Spin Physics Working Group Report

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Abstract

We collect the findings of the RHIC-II Spin Physics Working Group. The introduction gives a brief overview of the history of Nucleon Spin Physics and of the motivation for the ongoing Spin Physics Program at RHIC, and identifies the current compelling questions. In subsequent sections we focus on new physics opportunities in the transition from RHIC to RHIC-II.

1 Introduction

1.1 History and Motivation

The pursuit of the nucleon spin in the physics programs at RHIC has largely been motivated by the unexpected and nonintuitive results from polarized deep-inelastic lepton-nucleon scattering experiments. In these deep-inelastic scattering experiments a polarized photon with virtuality Q probes the charged substructure of a polarized nucleon. The nucleon is understood as being composed of quarks, gluons, and anti-quarks, and one would expect the nucleon spin to be carried dominantly by the valence quarks. Among the most important results from the extensive polarized deep-inelastic scattering programs is the smallness of the spin-dependent cross-section, or the spin structure function, which means that the quark and anti-quark spins combined provide only a nonintuitively small fraction (about 20%) of the nucleon spin. This result is in striking contrast with predictions from constituent quark models, which enjoyed success in describing hadron magnetic moments and spectroscopy, and has been dubbed the "proton spin crisis". Further investigation of the nucleon spin structure is clearly called for.
An examination of angular momentum in QCD tells us that the proton spin should be made up of contributions from the quark and anti-quark spins, gluon spins, and quark and anti-quark an gluon orbital angular momenta,

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

This spin sum motivates a substantial part of the RHIC spin physics program, and of nearly all other current activities in the field of high-energy nucleon spin physics.

1.2 Open questions in Nucleon Spin Physics

How do gluons contribute to the proton spin? Δg has been left virtually undetermined by the polarized-DIS data -- the virtual DIS photon primarily probes quarks and antiquarks. There are good reasons to be interested in Δg. First of all, its integral could well be an important contributor to the proton spin, by virtue of the spin sum. It is a remarkable feature of QCD that the integral of $\Delta g(x,Q^2)$ evolves as $1/\alpha_s(Q^2)$, that is, rises logarithmically with Q. This peculiar evolution pattern is a very deep prediction of QCD, related to its so-called axial anomaly. It has inspired ideas that a reason for the smallness of the quark spin contribution should be sought in a "shielding" of the quark spins due to a particular perturbative part of the DIS process $\gamma^* g \rightarrow q\bar{q}$. The associated cross section is of order $\alpha_s(Q^2)$; however, the peculiar Q^2-evolution of $\langle S_g \rangle$ would compensate this suppression. To be of any practical relevance, such models would require a very large positive gluon spin contribution, $\langle S_g \rangle > 1.5$, even at a low "hadronic" scale of 1 GeV or so. Such a large polarization of the confining fields inside a nucleon, even though suggested by some models of nucleon structure, would be a very puzzling phenomenon and would once again challenge our picture of the nucleon. Initial results from RHIC now suggest that Δg is not of such a large size. To obtain detailed information on Δg and its integral -- a DOE performance milestone for 2008 -- will be the outstanding task for RHIC-Spin for the mid-term. The eventual goal must be to determine the integral with precision of about 0.1, so that the gluon spin contribution to the proton spin becomes known to a level of the size of the quark spin contribution, or to about 20% of the proton spin. This will likely be a multi-year effort. It should be emphasized that the quest for measuring Δg is a world-wide one. The Compass collaboration at CERN and Hermes at DESY are attempting to constrain Δg by selecting particular heavy-flavor and hadron-pair final states in fixed-target lepton-proton scattering. Two features make RHIC the by far superior facility for studying gluon polarization: (1) a variety of probes of Δg is available. Over the next few years, a succession of channels, beginning with the more copious pion and jet productions and continuing with prompt-photon, photon-plus-jet, and heavy-flavor production, will serve to pin down Δg in ever more detail. (2) thanks to RHIC's high energy, the underlying theoretical calculations based on asymptotic freedom of QCD are generally better understood and more successful than in the fixed-target regime. In addition, at least two different energies are available at RHIC, offering large kinematical coverage and allowing tests of the underlying calculations. In any case, information from lepton-proton and proton-proton scattering is complementary.

