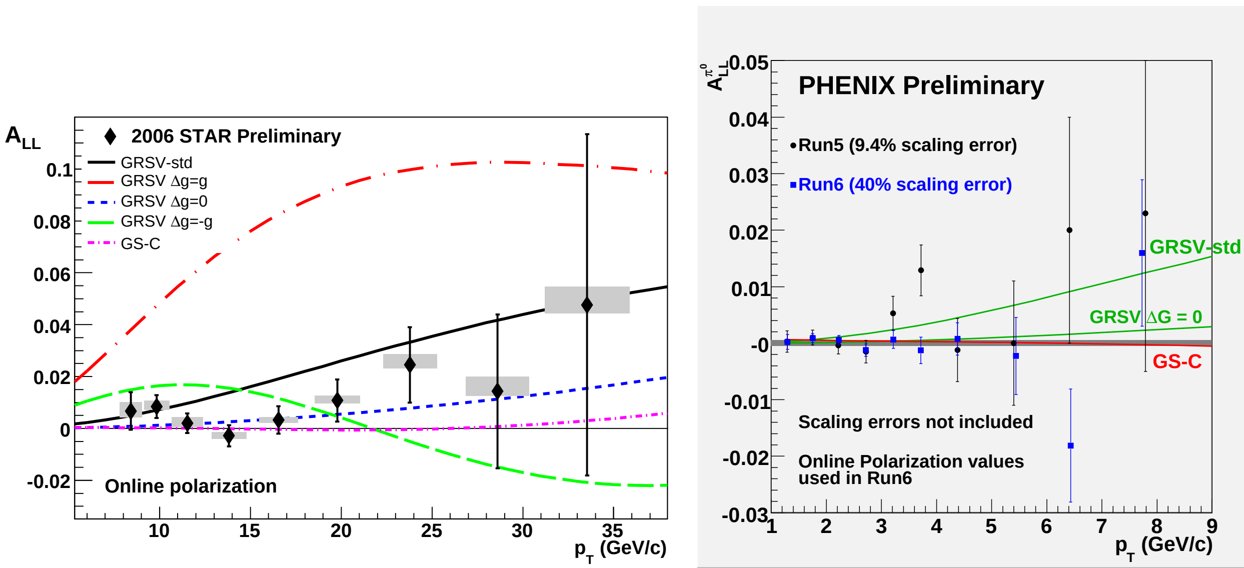

Figure 4: *A_{LL} for 2006 inclusive jet data from STAR (left) and π^0 data from PHENIX (right). The theoretical NLO curves [43, 44] are based on different models of gluon polarization from GRSV [45], including their best fit "GRSV-std", and the GS-C fit of [46], which is characterized by a node vs. x but still has a large integral ΔG resulting from its low-x dependence. Also shown is a simple GRSV model with $\Delta g(x) = 0$ at the input scale. In the left-hand figure the results for two extreme assumptions about Δg, maximally aligned ($\Delta g(x) = g(x)$) and anti-aligned ($\Delta g(x) = -g(x)$) at the input scale, are also shown. We note that final polarization calibrations have been completed and the scale uncertainty for A_{LL} for 2006 measurements will be below 10%.*

constraints on the functional form of $\Delta g(x)$ will be necessary to determine the full integral ΔG.

4.1.2 Other experiments

The broad interest in understanding the nucleon's spin structure has led to a world-wide experimental program in polarized DIS. The efforts of the COMPASS experiment at CERN, the recently completed HERMES experiment at DESY, and many experiments at Jefferson Laboratory are well documented elsewhere [4], and we provide only a brief update on the status of Δg studies from these lepton scattering experiments.

First and foremost, deep inelastic lepton scattering provides information on the polarized gluon distribution via scaling violations of the structure function g_1. The results from COMPASS, HERMES, JLab and earlier experiments are an integral part of a global analysis [14], and their combined impact on determining $\Delta g(x)$ is also shown in the upper right panel of Fig. 5. The analysis of DIS data is well developed and there are many practitioners [45, 46, 47, 48, 49, 50, 51]. These most recent fits show considerable progress, but still substantial uncertainty in the shape of $\Delta g(x)$ and sign of the integral ΔG remain.

The HERMES and COMPASS experiments have also pursued $\Delta g(x)$ via photon-gluon fusion detected by high p_T hadron pairs [9, 10, 52, 53] and, in the case of COMPASS, open charm production [11]. These are leading order extractions and are thus not included the DSSV global

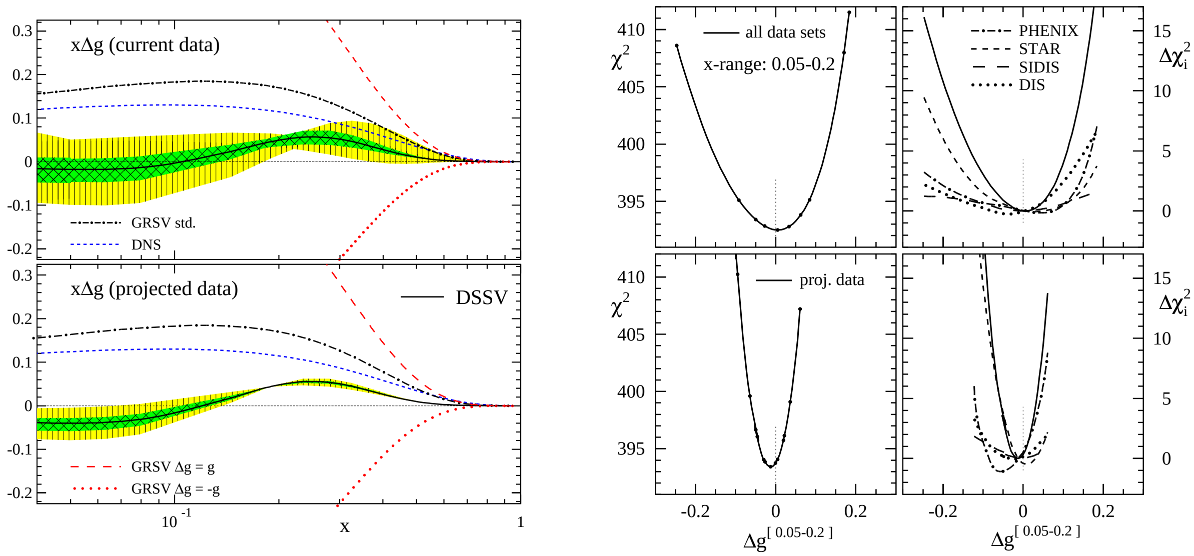

Figure 5: *Upper row: $x\Delta g$ ($Q^2 = 10$ GeV^2) from the global NLO QCD analysis by DSSV [14] (left) and partial contributions $\Delta\chi_i^2$ of the fitted data sets to the total χ^2 for variation of $\int_{0.05}^{0.2} \Delta g(x)dx$ (right). The uncertainty bands correspond to $\Delta\chi^2$ = 1 (green/cross-hatched) and $\Delta\chi^2/\chi^2$ = 2% (yellow/vertically hatched). Also shown are results for $\Delta g(x)$ from previous GRSV [45] and DNS [47] analyses. Lower panels: same as above when the RHIC data errors are scaled down by a factor of 4 as expected from the next long RHIC pp run at 200 GeV (50 pb^{-1} with a polarization of 60%).*

analysis. The $\Delta g(x)/g(x)$ results are consistent with zero to within uncertainties of ~ 0.1, for $x \sim 0.15$.

The overall conclusion is that results from lepton scattering experiments and the RHIC program are in agreement. Large contributions from the gluonic spin to the proton spin in the range directly examined so far, $0.02 < x < 0.3$, are unlikely. However the possibility of an interesting x dependence for $\Delta g(x)$ and the importance of the lower-x range have been brought to the fore.

4.2 Δg and RHIC Spin: Next Five Years 2009-2013

With upgrades newly completed or under construction, with planned increases in luminosity and runs at 500 GeV, RHIC and its two experiments, STAR and PHENIX, are uniquely positioned to add significant new constraints on the magnitude and functional form of $\Delta g(x)$. In this section we describe these new capabilities, measurements and their expected impact.

4.2.1 Semi-inclusive channels

As the luminosity of RHIC grows, the already large STAR detector acceptance and the wider acceptance windows becoming accessible to PHENIX due to its detector upgrades (Si VTX tracker and Nose Cone Calorimeter) will allow measurements of "two-particle" correlations such

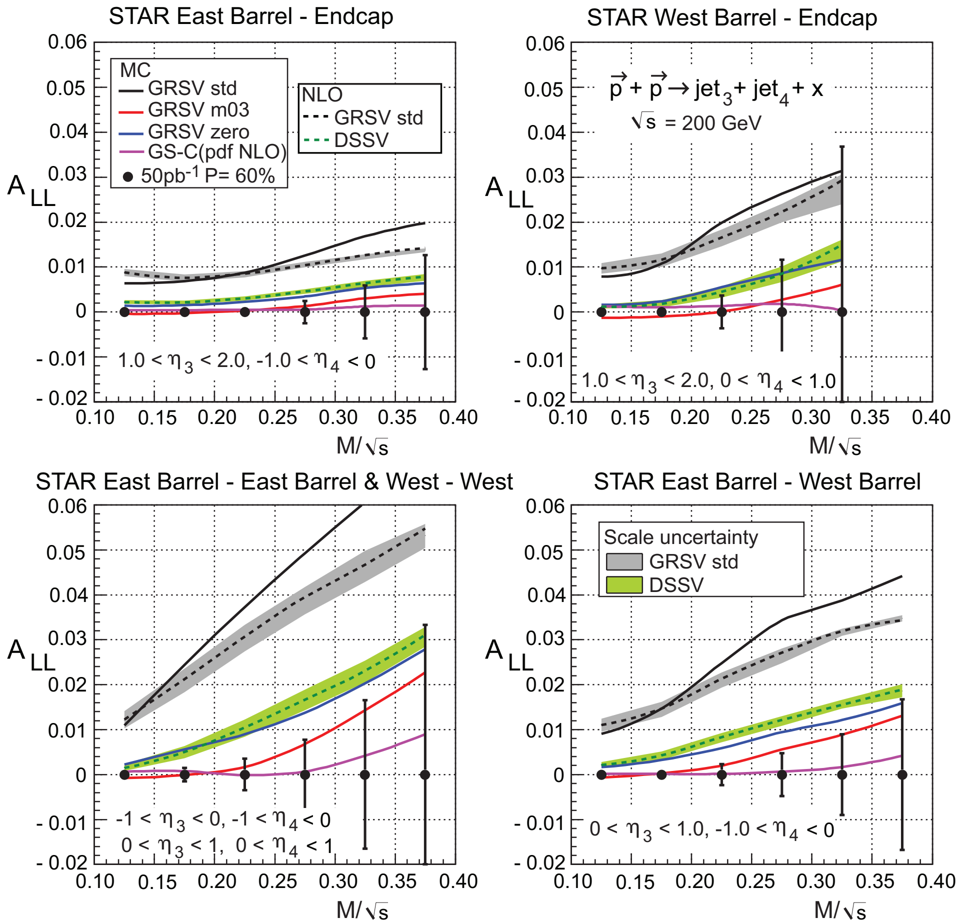

Figure 6: *A_{LL} vs. $M/\sqrt{s}$ for di-jets of pair mass M, produced at $\sqrt{s}$ = 200 GeV. Individual plots represent di-jets shared between various regions of the STAR EM calorimeters. The uncertainties shown are expected for an integrated luminosity of 50pb^{-1} and a polarization of 60%. The curves represent the results obtained from a Monte-Carlo calculation for various sets of polarized parton distribution functions: GRSV-std [45], GRSV $\Delta g = 0$, GRSV with a gluon distribution having an integral -0.3 at the initial scale, and GS-C [46]. In addition, NLO calculations [54] for the GRSV-std and DSSV [14] sets are also shown.*

as jet-jet, hadron-hadron and photon-jet coincident events. The x-range probed in this way, $\sim 2 \times 10^{-3} < x < 0.3$, far exceeds that of any other experiment in the near future. At leading order, the hard scattering subprocess kinematics can be calculated on an event by event basis. This allows to address one of the goals mentioned earlier, namely to extract $\Delta g(x)$ directly, “locally” in x. While such LO extractions must be followed up with full theoretical work associated with evaluation of cross sections and asymmetries at next-to-leading order, they illustrate that individual measured points in the correlations are sensitive to a narrow range of gluon momentum fraction x, so that the points map out the x dependence of $\Delta g(x)$.

With realistic expectations on luminosity, our best knowledge regarding $\Delta g(x)$ in the range $0.02 < x < 0.3$ will come from the di-jet channel, with γ-jet correlations supplying important independent information, however with less statistical precision. Using two-body kinematics, the di-jet data can be plotted vs. a number of different kinematic variables, with cuts applied on others. This provides near double-differential distributions. In Fig. 6 we show the expected statistics for di-jets at $\sqrt{s} = 200$ GeV plotted vs. $M/\sqrt{s}$, where M is the pair invariant mass. Note that at leading order one has $M/\sqrt{s} = \sqrt{x_1 x_2}$, where x_1, x_2 are the momentum fractions of the two colliding partons. Each panel in the figure represents a different combination of EM calorimeter sections contributing to the di-jet yield. Thus each panel represents a different selection of x_1/x_2 and $\cos\theta^*$, where θ^* is the scattering angle in the partonic center-of-mass frame, and each point is sensitive to $\Delta g(x)/g(x)$ over a narrow range in x. For example, the first three points in the lower left panel of Fig. 6, for which $0 \leq |\eta_{3,4}| \leq 1$ (with η_3, η_4 the two jet pseudo-rapidities) represent approximately non-overlapping x bins centered at 0.076, 0.10 and 0.13. A leading order study, considering the known average quark polarization at these x values, and taking into account some dilution from gg and qq scattering, leads to an estimate that these points each determine the gluon polarization $\Delta g(x)/g(x)$ to an absolute accuracy of about $0.02 - 0.03$. The bins corresponding to $M/\sqrt{s} = 0.15 - 0.2$ in the upper and lower right panels of Fig. 6 correspond to an x of 0.06 and 0.16, respectively. Note that the asymmetries are often larger than for inclusive jets and that there is sensitivity on the scale of the currently allowed range of polarized gluon distributions, as represented by the results for GRSV ($\Delta g = 0$) and GS-C obtained from a Monte-Carlo study. Also shown are NLO calculations [54] for DSSV and GRSV-std, with scale uncertainties. The latter are quite small and thus give strong indication that the process is under good theoretical control. We emphasize that the goal of the measurements is to directly extract the functional form of $\Delta g(x)$ from the data.

For particle production at forward pseudo-rapidities, a combination of a rise in the underlying partonic asymmetry correlates with a rise in the back-angle qg Compton scattering cross section, which may result in a very competitive measurement of the gluon polarization. With completion of the FMS in the past year, STAR now has EM calorimetric coverage in pseudo-rapidity from $-1 < \eta < 4$. The relationship $\eta_3 + \eta_4 = \ln(x_1/x_2)$ illustrates that correlations between direct photons in the FMS ($\eta = 3.3$) and jets at mid-rapidity ($-1 < \eta < 2$) can be used to probe gluons with x values as low as a few times 10^{-3} with highly polarized large-x ("valence") quarks, whose distribution is accurately known from DIS measurements. The experimental issues related to the direct-photon jet channel, such as suppressing the fragmentation photon background and detecting the low p_T ($\sim$2.5 GeV/c) jet at mid-rapidity, are identical to those described below in Sec. 6. Initial studies indicate that a signal to background ratio of 2:1 is achievable before considering the coincidence with the awayside jet, as shown in Fig. 7. This should allow measurements of the gluon polarization for $x \ll 0.02$ at a level that can provide constraints within the range allowed by current fits in a run of 50 pb^{-1}. More detailed simulations and studies of data taken in run 8 are required before more quantitative sensitivities can be provided.

The γ-jet channel also has important contributions to make at higher x, despite the statistical advantages of the di-jets in the relevant mid-rapidity regions. The direct photons will provide independent information where the initial state is dominated by the qg process, the final state has little or no strong interactions, and where the scale dependence of the theoretical description is smaller [56]. It is recognized that extracting the γ-jet signal from the prolific number of di-jets is a challenging problem, as illustrated in early simulations [57]. Considerable progress using full detector simulations and data from 2006 has been made in understanding this problem, but we have not yet reached the stage where quantitative sensitivity projections can be made. However, sufficient yield is produced with the luminosities expected in the next few years to make measurements with physics impact in the γ-jet channel, assuming high efficiency and reasonable background suppression are proven. The measurements will greatly benefit from higher statistics

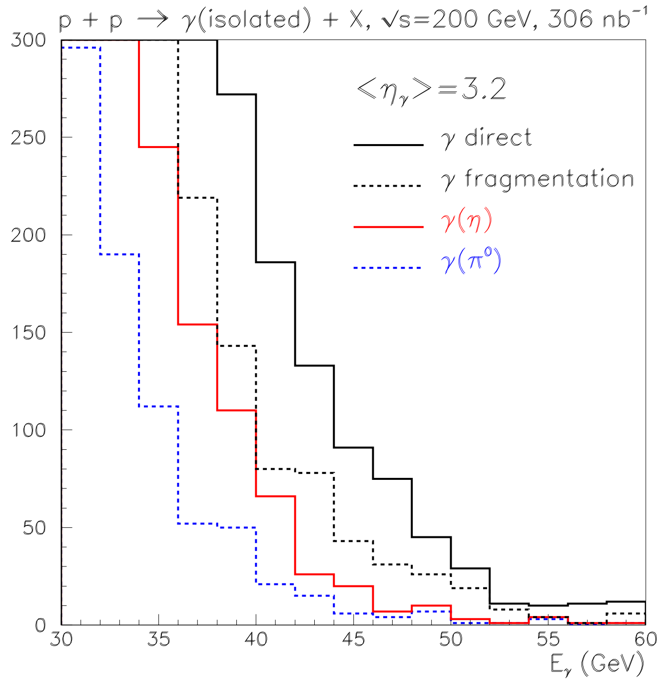

Figure 7: *Simulation of the inclusive forward photon spectrum. Direct photon candidates are detected in a small fiducial volume within the FMS, at* $3.1 < \eta < 3.4$*. The remainder of the large area FMS, with* $2.5 < \eta < 4$*, is used as a veto to require that the candidate be isolated. Only candidates with energy above 35 GeV are considered, in order to avoid the increasing fragmentation background for lower energies. The signal to background ratio is already 2:1 with these simple cuts.*

to come later in the five-year period when the experiments return to collect large luminosity at 200 GeV for heavy ion comparison data after the tracking upgrades are in place. Even then the measurements will still be statistics limited and additional running could be pursued beyond the five-year time frame based on the status at that time.

The programs for di-jets and γ-jets will be extended to 500 GeV for both STAR and PHENIX. At this energy, a given p_T will correspond to an x value lower by a factor of 2.5 than for 200 GeV collisions. It is expected that luminosity requirements will be driven by the W program. Projections for di-jet measurements at STAR for 300 pb^{-1} at $\sqrt{s} = 500$ GeV are shown in Fig. 8.

4.2.2 Inclusive channels

Inclusive channels, with π^0s and jets being the most sensitive, have been the workhorse of the program to date. The increased luminosity expected in the coming years will permit these channels to provide far more precise information about $\Delta g(x)$, as illustrated in Fig. 9. The impact of including approximately another 50 pb^{-1} of inclusive π^0 data from PHENIX and jet data from STAR in a global fit is shown in the lower portion of Fig. 5. The projected uncertainty in the integral of Δg over the range $0.05 < x < 0.2$ is a factor of 2.4 smaller than at present.