What are the patterns of up, down, and strange quark and antiquark polarizations? Since the DIS process only "sees" the quark and antiquark squared charges, it provides access only to the combinations $\Delta q + \Delta \bar{q}$. To really understand the proton helicity structure in detail, one needs to learn about the various quark and antiquark densities, Δu, $\Delta \bar{u}$, Δd, $\Delta \bar{d}$, Δs, $\Delta \bar{s}$, individually. This would give us deeper insight into the question why the total spin contribution by quarks and antiquarks is so small. Is it indeed true, as believed by most, that the valence quarks follow the quark model predictions and make large contributions to the proton spin? Are the valence-u quarks aligned with the proton spin, while the valence-d is smaller and anti-aligned? Do the sea quarks and antiquarks strongly spin "against" the proton, hereby counteracting the valence contribution and leading to the observed small total quark and antiquark spin contribution? There are also more detailed questions in this context that are important for models of nucleon structure. For instance, models generally make clear qualitative predictions about the flavor asymmetry $\Delta \bar{u} - \Delta \bar{d}$ in the proton sea. These predictions are often related to fundamental concepts such as the Pauli principle: if valence-u quarks primarily spin along the proton spin direction, $u\bar{u}$ pairs in the sea will tend to have the u quark polarized opposite to the proton. Hence, if such pairs are in a spin singlet, one expects $\Delta \bar{u} > 0$ and, by the same reasoning, $\Delta \bar{d} < 0$. Such questions become all the more interesting due to the fact that rather large *unpolarized* asymmetries $\bar{u} - \bar{d} \neq 0$ have been observed in DIS and Drell-Yan measurements. As in the case of gluon polarization, there are world-wide efforts to address the questions about quark and antiquark polarizations experimentally. At the Jefferson Laboratory precise measurements of quark polarizations in the valence region (at large momentum fractions x) are made. Compass and Hermes study the semi-inclusive production of hadrons such as $\pi^{\pm}$, $K^{\pm}$, …, which serve as flavor "tags". Interesting results are emerging; however, it has been pointed out that at the energies available to Hermes and Compass the semi-inclusive DIS process may not be straightforward to analyze theoretically. Definitive information on quark and antiquark polarizations will come from RHIC over the next few years, where one will study spin asymmetries in the production of $W^{\pm}$ bosons, exploiting the phenomenon of parity-violation in nature. W bosons couple to left-handed quarks and right-handed antiquarks and hence are natural probes of their helicity structure in the proton. Producing a sufficiently large number of W's in pp collisions at RHIC is only possible with high-luminosity running at 500 GeV center-of-mass energy. Upgrades of the Star (tracking) and Phenix (forward trigger) detectors are vital as well. We note that the extractions of quark and antiquark polarizations from W measurements constitute another DOE performance milestone, for the year 2013.

Further fundamental questions about the structure of the polarized nucleon concern the polarization of strange quarks. The polarized DIS measurements point to a sizable negative polarization, in line with other observations of significant strange quark effects in nucleon structure. This could be investigated in more detail at RHIC, in the mid-term through measurements of the polarizations of produced Λ and $\overline{\Lambda}$ baryons (which carry valence (anti)strangeness), and further in the future through spin asymmetries in charm-tagged W production. The Λ and $\overline{\Lambda}$ studies might even help to detect any difference between strange and anti-strange polarizations in the proton. Recently, in the unpolarized case, the asymmetry between strange and anti-strange distributions has attracted much attention, due to its interest for nucleon models, but also due to its possible implications for an explanation of the ~3σ "anomaly" in the Fermilab-NuTeV measurement of the Weinberg angle.

What orbital angular momenta do partons carry? The spin sum shows that quark and gluon orbital angular momenta are the other candidates for the carriers of the proton spin. Consequently, theoretical work focused also on these in the years following the discovery of the "spin crisis". A conceptual breakthrough was made in the mid 1990s when it was realized that a particular class of "off-forward" nucleon matrix elements, in which the nucleon has different momentum in the initial and final states, measure total parton angular momenta. Put simply, orbital angular momentum is $\mathbf{r} \times \mathbf{p}$, with $\mathbf{r}$ corresponding to a derivative with respect to momentum transfer. Thus, in analogy with the measurement of the Pauli form factor, it takes a finite momentum transfer on the nucleon to access matrix elements with operators containing a factor **r**. It was also shown how these "off-forward" distributions, really generalizations of the ordinary parton distributions, may be experimentally determined from certain rare exclusive processes in lepton-nucleon scattering, the prime example being "Deeply-Virtual Compton Scattering (DVCS)", $\gamma^* p \rightarrow \gamma\, p$. They also provide insights into spatial distributions of partons in the nucleon. A major emphasis in current and future experimental activities in lepton scattering is on DVCS and related reactions. There are, however, other observables that may provide information on orbital angular momenta of nucleon constituents. One of these contributes to spin asymmetries measured with a single transversely polarized proton and an unpolarized one. This brings us to the next compelling question.

What is the role of transverse spin in QCD? So far, we have only considered the helicity structure of the nucleon, that is, the partonic structure we find when we probe the nucleon when its spin is aligned with its momentum. High-energy protons may also be studied when *transversely* polarized, and it has been known for a long time now that very interesting spin effects are associated with this in QCD. Partly this is known from theoretical studies, which revealed that besides the helicity distributions Δf discussed so far, for transverse polarization there is a new set of parton densities, called "transversity". These are defined analogously to Eq. (1), but now for transversely polarized partons polarized along or opposite to the transversely polarized proton. Nothing is known so far experimentally about the transversity densities. Their measurement is highly desirable, for a number of reasons. Not only does transversity complete the set of nucleon parton distributions. Differences between the helicity and transversity densities give information about relativistic effects in the nucleon. The transversity densities also give the nucleon tensor charge, one of the fundamental charges of the nucleon, along with its vector and axial charges. Finally, transversity also plays a role in predictions for the neutron electric dipole moment. To perform initial transversity measurements will be an important mid-term task for RHIC.

The other reason why transverse spin has captured the attention of researchers in QCD for a long time is related to experimental observations of very large single-transverse spin asymmetries in pp scattering, where really none had been expected. Related azimuthal asymmetries were seen in lepton scattering more recently by the Hermes and Compass collaborations. Often, when simple expectations are refuted experimentally, new insights emerge, and this has been no different in this case. With time it was realized that single-spin asymmetries tell us many more things about QCD and the nucleon than previously anticipated. With regard to nucleon structure, it is of particular interest that single-transverse spin asymmetries may provide information on parton orbital angular momenta, through novel parton distributions known as "Sivers" functions. In addition to the longitudinal momentum fraction x, these depend on intrinsic parton *transverse* momenta in the nucleon and express a correlation $\sim \mathbf{s}_\perp \cdot (\mathbf{p} \times \mathbf{k}_\perp)$ between the transverse nucleon spin vector $\mathbf{s}_\perp$, its momentum $\mathbf{p}$, and the parton transverse momentum $\mathbf{k}_\perp$. For a long time, such correlations in parton distributions were blieved to be forbidden by time-reversal invariance of QCD. However, it was recently realized that the time-reversal constraint does not apply if there is a rescattering of the parton in the color field of the nucleon remnant. Depdending on the process, the associated color Lorentz forces will act in different ways on the parton. In DIS, so far explored experimentally by the Hermes and Compass collaborations, the final-state interaction between the struck parton and the nucleon remnant is attractive. In contrast, for the Drell-Yan process it is repulsive. Therefore, the Sivers functions contribute with opposite signs to the single-spin asymmetries for these two processes. It is up to RHIC to verify this fundamental prediction, which really tests all concepts we know of for analyzing hard-scattering reactions in strong interactions.