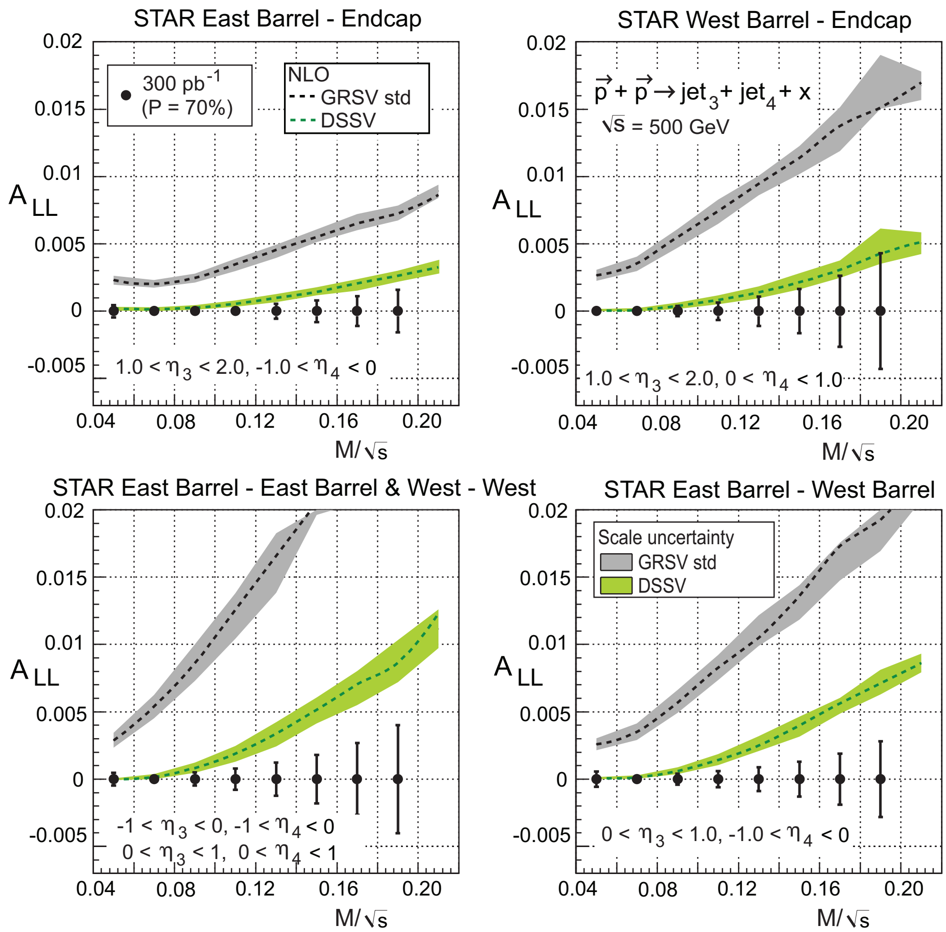

Figure 8: A_{LL} *vs.* $M/\sqrt{s}$ *for di-jets at* $\sqrt{s}$ *= 500 GeV. Individual plots represent di-jets shared between various regions of the STAR EM calorimeters. Uncertainties shown are based on an integrated luminosity of 300 pb*$^{-1}$ *and polarization of 70%. The curves represent NLO calculations [54] using the GRSV-std [45] and DSSV [14] sets.*

There are two principal inclusive channels, direct photons and charged pions, whose impact has been limited by statistics with the luminosities delivered so far. With an additional 20−30 pb^{-1}, these will start to play a role. As we discussed earlier, direct photon production is dominated by quark-gluon Compton scattering, so that the spin asymmetry is linear in $\Delta g(x)$. Moreover, the combination of quark and anti-quark polarizations that also enters the polarized qg process has been measured accurately by the spin asymmetry A_1^p in the past DIS experiments. Thus the inclusive direct photon process offers an independent and complementary probe of the polarized gluon distribution. The quark-gluon subprocess also dominates for midrapidity pion production at about $p_T > 5$ GeV/c, leading to an approximately linear dependence of the asymmetries on $\Delta g(x)$. The preferred fragmentation of π^+ from an up quark and π^- from a down quark and the fact that Δu and Δd are known from the polarized-DIS measurements to have opposite signs, lead to an ordering of the pion asymmetries that depends on the sign of $\Delta g(x)$ [55]. Thus charged-pion A_{LL} measurements at high p_T will provide enhanced sensitivity to the sign of Δg, compared to neutral pions alone.

In the next few years the pp running will turn to $\sqrt{s} = 500$ GeV. It is fully expected that the

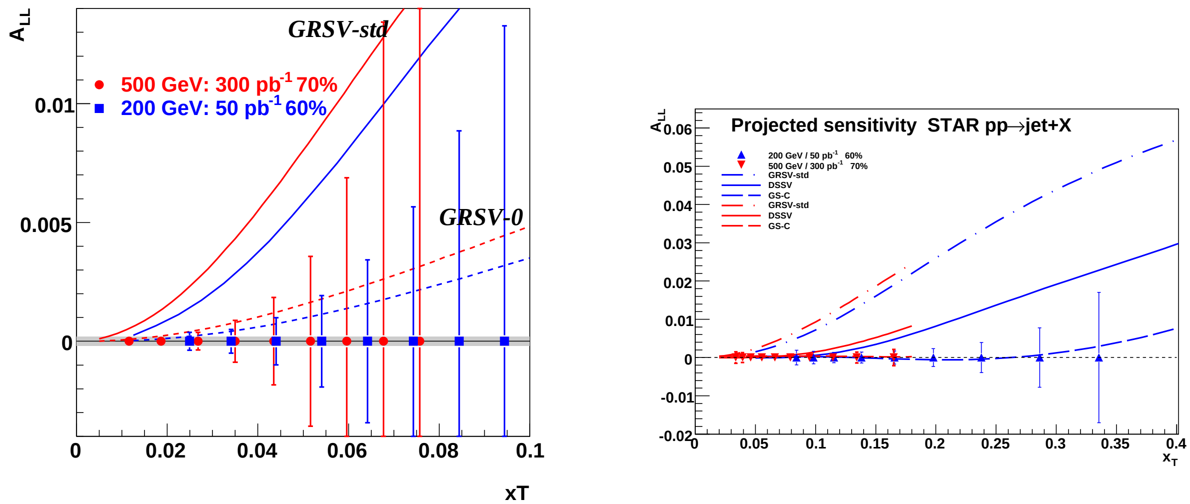

Figure 9: *Left: PHENIX estimated statistics for* A_{LL} *vs* $x_T = 2p_T/\sqrt{s}$ *for inclusive* π^0*s at* $\sqrt{s} = 200$ *GeV (50 pb*$^{-1}$ *with a polarization of 60%) and 500 GeV (300 pb*$^{-1}$ *with a polarization of 70%). Right: STAR estimated statistics for inclusive jet production at 200 and 500 GeV under the same assumptions. The panels also show NLO calculations [43, 44] of* A_{LL}*, obtained for GRSV std [45], a GRSV model with* $\Delta g = 0$ *at the initial scale, and (for jets) the GS-C fit of [46].*

inclusive channels will again provide the first results at this energy. A given p_T will naturally probe lower x for the gluon and thus assist in our effort to constrain $\Delta g(x)$, as can be seen in Fig. 9. However, the main inclusive channels will be dominated by gluon-gluon scattering in a momentum range where the unpolarized gluon density is quite large. Thus, the asymmetries are quite small. In the left part of Fig. 9 we show estimates of inclusive π^0 statistics expected at PHENIX for 200 GeV and 500 GeV collisions. Integrated luminosities of 50 pb^{-1} and 300 pb^{-1}, respectively, are assumed, along with realistic estimates of trigger efficiencies based on previous runs. As well, the lowest p_T point uncertainties assume the use of spin-flipping during RHIC stores to reduce systematic uncertainties. The right panel shows STAR estimated statistics for inclusive jet production at 200 and 500 GeV, under the same assumptions for luminosity and polarization. As the left part of the figure shows, using A_{LL} for π^0 with running at 500 GeV, one can reach down to $x_T = 2p_T/\sqrt{s} \sim 0.01$. We also show two NLO theoretical calculations. The comparison of the asymmetries at the two energies demonstrates that they approximately scale with x_T.

5 Measurement of the Quark and Anti-Quark Polarizations with W Bosons at RHIC

5.1 Introduction

Parity violation was first discovered in β decays and is well established. So far, most parity violating signals observed in the quark sector have been on the sub per cent level due to the dominance of electromagnetic or strong processes. In contrast, W-production in polarized proton-proton collisions at RHIC will observe the pure weak interaction and generate parity violating single spin asymmetries of more than 50%. W production will provide the first direct (flavor separated) measurement of the spin dependent quark- and anti-quark-distributions for up- and down-quarks in the proton. The high energy scale set by the W-mass makes it possible to extract quark- and anti-quark polarizations from inclusive lepton spin asymmetries in W-production with minimal theoretical uncertainties. Sub-leading twist and higher-order terms in the perturbative QCD expansion are strongly suppressed, and a direct extraction without additional assumptions becomes possible. Past measurements in semi inclusive deep inelastic lepton nucleon scattering were carried out with significant experimental precision only for the up-quark spin-dependent distribution. The W measurements can complete the knowledge of quark and anti-quark polarizations.

Highlights of the W-program include the striking sensitivity to anti-u-quark polarization from W^--asymmetries in the backward rapidity region, the similarly large sensitivity to the anti-d-quark polarization at mid rapidity for W^+, and the sensitivity to $\Delta d(x)/d(x)$ from W^--asymmetries measured in the forward direction (an ongoing study). The $\Delta d(x)/d(x)$ measurement would test whether the d-quark polarization remains negative as $x \to 1$, or whether it changes sign and approaches $+1$ as $x \to 1$, as expected from perturbative QCD power-counting considerations. The high precision measurements of spin asymmetries in W-production at high $Q^2 = 6400$ GeV^2 will also have a large impact on the global QCD analysis of helicity parton distributions. Furthermore, the measurement of quark and anti-quark polarization at the W mass will provide a considerable lever arm compared to semi-inclusive measurements at fixed target energies to obtain the polarized gluon distribution Δg from evolution.

5.2 Quark and Anti-quark Polarizations from W Asymmetries

Production of W bosons in pp collisions is uniquely suited for testing the symmetry of the light ($\bar{u}$ and $\bar{d}$) anti-quark sea in both unpolarized and polarized collisions. Indeed, if heavier quarks are ignored, the charge of the W immediately selects either a $\bar{d}$ anti-quark from one proton in conjunction with a u-quark from the other proton in W^+ production, or a $\bar{u}$ anti-quark and a d quark in W^- production. At forward W rapidities one probes predominantly higher-x valence quarks from one beam and sea anti-quarks at lower x from the other beam. Both unpolarized and polarized sea components can be simultaneously measured in this process. W boson production selects the quark flavors through their charge and, due to the maximally parity-violating weak interaction, it also selects only one helicity of nearly massless quarks: left-handed helicity for quarks and right-handed helicity for anti-quarks. Thus, in a proton with spin along its momentum direction, only the density of quarks with spin anti-parallel to the proton's spin, $q^-(x)$, is probed, while in a