We are still far from a complete understanding of these issues and the further mechanisms that may be involved in single-spin asymmetries. RHIC is poised to provide answers over the next few years. To achieve this goal, detector upgrades are important. It has been found so far that single-spin asymmetries are most significant in the "valence" region, which at RHIC implies production at forward angles with respect to the polarized beam. This motivates the planned upgrades for forward particle measurements that will allow to study many transverse-spin phenomena and collect information from various probes, such as photons, pions, and Drell-Yan muon pairs.

2 Physics opportunities with electroweak bosons at RHIC

2.1 Precision studies of polarized quark and anti-quark distributions

Deep-inelastic scattering data provide access only to the sum of quark and anti-quark densities for each flavor. To really understand the proton helicity structure in detail, one needs to learn about the various quark and antiquark densities, Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$, Δs, and $\Delta\bar{s}$, *individually*. This would give us deeper insight into the question why the total spin contribution by quarks and antiquarks is so small. In addition, precision measurements of these quantities also challenge theoretical models of nucleon structure which, for instance, generally make clear qualitative predictions about the flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ in the proton sea. These predictions are often related to fundamental concepts such as the Pauli principle: if valence-u quarks primarily spin along the proton spin direction, $u\bar{u}$ pairs in the sea will tend to have the u quark polarized opposite to the proton. Hence, if such pairs are in a spin singlet, one expects $\Delta\bar{u} > 0$ and, by the same reasoning, $\Delta\bar{d} < 0$. Such questions become all the more exciting due to the fact that rather large *unpolarized* asymmetries $\bar{u} - \bar{d} \neq 0$ have been observed in DIS and Drell-Yan measurements.

As in the case of gluon polarization, there are world-wide efforts to address the questions about quark and antiquark polarizations experimentally. Interesting results are emerging about quark polarizations in the valence region (i.e., at large momentum fractions x) from Jefferson Laboratory and about the flavor decomposition from studies of semi-inclusive production of hadrons such as $\pi^{\pm}$, $K^{\pm}$, …, by the HERMES experiment at DESY. In the latter case, one uses correlations in the fragmentation process between the type of hadron and the flavor of its parton progenitor, expressed by non-perturbative fragmentation functions. The rather poor knowledge of the hadronization process puts some limits on the accuracy of this method. In addition, it has been pointed out that at the energies available to fixed-target experiments, processes in general may not be analyzed straightforwardly in terms of parton distribution functions. Definitive information on quark and antiquark polarizations will come from RHIC over the next few years, where one will study single-spin asymmetries in the production of $W^{\pm}$-bosons, exploiting the phenomenon of parity-violation in nature: W-bosons only couple to left-handed quarks and right-handed antiquarks and hence are natural and clean probes of their helicity structure in the proton.

The basic theoretical concepts and the relevant experimental aspects on W-boson production at RHIC have already been studied in great detail in [SPIN-REP] and need not be repeated here. We only recall that producing a sufficiently large number of W's in pp collisions at RHIC is only possible with *high-luminosity running* at 500 GeV center-of-mass energy. Upgrades of the STAR (tracking) and PHENIX (forward trigger) detectors are vital as well. We note that the extractions of quark and antiquark polarizations from W-boson measurements constitute one of the DOE performance milestone for the year 2013. Integrated luminosities much in excess of $1\,\mathrm{fb}^{-1}$ as targeted for phase-II of RHIC operations would clearly turn these measurements into high-precision studies of polarized quark and anti-quark densities.