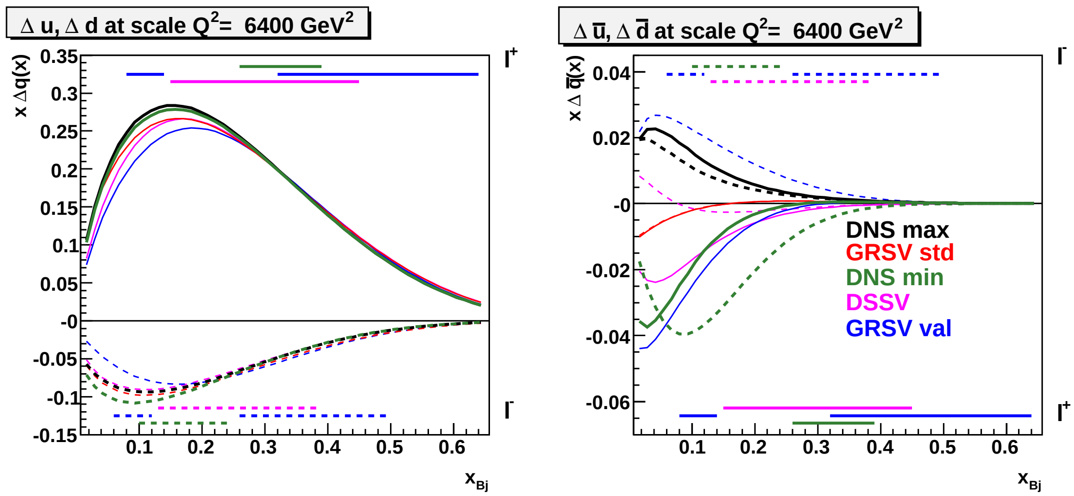

Figure 10: *Parameterizations of the polarized parton distribution functions as a function of x for the GRSV standard and valence scenarios [45], DSSV [14], and the maximal and minimal sea polarization scenarios of DNS [47]. Left figure: $\Delta u(x)$ (continuous lines) and $\Delta d(x)$ (dashed lines), right figure: $\Delta\bar{d}(x)$ (continuous lines) and $\Delta\bar{u}(x)$ (dashed lines). The horizontal lines correspond to the RMS ranges of x to be probed in inclusive $W \rightarrow$ lepton asymmetries in the PHENIX central (green), backward and forward (blue) and STAR (purple) regions for positive leptons (continuous lines) and negative leptons (dashed lines).*

proton with spin against its momentum direction, only q^+ is probed. For the anti-quarks, the situation is reversed. A single-spin asymmetry $A_L^W = \frac{1}{P} \times (N^+(W) - N^-(W))/(N^+(W) + N^-(W))$ of count rates $N^{\pm}(W)$ of Ws originating from protons with spin parallel and anti-parallel to the momentum, is then proportional to the helicity distributions $\Delta q(x) = q^+(x) - q^-(x)$ and $\Delta\bar{q}(x) = \bar{q}^+(x) - \bar{q}^-(x)$:

$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}, \tag{3}$$

and similarly for W^- by exchanging $u \rightarrow d$ and $\bar{d} \rightarrow \bar{u}$. One is generally more sensitive to the u and d polarizations for forward W rapidities with respect to the polarized proton, while the anti-quark polarizations are probed in the backward direction. The quark polarizations, particularly for the u quarks, are already fairly well known, while the sea polarizations are largely unknown. Most present knowledge on the flavor separated polarized quark distributions is obtained from semi-inclusive measurements. These measurements are currently limited by the knowledge of fragmentation functions. In contrast, the quark and anti-quark polarizations are directly probed in W production at the scale of the W mass without the need of fragmentation functions. Fig. 10 shows an overview over a set of polarized distribution functions for light quarks and anti-quarks. While the valence quark polarizations are mainly consistent, one clearly sees large differences between these parameterizations for the anti-quarks. Although the latest analysis from DSSV [14] including DIS, SIDIS and pp data reduced the uncertainties on the gluon polarization and strange polarizations significantly, the uncertainties on $\Delta\bar{u}$ and $\Delta\bar{d}$ improved only moderately. In the following we therefore compare the impact of the maximal and minimal DNS sea polarizations (as given by a $\Delta\chi^2$ of 2% in their fit) [47] on the measured asymmetries, as these parameterizations are available for the simulations.

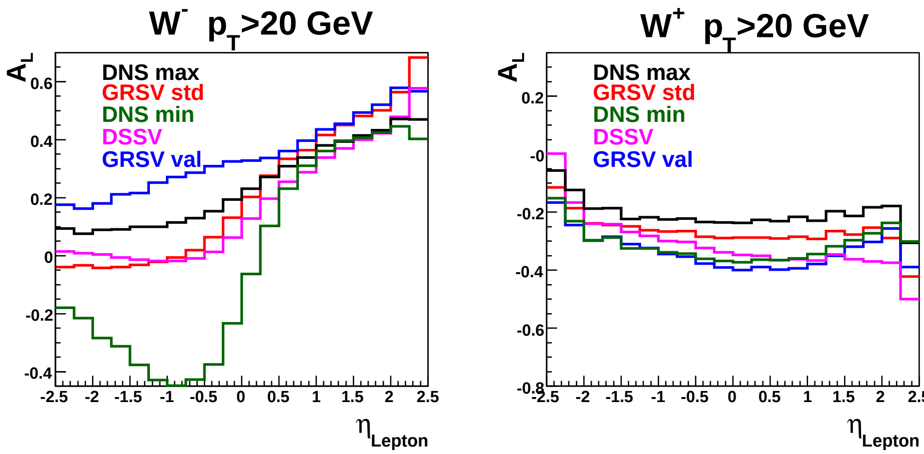

Figure 11: *Inclusive asymmetries A_L obtained by RHICBOS [58] for the polarized parton distribution functions GRSV standard, GRSV valence [45], DSSV [14], and DNS [47] using a maximal and minimal sea polarization scenario. The asymmetries $A_L^{l^-}$ (left) and $A_L^{l^+}$ (right) are shown as functions of the lepton rapidity $\eta_{\rm lepton}$ with $p_T > 20$ GeV.*

As the RHIC detectors are not hermetic, one inclusively measures the decay leptons without information on missing energy. This smears the distinction of quark and anti-quark contributions as a function of rapidity due to the fixed helicity of the (anti)neutrino. While the forward-backward separation of quarks and anti-quarks for negative leptons is enhanced, for positive leptons the quark and anti-quark contributions are mixed. However, one is sensitive to the anti-quark polarizations, predominantly in backward lepton rapidities for W^- production and at central rapidities for W^+ production. According to an NLO simulation with Q_T-resummation implemented in the generator RHICBOS [58], the single spin parity-violating asymmetries are expected to be sizable, as can be seen in Fig. 11. The different polarized parameterizations which all describe the (SI)DIS data correspond to very distinct A_L asymmetries due to the differences in the sea polarizations, while their quark polarizations are quite similar. When used as an input to a global analysis together with the (SI)DIS data, the obtained single spin W asymmetries will significantly improve the knowledge of the quark polarizations and enable the first direct determination of the anti-quark polarizations. It will be possible to determine, first at a lower luminosity, whether the anti-quarks are polarized, and, at an increased luminosity, whether there is a symmetry between the polarizations of $\bar{u}$ and $\bar{d}$ anti-quarks in the proton or not.

5.2.1 Experimental readiness for W physics

Experimentally, obtaining the desired single spin asymmetries requires running at a center-of-mass energy of $\sqrt{s} = 500$ GeV with at least 300 pb^{-1} of luminosity as projected for 2010–2013. It is necessary to distinguish the leptons from hadron background and to correctly identify their charge. Furthermore the background has to be understood and corrected for. As the hadron background does not originate from Ws, it is not parity-violating and only dilutes the asymmetries.

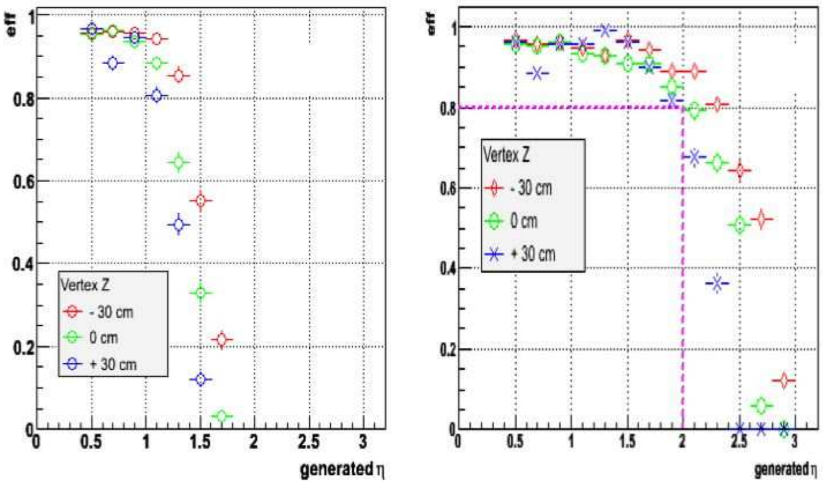

Figure 12: *Charge sign discrimination probability (ratio of the number of reconstructed tracks with correctly reconstructed charge sign divided by the number of generated tracks) in STAR for the current detector design and under inclusion of the FGT as a function of the rapidity η.*

STAR: In the Barrel part of the STAR detector existing tracking and calorimetry make it possible to study W bosons. With the Barrel electromagnetic calorimeter an electron-hadron separation of at least two orders of magnitude is expected based on various QCD background studies taking into account the BEMC layout in combination with the STAR TPC. Studies of potential TPC space charge distortions at high luminosity have not been completed as of now. However, all estimates below are based on a TPC hit resolution, which is approximately three times larger compared to the current TPC performance. In the forward region of the Endcap electromagnetic calorimeter ($1 < \eta < 2$) a new tracking upgrade is needed to successfully determine the charge of highly energetic electrons/positrons. The Forward GEM Tracker (FGT) upgrade will allow such a charge detection by including six disks of triple GEM detectors to obtain a precise tracking information, as can be seen in Fig. 12. Such a disk geometry is favorable especially at forward rapidities. The GEM disks will sit inside the inner field cage of the STAR Time Projection Chamber (TPC), and have an outer radius of 39 cm and an inner radius of 11 cm. Each triple-GEM disk is subdivided into quarter sections whose boundaries are aligned with respect to the TPC sector and EEMC boundaries. All mechanical details and gas piping have been implemented along with the design of a new west support structure. The FGT upgrade has been reviewed by STAR and BNL and it has been recommended to fund it through capital equipment funds. It is planned to install the FGT in summer 2010. In addition detailed simulations of the Endcap calorimeter show that the electron hadron separation can be successfully performed to reduce the hadron background by at least two orders of magnitude and thus, below the expected W yield with a signal over background ratio of approximately three, depending on transverse energy E_T.

Fig. 13 shows the projected sensitivity for A_L for STAR in the EEMC region of $1 < \eta < 2$ for forward (backward) configurations, i.e. e^-/e^+ with respect to the polarized proton beam heading toward (and away) from the STAR EEMC. These estimates are based on full PYTHIA simulations of W signal and QCD background events. Asymmetries have been determined using the RHICBOS framework. Projected uncertainties are shown in comparison to the size of A_L for different polarized distribution functions capturing their overall uncertainty. Good sensitivity to $\Delta\bar{u}$ is obtained for a beam polarization of 70% and an integrated luminosity of $300\,\mathrm{pb}^{-1}$.

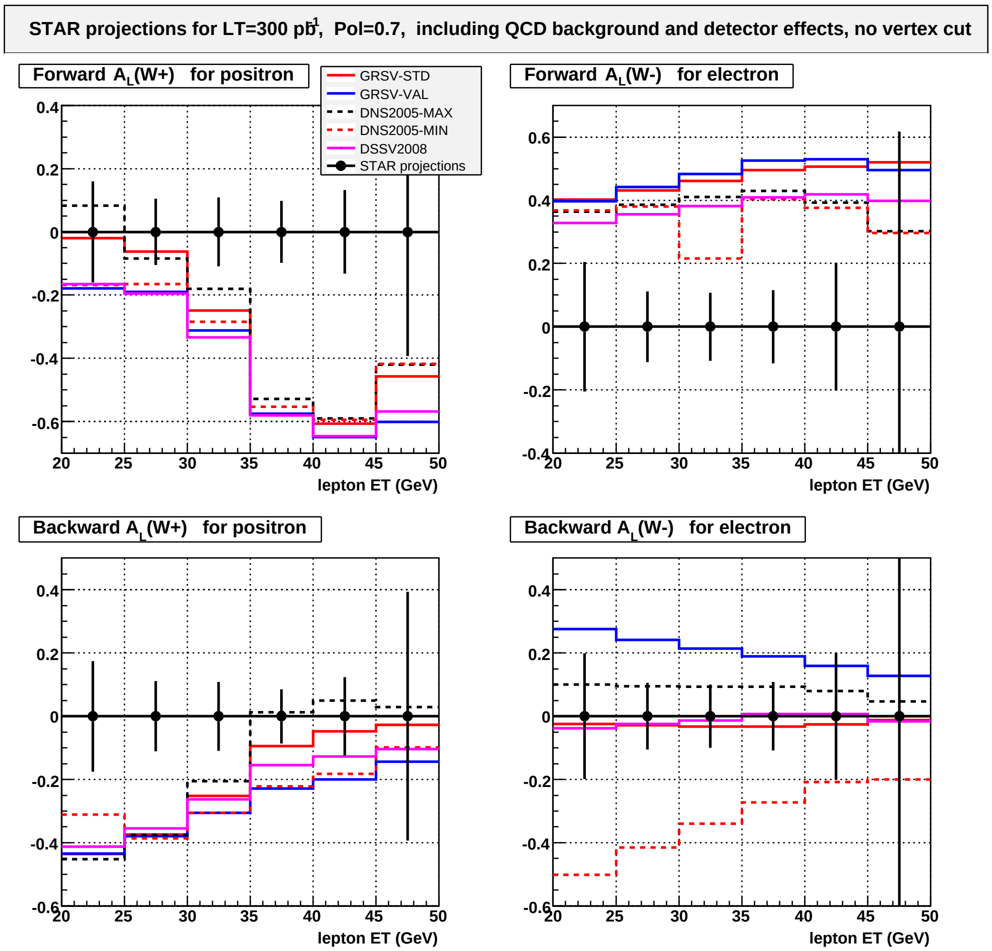

Figure 13: *Projected asymmetries in the forward/backward STAR region as a function of lepton transverse energy, E_T. The data has been obtained for GRSV standard, GRSV valence [45], DSSV [14], and DNS [47] using a maximal and minimal sea polarization scenario in RHIC-BOS [58] after detector simulation and inclusion of background for 300 pb^{-1} assuming 70% polarization.*

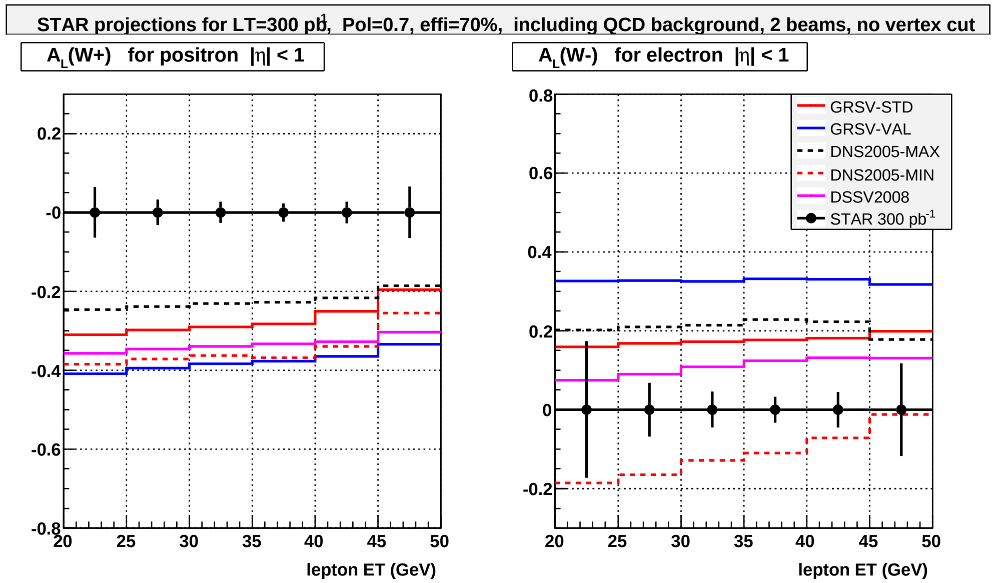

Figure 14: *Projected uncertainties for* $300\,pb^{-1}$ *and* 70% *beam polarization of* A_L *as a function of* E_T *in the mid-rapidity acceptance region of the STAR BEMC (*$-1 < \eta < 1$*).*

Figure 14 shows the projected uncertainties for $300\,\mathrm{pb}^{-1}$ and 70% beam polarization of A_L as a function of E_T in the mid-rapidity acceptance region of the STAR BEMC ($-1 < \eta < 1$). QCD background effects have been included and set to be equal to those determined for each E_T bin in the STAR EEMC region. It is expected that the actual signal versus background distribution at mid-rapidity leads to a smaller overall background contribution compared to the STAR EEMC region. An electron finding efficiency of 70% has been taken into account similar to the STAR EEMC acceptance region of $1 < \eta < 2$. It is expected that the mid-rapidity region will provide additional important constraints on the polarized anti-quark distribution functions, in particular the polarized anti-d distribution function.

PHENIX: In the PHENIX Muon arms the dominant trigger background based on detailed simulations, for W measurements, are low-energetic muons which dominate over the W decay muons. For this purpose a new energy sensitive muon trigger is being developed to select high-p_T muons only. It is separated into two parts: Additional fast front end electronics (FEE) for the existing Muon tracking and three planes of resistive plate counters (RPCs) in each arm. The front-end electronics upgrade consists of splitting off a fraction of the existing readout pad signal to obtain the strip hit information within a timing window of several ns. The hits then provide a fast momentum trigger using a look-up table. This upgrade is funded by JSPS and has been successfully reviewed. The north Muon arm's FEE will be installed in summer 2008, the south Muon arm's FEE will follow in summer 2009.

The RPC upgrade adds three planes of RPCs in each arm, one each upstream (RPC1) and downstream (RPC2) of the Muon tracker and one downstream of the last plane of the Muon Steel absorber (RPC3). The timing resolution is on the order of 2 ns which will cut out non-collision related backgrounds. In addition, it provides the beam crossing information offline and low energy muon rejection. This upgrade is funded by a NSF-MRI and prototypes have been produced.

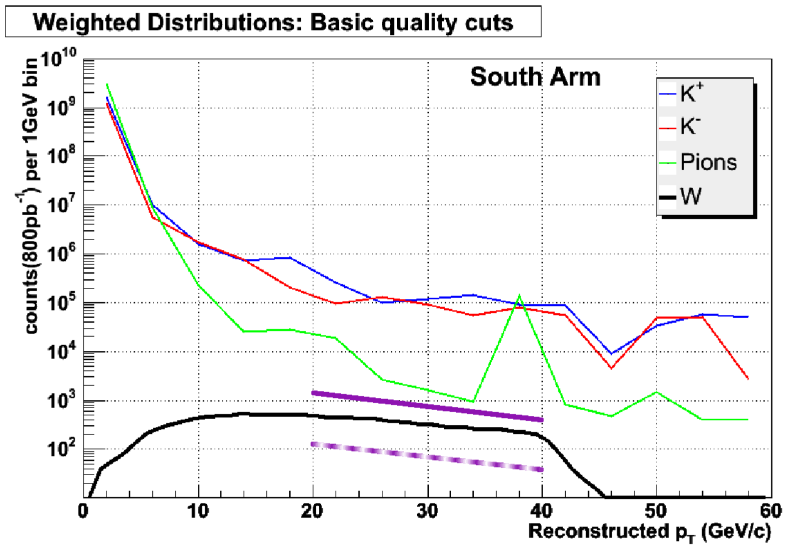

Figure 15: *Background distribution of false high-p_T muons from hadron decays in the forward region of PHENIX using basic cuts (lines) and, schematically, after application of tight cuts (purple line) and after installation of an additional absorber (dashed purple line). The W signal as obtained from Pythia is also shown.*

Two complete half-octants will be installed in summer 2008, while the main installation of RPCs 2 and 3 on the north arm is planned for summer 2009. Therefore a first muon trigger with full functionality consisting of the three planes of FEEs and two planes of RPCs will be available for RHIC run 10. In the summer of 2010 the south muon arm's RPCs 2 and 3 will be installed and in 2011 the full upgrade will be completed with the installation of the station 1 on both sides. In the forward arms the momentum reconstruction and charge reconstruction are sufficient to identify the muon charge, based on full detector simulations. The charge reconstruction efficiency is about 97% for 40 GeV muons. The most significant offline background has been identified to be low-energetic hadrons. A small fraction of them penetrate the existing absorber material in front of the muon Trackers and decay within the tracker volume, mimicking a high-p_T muon track. From full detector simulations a tight set of tracking cuts results in a signal to background ratio of 1/3 for muon candidates with $p_T > 20$ GeV. Installing an additional two interaction lengths of absorber reduces the background by another order of magnitude, based on simulation studies, described in Appendix D. The resulting signal to background ratio is expected to be 3, as indicated in Fig. 15.

The expected parity-violating asymmetries are plotted vs. muon p_T for the muon arms in Fig. 16. For forward μ^+, $\sim 4\,\sigma$ discrimination for 300 pb^{-1} is expected for the lowest momentum bin, where the different curves reflect different $\Delta\bar{d}/\bar{d}$. For backward μ^-, $\sim 12\,\sigma$ sensitivity to different $\Delta\bar{u}/\bar{u}$ is expected over the whole transverse momentum range. In Fig. 16, the scaled sensitivities for 1300 pb^{-1} are also shown to emphasize the precision available with additional RHIC luminosity improvements.