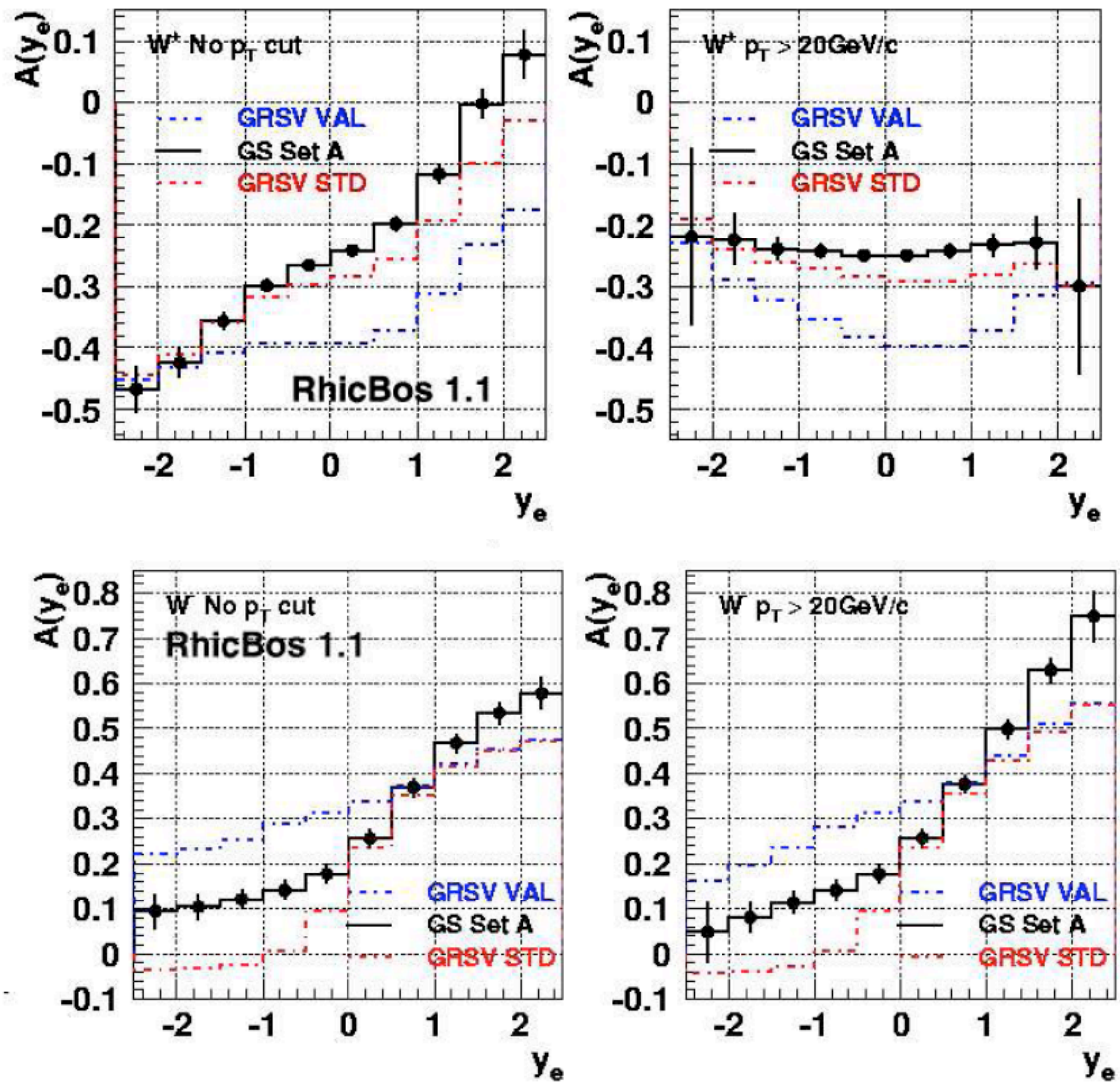


Figure ??: *Single-spin asymmetry for* W^+ *and* W^- *production at RHIC at the decay lepton level at 500 GeV center-of-mass energy for different assumptions about the polarized quark and anti-quark distributions. The projections of the statistical accuracy are for 800* pb^{-1} *and 70% beam polarization.*