In PHENIX the central arms have sufficient charge reconstruction efficiency to identify $W^\pm \to e^\pm$. In addition, the electromagnetic calorimeter response for hadrons and electrons is very different. While electrons deposit almost all their energy, hadrons only deposit a fraction. The hadron

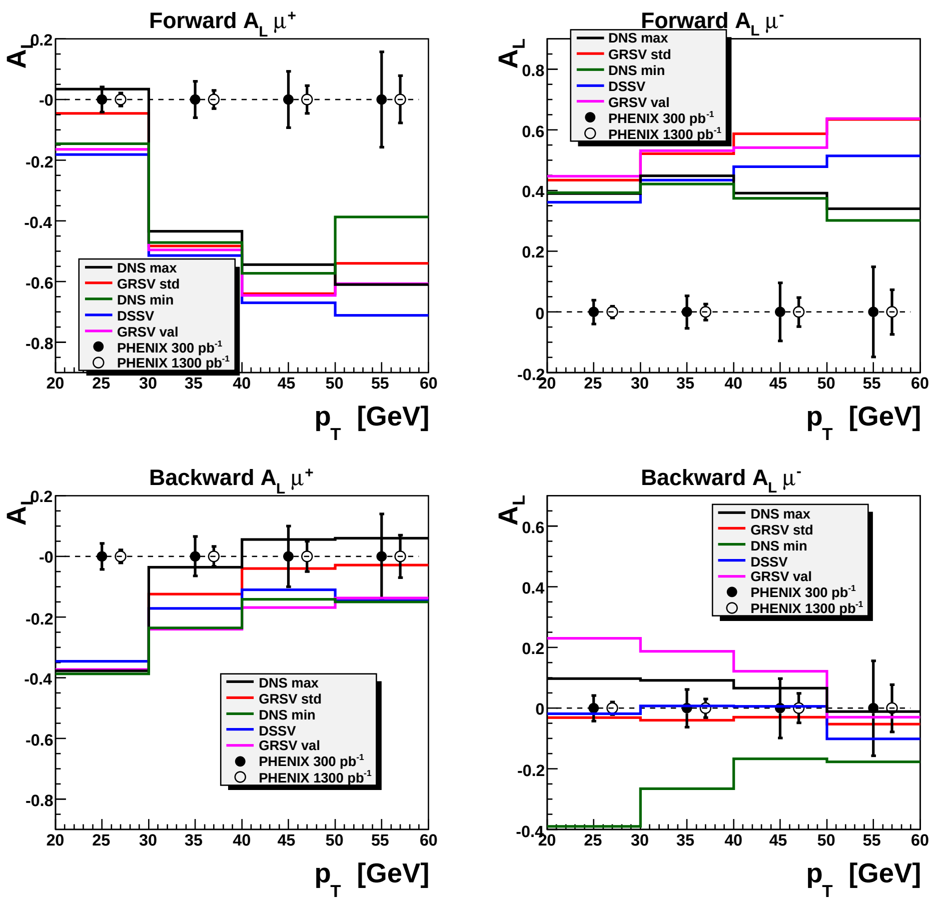

Figure 16: *Longitudinal single spin asymmetries for μ^+ and μ^- in the forward (top plots) and backward (bottom plots) regions of the PHENIX detector as a function of the reconstructed muon p_T. The data has been obtained for GRSV standard, GRSV valence [45], DSSV [14], and DNS [47] using a maximal and minimal sea polarization scenario in RHICBOS [58] after detector simulation and inclusion of background for 300 pb^{-1} (full symbols) and 1300 pb^{-1} (open symbols) assuming 70% beam polarization.*

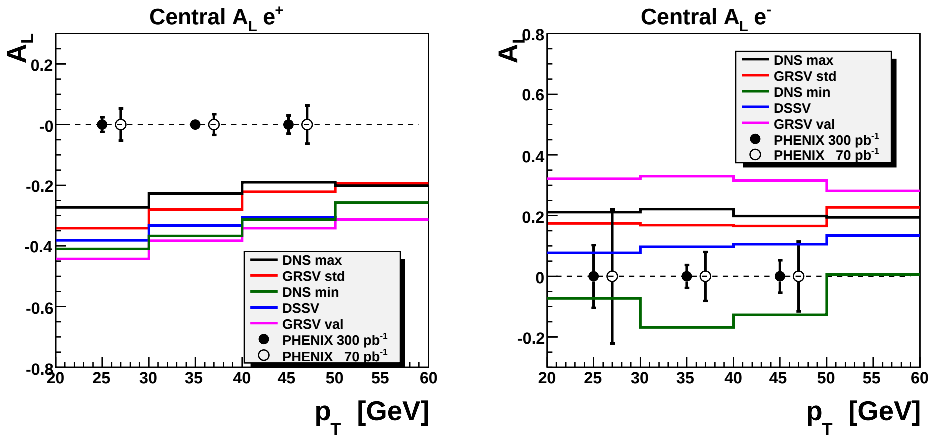

Figure 17: *Simulated asymmetries in the PHENIX central arms for $W^+ \to e^+\nu$ (left plot) and $W^- \to e^-\bar{\nu}$ as functions of p_T. The data has been obtained for GRSV standard, GRSV valence [45], DSSV [14], and DNS [47] using a maximal and minimal sea polarization scenario in RHICBOS [58] for 300 pb^{-1} (full symbols) and 70 pb^{-1} (open symbols) assuming 70% beam polarization.*

background with a similar energy deposited as the electrons has to have much larger momenta and is thus suppressed. It is expected, based on calculation (simulation yet to be done), that the remaining background will be minimal. Ws at central rapidities distinguish between different parameterizations, as can be seen in Fig. 17. The asymmetries shown are simulated asymmetries without detector response and without background. In particular the central arm will be most sensitive to $\Delta\bar{d}$ due to the W^+ decay kinematics.

5.3 Conclusion

In the running over the next years several steps toward the measurement of the quark and anti-quark polarizations can be identified:

- Commissioning running at $\sqrt{s} = 500$ GeV with a few pb^{-1} will establish a baseline for the expected backgrounds for the W measurements. First W cross section measurements will be made.
- With the expected recorded luminosity of ~ 70 pb^{-1} in the first major $\sqrt{s} = 500$ GeV run it will be possible to confirm the quark polarizations in a completely new process at high scale.
- With a recorded luminosity of 300 pb^{-1} it will be possible to measure the $\Delta\bar{u}(x)$ polarization and thus obtain the first direct determination of the sea polarization. The distinction between a maximal and a minimal DNS $\Delta\bar{u}(x)$ can be made at the 12 σ level in the PHENIX backward muon region and at the 9 σ level in the STAR backward region. The reason for the differences is the very different background situation for electrons in STAR and muons behind significant amount of absorbing material in PHENIX.

- At mid-rapidity, both the W^+ and W^- measurements will significantly constrain the $\bar{d}$ and $\bar{u}$ anti-quark polarizations at a multi-sigma level. Indeed, mid-rapidity measurements will provide the strongest constraint on $\Delta\bar{d}$. The presented mid-rapidity sensitivities for PHENIX are based on simulated asymmetries, without background or detector efficiencies. The presented sensitivities for STAR, at mid-rapidity, have been calculated assuming comparable lepton efficiency and hadron background levels as found with simulations at forward/backward rapidity.

Additional luminosity beyond 300 pb^{-1} will provide precision measurements of the anti-quark polarizations. It will also open the possibility to access the strange quark polarization, measuring W decays in coincidence with charmed mesons. Furthermore, including the W results into a global analysis will also further reduce the uncertainties on the valence quark polarizations. It is also quite important that these W results at high scale will serve as a first large lever arm for the QCD evolution of the polarized parton distributions which can even further reduce the uncertainties on the gluon polarization. These are discussed in Appendix D. To achieve the milestone of measuring the sea polarizations, significant luminosity has to be delivered with high polarization (70% is assumed in the presented sensitivities), which requires significant beam development each year in addition to the ongoing detector upgrades.

6 Transverse Spin

This section summarizes progress by experiment and theory on transverse spin physics at RHIC, identifies the key questions to be addressed, and defines a plan for the future.

The goal of the RHIC spin program is to identify how the proton gets its spin from its quark and gluon constituents. Addressing this goal when the proton spin and momentum vectors are orthogonal is of great interest since windows onto partonic orbital motion are available, and the proton gets no contribution from gluon polarization when its spin is transverse to its momentum. Transverse single spin asymmetries (SSA) play a special role in questions about the transverse spin structure of the proton because only very small transverse SSA are expected in the scattering of collinear gluons and quarks mediated by gauge interactions, particularly for the light up and down valence quarks of the proton. Consequently, extensions beyond the simple collinear, leading-twist perturbative QCD (pQCD) picture of hard scattering are required, since strikingly large spin effects are observed at RHIC energies where cross sections are found to be in agreement with theoretical expectations.

Extensions to the simplest hard-scattering picture fall into two broad categories, both of which make contact with fundamental questions about the transverse spin structure of the proton. In the Sivers mechanism [29], one requirement to produce a transverse SSA is the presence of a spin-correlated transverse momentum in the distribution functions associated with the proton. The presence of partonic transverse momentum within the proton is related to its orbital motion, although extraction of the orbital angular momentum can at present only be done through models. In the Collins mechanism [41], transversely polarized quarks must be present in a transversely polarized proton. This transverse quark polarization is given by transversity [59], a leading-twist distribution function whose integral provides the tensor charge of the proton. In the Collins

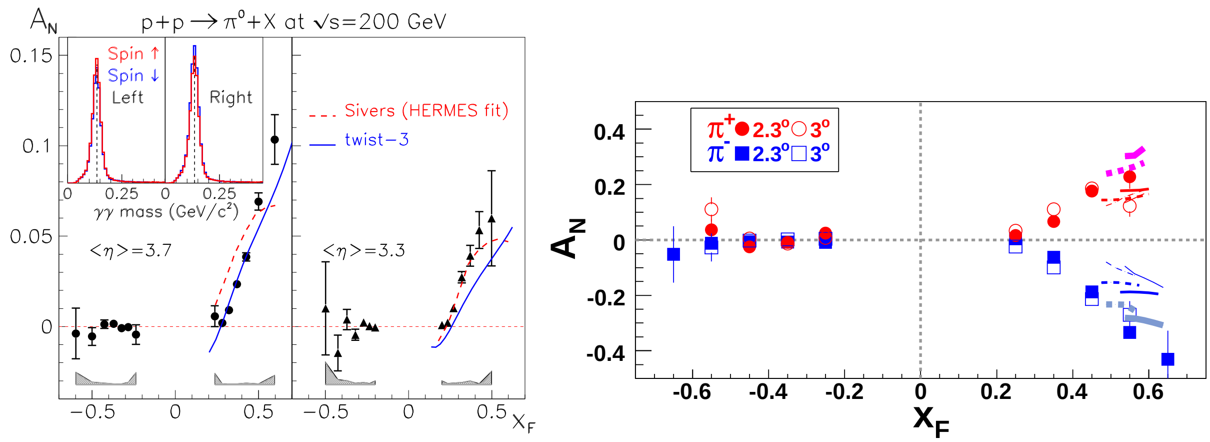

Figure 18: *Transverse single spin asymmetries (SSA) in x_F bins for forward π production at RHIC energies. (left) π^0 production for $\sqrt{s}$ = 200 GeV collisions, at two different pseudorapidities [23]. (right) $\pi^{\pm}$ production for $\sqrt{s}$ = 62 GeV collisions, at two different scattering angles [25]. The $x_F > 0$ dependence of the measured transverse SSA is mostly consistent with new theoretical calculations described below.*

mechanism, quark transverse polarization is revealed following the hard scattering by a spin-correlated transverse momentum in fragmentation to the observed hadrons. Transverse quark polarization can also be revealed by a chiral-odd fragmentation function, such as the interference fragmentation function [42].

Transverse SSA effects are observed to be strikingly large by experiments at RHIC energies [23, 25], but their understanding is in general quite subtle and involves substantial theoretical effort to quantify. The concurrent progress between theory and experiment has identified a clear path to test present understanding.

6.1 Present Status of Experiments and Theoretical Understanding

RHIC run 6 provided a wealth of experimental information about spin physics. The versatility of RHIC was demonstrated by spending a portion of the run with transversely polarized colliding beams, and the majority of the run with longitudinally polarized colliding beams, for both $\sqrt{s} = 62$ and 200 GeV collision energies. Transversely polarized proton collisions resulted in the observation of strikingly large spin effects for forward $\pi^0, \pi^{\pm}$ production (Fig. 18) [23, 25]. At large Feynman-x (x_F), positive asymmetries are observed for π^+ production and negative asymmetries for π^- production, consistent with opposite signs for u and d quarks extracted for Sivers functions in phenomenological fits to semi-inclusive deep inelastic scattering (SIDIS) data [26, 27]. The π^0 asymmetries are positive due to u-quark dominance. What is special about making these measurements at RHIC energies, is that unpolarized cross sections in the same kinematics as the observed transverse SSA are described by next-to-leading order (NLO) pQCD calculations, and have been shown to help constrain fragmentation functions in a global QCD analysis [60].

This is quite different from the situation at lower collision energies, where measured cross sections exceed NLO pQCD expectations by progressively larger factors as $\sqrt{s}$ decreases.

The calculations in Fig. 18 are an outgrowth of intense theoretical activity concurrent with the ongoing experiments. The principal findings of the theoretical work are summarized here. Calculations that employ spin- and transverse-momentum dependent distribution functions (Sivers functions) and calculations that explicitly treat higher twist effects [61, 62] have been found to be equivalent over part of the kinematics for Drell Yan production of dileptons [63]. The Sivers functions have been found to be related to partonic orbital motion in model dependent analyses [64]. Although rigorous proofs of their more general use remain to be found, model calculations [65, 66] using Sivers functions extracted from SIDIS measurements can explain most features of the x_F dependence of the forward pion results at RHIC (Fig. 18). As discussed in more detail in Appendix E, first measurements of the p_T dependence of transverse SSA for $p_\uparrow + p \to \pi + X$ at RHIC energies suggest that the understanding of these spin effects is still incomplete.

Very recent work [67] suggests that contributions from the Collins mechanism, where a spin dependent fragmentation function analyzes the scattered quark polarization, are not negligible in $p_\uparrow + p \to \pi + X$. Recent work by a RIKEN BNL Research Center group has resulted in the first experimental observation of spin dependent fragmentation in e^+e^- collisions [28]. The Collins function is found to be large. An analysis has been completed, combining the experimentally determined Collins function from e^+e^- and Collins moments from SIDIS, to make the first extraction of transversity [40]. It remains a task for RHIC experiments, and theory, to identify a method to quantitatively separate Collins and Sivers contributions to transverse SSA in $p_\uparrow + p$ collisions, so as to establish the universality properties of transversity and the Collins fragmentation function.

First measurements of transverse SSA for di-jet production near midrapidity were also completed in RHIC run 6 [36], with the intent of directly measuring the spin dependence of the transverse momentum imbalance between the jets [68]. Transverse SSA for midrapidity dijet production is found to be consistent with zero. Theoretical understanding of the complex color-charge interactions that arise in di-jet production was stimulated by these results. A synopsis of that understanding is that the Sivers functions are probed in different ways in different hard scattering processes. For semi-inclusive deep inelastic scattering, there is an *attractive final-state color charge* interaction required by gauge invariance, and provides the required amplitude interference in the Sivers mechanism [30]. For the Drell-Yan process, this becomes a *repulsive initial-state color charge* interaction [31, 32, 33]. For di-jet production, both attractive and repulsive color charge interactions are present resulting in cancellations that explain the null result from experiment [35]. An outgrowth of this understanding is the theoretical prediction [34] that for forward photon + jet, repulsive initial-state color-charge interactions will predominate, meaning that transverse SSA for a future RHIC experiment should be opposite in sign from what has been measured in SIDIS. Direct photon production has contributions only from the Sivers mechanism.

The RHIC experiments have both completed forward calorimeter upgrades. STAR built a forward meson spectrometer (FMS) spanning the full azimuth for the pseudorapidity range $2.5 < \eta < 4.0$. The FMS addition provides STAR with nearly contiguous electromagnetic calorimetry for $-1 < \eta < 4$. PHENIX constructed muon piston calorimeters at both positive and negative pseudorapidity that span the full azimuth for $3.1 < |\eta| < 3.9$. The experiments can use these forward calorimeters, in addition to midrapidity detectors for away-side jet detection, to test the prediction that spin-correlated momentum imbalance for forward photon+jet will be opposite in sign to the Sivers asymmetry measured in SIDIS.

A key issue that must be addressed is the discrimination of direct photons from fragmentation photons. It is expected that spin effects for prompt photons will be severely diluted unless robust discrimination against fragmentation photons is made [62]. The large acceptance of the recently completed forward calorimeters should allow effective application of isolation cuts for this purpose, but it remains important to experimentally demonstrate that fragmentation photon backgrounds can be adequately suppressed.

6.2 Key Questions for the Future

Future studies of transversely polarized proton collisions at RHIC will address key questions listed below.

• Is the present understanding of the Sivers mechanism correct?

Experimental confirmation of the theoretically predicted sign change is a tremendous future opportunity for RHIC. Transverse SSA for Drell-Yan (DY) production of dilepton pairs is the cleanest test of this prediction, but will require luminosity development and upgrades to the experiments. As documented in [69] and based on detailed comparison of data to simulation, PHENIX will need to suppress contributions from weak decays of open beauty and open charm production to low mass $\mu^+\mu^-$ pairs to cleanly identify the DY process for a future transverse SSA measurement. It is expected that open heavy flavor contributions can be suppressed by isolation cuts using the planned nose cone calorimeter and the forward vertex tracker upgrades. STAR has the potential for a transverse spin DY experiment by observing e^+e^- pairs at large rapidity with its FMS. Fast tracking at large rapidity is a required addition for STAR to discriminate electrons from positrons. From considerations of both integrated luminosity and the necessary upgrades to the experiments, a transverse spin DY program is envisioned for the future.

The predicted sign change is of fundamental importance, not only because it verifies the presence of partonic orbital motion, but also because it establishes the reality of attractive interactions between unlike color charges and repulsive interactions between like color charges. Before embarking on a transverse spin DY program, forward γ + jet can rigorously test present theoretical understanding, since the repulsive color charge interactions are predicted to be present for this rare, but presently accessible, final state.

• Can experimental sensitivity to transversity be established at RHIC?

Measurements of transversity at RHIC will necessarily be exploratory, since no firm theoretical predictions exist, at present. Transverse SSA are again expected to play a special role, since two-spin observables such as A_{TT} are predicted to be small at RHIC energies. Single spin asymmetries can provide a window onto transversity either through the Collins mechanism or via the interference fragmentation function. Given that transversity is largest in the valence region, and the Collins function is largest for hadrons that carry large fractions of the momentum of the fragmenting parton, it is expected that the forward region will continue to play a special role. Exploratory studies of spin correlations with the azimuthal orientation of two particles detected in the forward direction can be conducted in parallel with experiments targeted at measuring transverse SSA for forward γ + jet to test the understanding of the Sivers mechanism.

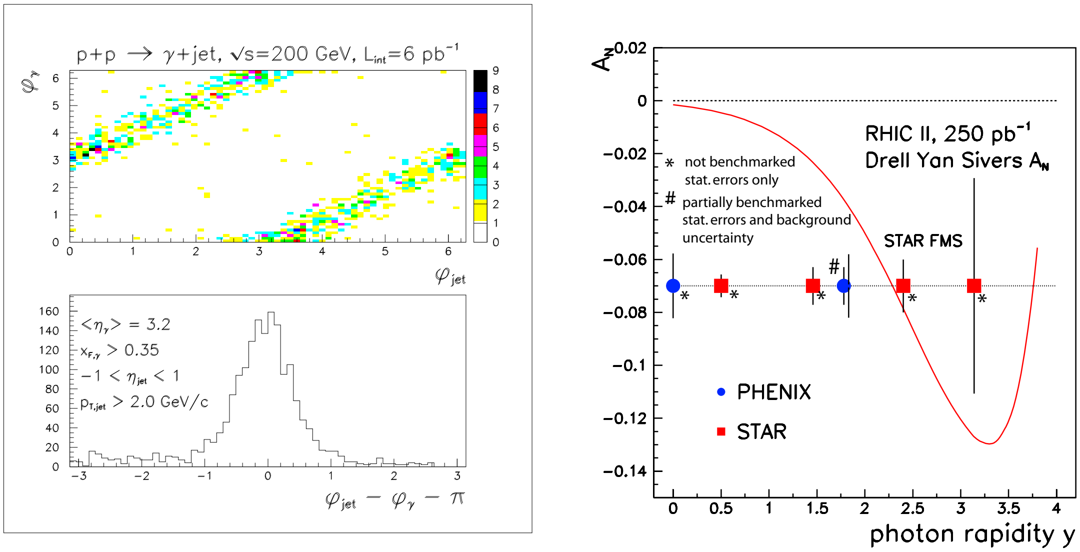

Figure 19: *Tests of the Sivers mechanism through measurement of transverse single spin asymmetries for (left) forward photon + jet final states. The signature of repulsive color charge interactions would be a negative asymmetry for the spin-correlated momentum imbalance, related to the $\Delta\phi = \phi_{\rm jet} - \phi_\gamma - \pi$ simulations. (right) Transverse single spin asymmetries for Drell-Yan production of dilepton pairs at $\sqrt{s} = 200$ GeV [69].*

• Are there ways to robustly separate flavor contributions to Sivers functions and to transversity?