On the theory side much progress has been made in recent years. All relevant cross sections are available at least to NLO accuracy. With RESBOS/RHICBOS, a Monte-Carlo integrator is hand which properly takes into account the W-boson's width and decay, electroweak corrections, resummations of soft gluon emission, and decay lepton distributions for realistic detector acceptance. Needless to mention that RHIC will also significantly contribute to our knowledge about the unpolarized parton densities of the proton in a completely different kinematical domain than the TeVatron or the LHC. In particular, the ratio of unpolarized W^+ and W^--boson cross sections will directly probe the $\bar{d}/\bar{u}$ ratio.

2.2 Precision studies of hadronic decays of W-bosons (P. Nadolsky) and electroweak effects in single-spin asymmetries (Moretti et al.)

So far, all studies and simulations for RHIC [SPIN-REP] have focussed on the leptonic decay channels of W-bosons – the "golden modes" for studying helicity-dependent parton densities in single-spin asymmetries provided large enough luminosities can be reached. Apart from being interesting in their own right, hadronic decays of the W-bosons into two jets may deserve further investigations as well. At initially lower luminosities and perhaps reduced instrumentation without lepton charge identification many advantages of the leptonic decay channels are lost and hadronic decays may be competetive at RHIC. Their main advantages are the sixth-fold enhanced branching fraction with respect to leptonic decays, the possibility to directly reconstruct the rapidity of the W-boson, and the reduced dependence on the detector acceptance due to the more symmetric angular distribution of the jets compared to the decay leptons.

On the downside, one cannot easily distinguish between W^+ and W^--bosons unless charged pions are used as jet surrogates (by looking into $\pi^{\pm}\pi^0$ decay modes), nor fully separate W and Z-boson signals as a consequence of the low invariant mass resolution. Contamination by Z-bosons is roughly three times larger in the di-jet mode than in the leptonic decays, because the Z-boson cross section is enhanced even more by the branching ratio in the hadronic channel than for W's. Clearly, the QCD background is large in the di-jet channel with background-to-signal of about 20. However, the background is smooth and can be estimated in the W/Z resonance region by extrapolating from the side-bands in the di-jet mass distribution.

In addition, there is no pure QCD background for the single-spin cross section and asymmetry accessible at RHIC as a result of parity conservation of the strong interactions. This possibility to reduce the background makes the measurement of the hadronic W decay mode more attractive at RHIC than at the TeVatron or the LHC. Even without polarization, the QCD background is greatly reduced at RHIC as a result of the smaller center-of-mass energy at RHIC. Experience from measurements of the di-jet invariant mass distribution in W/Z decays at the SPS, $\sqrt{S} = 630$ GeV, with less than $1\,\text{pb}^{-1}$ tells us that the luminosity will not be a limiting factor in the hadronic decay channel at RHIC. The main difference between RHIC and SPS are the collision energy and the beam type (pp vs. $p\bar{p}$). The smaller center-of-mass energy $\sqrt{S}$ reduces slightly the QCD background from gluon scattering. More importantly, the W-signal cross section is about three times smaller at the pp collider RHIC than at the $p\bar{p}$ collider SPS. This reduction is roughly equal to the ratio of the leading parton luminosities at both colliders: $u(\tau)\bar{d}(\tau)$ at RHIC and $u(\tau)d(\tau)$ at SPS in W^+-production, with $\tau = Q/\sqrt{S}$. The QCD background arising from $q\bar{q}$-scattering is reduced together with the signal. However, the other types of QCD backgrounds (from qq, qg, and gg-scattering) should be roughly the same at both colliders. Assuming the qg and gg-contributions are negligible, we need mostly worry about the background from qq-scattering via t-channel gluon exchange, which can be possibly removed by utilizing its difference dependence on the polar angle θ in the W-boson rest frame. From this we expect that a background-to-signal ration of 20-30 may be achievable in the hadronic decay mode at RHIC.

Parity-violating electroweak effects to single-spin asymmetries for single-inclusice jet production are also interesting in their own right as they never have been measured before.

Apart from small purely $O(\alpha_{ew}^2)$ electroweak contributions, responsible for the characteristic ``Jacobian peak`` at jet transverse momenta of about $p_T \approx M_{W,Z}/2$, one has to consider all $O(\alpha_s \alpha_{ew})$ electroweak-QCD interference contributions at the tree-level approximation. Recently, all one-loop $O(\alpha_s^2 \alpha_{ew})$ contributions have been computed and turned out to be of extreme relevance, see Figure XX. For instance, for processes with external gluons no parity-violation occurs at the tree-level, so that $O(\alpha_s^2 \alpha_{ew})$ is the first non-trivial order where they show up.

Although current search limits for physics beyond the Standard Model from the TeVatron do not make it very likely that anything can be found at RHIC energies but the parameter space is vast and not everything can be excluded. Deviations from the Standard Model prediction for parity-violating single-spin asymmetries would definitively indicate the presence of new physics. Several possible signatures for new physics at RHIC have been studied in some detail in the past [SPIN-REP] ranging from compositeness to models with new neutral gauge bosons like the leptophobic Z`.

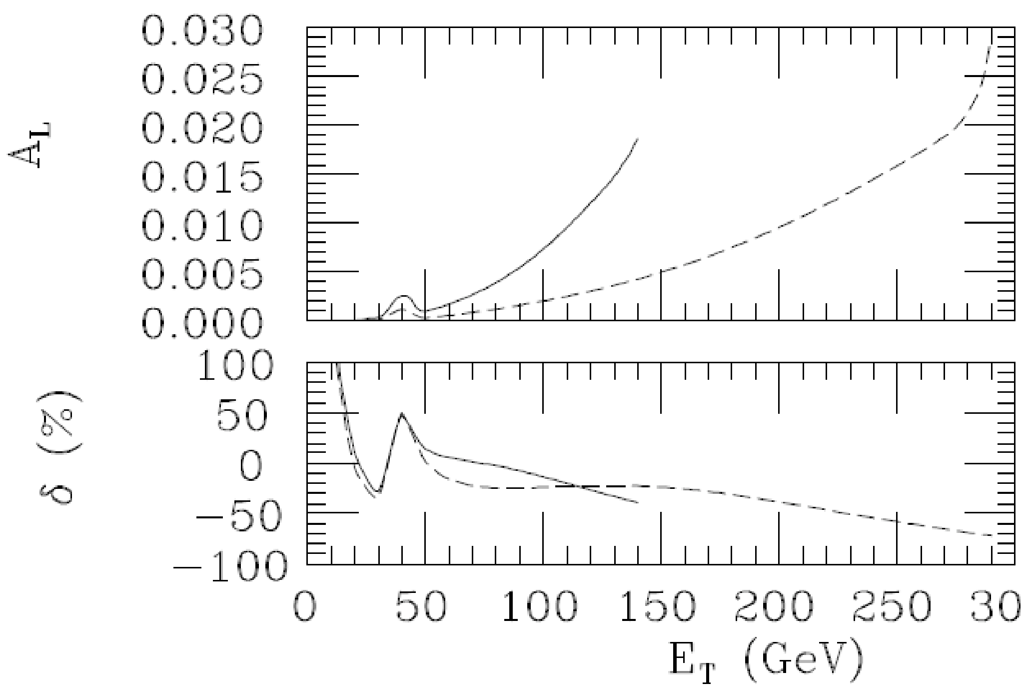
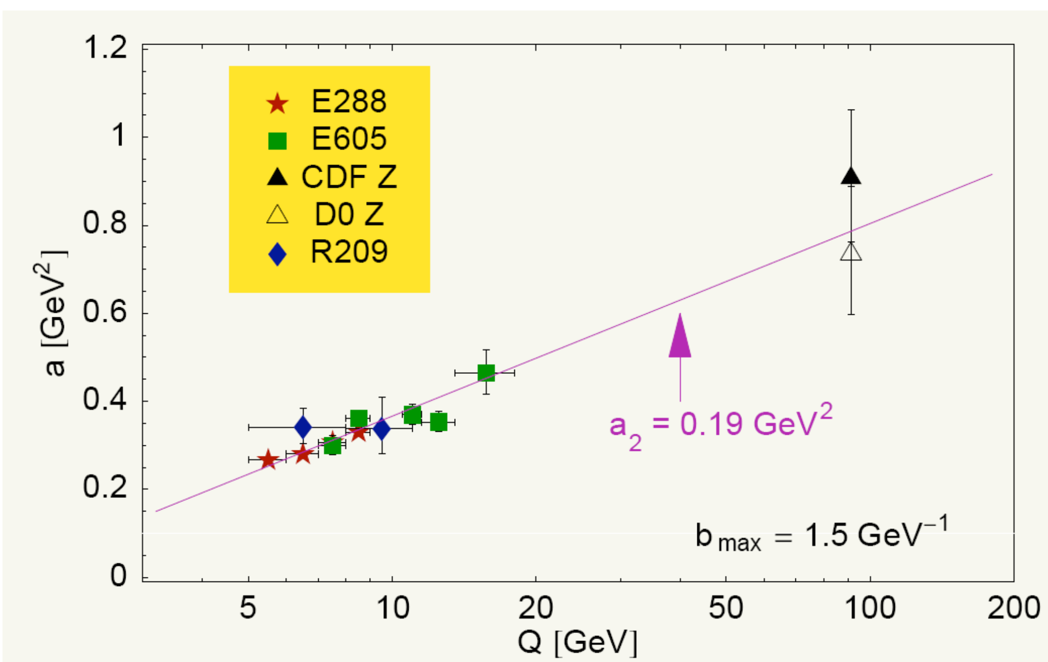