The mirror transverse SSA for forward $\pi^\pm$ production are consistent with opposite signed contributions to transverse spin effects from up and down quarks. One way to clearly separate flavor contributions is to compare results from proton transverse SSA to those from neutron transverse SSA. The latter would require development of either vector polarized deuteron beams or of polarized ^{3}He beams at RHIC.

6.3 Summary and Plan

Future opportunities for transverse spin physics at RHIC are now focused on theoretical predictions based on understanding of SIDIS, e^+e^- and RHIC results. Experiments to test this understanding include near-term opportunities, for which both accelerator performance and experiment readiness is complete. There are longer term opportunities, with time and resources required to prepare for future measurements of transverse spin effects in the production of rare final states. When both near-term and future opportunities are realized, these targeted data sets that will address specific theoretical predictions can also be used for more exploratory studies, for example to identify a means of robustly separating Collins and Sivers contributions.

A key future goal is to quantitatively test the prediction that initial-state repulsive color charge interactions provide the amplitude interference required by the Sivers mechanism for $p_\uparrow + p$. The cleanest test of this is for Drell Yan production of dilepton pairs. Considerations of the kinematics and luminosity suggest that $\sqrt{s} = 200$ GeV $p + p$ collisions optimize the opportunity for both PHENIX and STAR to complete the measurement, at parton momentum fractions that emphasize valence quarks. Continued luminosity development at RHIC for polarized proton operation is required to produce the 250 pb^{-1} data sample required for the measurements. Targeted upgrades to the experiments can be embarked upon during the execution of the W physics program, to prepare the experiments for measurements in 2015 and 2016.

The sign change between what has been observed in SIDIS and what is predicted for transverse spin DY tests a fundamental aspect of QCD, since unlike color charges are responsible for the final-state attractive interaction in SIDIS, and like color charges are predicted to give exactly the opposite sign Sivers effect in the $p + p$ DY production.

Theoretical understanding of the Sivers mechanism can be subjected to an experimental test prior to embarking on a transverse spin DY measurement. In particular, continuing commitment of a fraction of RHIC spin runs to transversely polarized collisions is required to complete measurements of transverse SSA for forward photon + jet, with sufficient precision to establish the sign of the spin asymmetries. The optimal plan would be to obtain a data sample of 6 pb^{-1} with 65% polarization in RHIC run 9 to establish that robust discrimination between direct and fragmentation photons can be made. Completion of the measurement is estimated to require a total sample of 30 pb^{-1} with 65% polarization and is envisioned for a subsequent RHIC run, prior to the start of the 500-GeV program. Concurrent with these targeted measurements, more exploratory measurements aimed at identifying transversity contributions can be embarked upon.

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[69] L.C. Bland *et al.*, http://spin.riken.bnl.gov/rsc/write-up/dy-final.pdf *(Transverse-Spin Drell-Yan Physics at RHIC)*.

Appendix A: The Charge

I would like to ask you to organize efforts, with the help of the others copied on this e-mail and whomever else you find useful, to address one of the major recommendations from last July's S&T review:

"Brookhaven National Laboratory (BNL) should develop and document a detailed plan with milestones that demonstrates the experimental sensitivity for the proposed proton spin measurements between 2008 and 2013 using the anticipated accelerator design capabilities and detector performance as a planning base. This plan should be submitted to DOE NP by May 31, 2008 and presented at the 2008 RHIC S&T Review."

What is called for is an update of the DOE Spin Report, but with a clear focus on 500 GeV running and W production (leading to the 2013 NP milestone on W production in polarized proton collisions). It should probably include brief updates on present projections of ΔG and transverse spin sensitivities to be attained in the remaining 200 GeV running, but I think the committee's primary focus arose from their not being convinced about the W production program viability on several fronts. Addressing those concerns will likely involve a new generation of detailed simulations for the detectors, and a detailed plan for attaining the necessary luminosities on the C-AD side. For that reason, developing the plan may take a while, so I am trying to launch the process early. Perhaps it should include a series of presentations about simulations and machine plans over the coming months, to help guide progress toward a realistic plan. For run planning, it is best to make the same 10-week per operating year assumption that was made in the previous Spin Plan, although we will in parallel be trying to update the Midterm Strategic Plan to incorporate aggressive pursuit of stochastic cooling for heavy-ion average luminosity upgrades. So we will have to integrate the spin plan with the updated midterm strategic plan before we present the report to DOE at the end of May 2008.

You can certainly refer to the existing Spin Report for theoretical and experimental background information - that does not need to be reproduced. But the report should address the following specific questions and concerns reviewers have raised at recent reviews:

1) Can the luminosity needed for a W production program with impact on sea antiquark polarizations be achieved?

2) Which detector upgrades are critical for the W program? DOE has ended up confused, for example, about how strong a role the PHENIX FVTX and NCC upgrades are for this program.

3) Can adequate hadronic background suppression be attained in realistic simulations of detector performance, in the absence of a conventional missing energy determination?

4) Is present or projected tracking resolution sufficient for adequate charge sign discrimination and for adequate determination of Bjorken x for the contributing sea antiquarks? What are the respective roles of detector performance and of kinematic ambiguities in limiting x resolution?

5) How will sea antiquark polarizations be extracted from RHIC measurements of W production?

6) Within projected funding profiles, can we meet the 2013 performance milestone? What are the critical milestones in a plan to get there?

7) Will there be sufficient integrated luminosity to attain the desired Delta G sensitivities in photon and photon-jet production? If not, are there alternatives?

I know that PHENIX and STAR are independently pursuing improved simulations relevant to the W production program with upgraded detectors, and your report can certainly benefit from these. But I would like you to coordinate the efforts among the two collaborations and C-AD. If you want to take this opportunity to say something more about transverse spin measurements for Drell-Yan, you should point out how such measurements would be incorporated in a plan, and what impact they might have on reaching the 2013 W production milestone. And I think it would also be a good idea in that case to get PAC feedback on the Drell-Yan concepts at the spring PAC meeting (I'm trying to organize this for mid-April at this point).

I would appreciate it if you let me know soon if you are willing to undertake this effort. I have to report to the BSA Science and Technology Steering Committee on Nov. 1-2 on the S&T review recommendations and what we are doing about addressing them. So it would be very useful to have some feedback from you by the end of October on how you plan to organize the efforts to provide the requested report in May.

Thanks a lot for considering this. It should be fun!

Steve

Appendix B: Accelerator Performance Improvements

We give here a more detailed account of the plan to increase the average store polarization and luminosity in RHIC.

The maximum polarization is limited by the source, the AGS polarization transmission, and by the tune and orbit control in RHIC. There is a continuous effort to increase the source polarization. However, after modifications for Run-8 the source polarization was only 80-82%, about 5% lower than in Run-7. The goal for Run-9 is a source polarization of again 85%. An R&D effort is under way for a high-intensity proton source with a high-uniformity superconducting solenoid with which a higher brightness beam can be produced.

For the next polarized proton run the Low Energy Beam Transport (LEBT), Medium Energy Beam Transport (MEBT), and Booster injection are modified. The LEBT and MEBT sections are optimized for high-intensity proton operation and are causing emittance increases for polarized protons. With these modifications and for comparable intensities an emittance reduction of 50% after the Linac, and about 20% in RHIC are anticipated, which is also expected to improve the polarization performance.

In the AGS, a stronger snake and a horizontal tune near an integer number were tested in Run-7. In Run-8 injection on the fly (without a constant dwell field) was tested. Both were attempts to reduce the intensity dependence of the polarization. In neither test a better polarization performance could be demonstrated, and for the final Run-8 operation the Run-6 setup was used again. Under investigation is now a scheme to jump all horizontal spin resonances in the AGS with fast quadrupoles. Such a scheme could increase the polarization out of the AGS by as much as 5% (absolute).

During Run-8 it became clear that the control of the orbit angles through the RHIC snakes is critical to maintain the polarization, and that some of the polarization problems in RHIC during Run-9 can be attributed to insufficient orbit control through the snakes. This will be addressed for future runs.

A spin flipper for the RHIC Blue ring is under construction for Run-9 with the goal of flipping the spin of all bunches under operational store conditions without the need of detuning the snakes. The new spin flipper will also allow measuring the spin tune at store. A spin flipper for the Yellow ring is planned for the following run.

The main limitation for the RHIC luminosity is the beam-beam effect in conjunction with other nonlinear effects and parameter modulations. With the limited time available in Run-8 only a modest (15%) improvement in the average store luminosity could be demonstrated. However, two important tests were made. In the first test a near integer working point was studied that is expected to accommodate a larger beam-beam parameter. This working point is currently not operationally usable because 10 Hz mechanical triplet vibration, enhanced at near integer working points, leads to an enhancement and large modulations in the experimental background. A reduction of the 10 Hz mechanical oscillation through passive or active damping of the cold mass movement, or an orbit feedback is under study. In a second test a lattice with a design value of $\beta^* = 65$ cm was commissioned but could not be made operational in the limited time available. For such a lattice, a nonlinear chromaticity correction, developed over the last two years, is essential. We expect that β^* can be ultimately reduced to 50 cm at 250 GeV beam energy.

For Run-9 a new 9 MHz radio frequency system will be commissioned. This allows preserving the longitudinal emittance upon beam injection into RHIC which is currently not possible. With the resulting shorter bunches at store the hour glass effect is reduced, leading to about 25% higher luminosity. The longer bunches at injection are also expected to reduce the incoherent emittance growth that was observed in previous runs, possibly caused by electron clouds.

Electron lenses are currently studied in simulations. These could mitigate the head-on beam-beam effect. Also studied is coherent electron cooling which could reduce the beam emittance at store.

Appendices C$-$E:

Please see:

http://spin.riken.bnl.gov/rsc/report/spinplan_2008/Appendix/AppendixC.pdf (gluon polarization)
http://spin.riken.bnl.gov/rsc/report/spinplan_2008/Appendix/AppendixD.pdf (W physics)
http://spin.riken.bnl.gov/rsc/report/spinplan_2008/Appendix/AppendixE.pdf (transverse spin)