Figure ??: Parity-violating *single-spin asymmetry at both RHIC energies (solid/dashed lines) as a function of the jet transverse energy. The pseudorapidity range of the jets is limited to* $|\eta| < 1$ *and the a standard jet cone requirement* $R_{cone} = 0.7$ *is imposed. The size of the* $O(\alpha_s^2 \alpha_{ew})$ *corrections is indicated in the lower panel.*

2.3 Precision tests of k_T-factorisation with W-bosons (P. Nadolsky)

Many interesting predictions for spin asymmetries involve k_T-factorization, a form of QCD factorization theorem preserving information about the transverse momentum of initial-state partons. A particular version of k_T-factorization has been used for more than twenty years to predict p_T-distributions in unpolarized Drell-Yan like processes, semi-inclusive DIS, and hadroproduction in e^+e^--annihilation. Very recently k_T-factorization has been proven for these processes in [??]. The predictive power of k_T-factorization is based on **(a)** computations of perturbative QCD corrections to the underlying hard scattering processes and **(b)** the universality, i.e., process independence, of certain non-perturbative functions: k_T-dependent parton densities and resummed soft, or Sudakov, exponentials. If the non-perturbative functions are indeed universal, they should emerge in a simultaneous (global) fit to all available experimental data. To disentangle different non-perturbative functions, the global fit must include precision data from different energies and targets. Until recently, such a separation was not entirely possible due to the limited data sets available, so that all non-perturbative functions were mapped into a cumulative Sudakov factor S_{NP}. A recent global analysis of unpolarized p_T-distributions in fixed-target Drell-Yan pair and Z-boson production at the TeVatron [??] suggests that S_{NP} can be approximated by a simple three parameter function. The energy dependence was found to be in close agreement with predicitons from infrared renormalons [??]. This agreement indicates that the soft contributions dominate in S_{NP}, which in turn suggests that its energy dependence must be *independent* of spin.



At RHIC, in particular in phase II with much improved luminosity, one could perform precision studies of p_T-distributions in unpolarized and – for the first time – also polarized low-mass Q Drell-Yan pair production at center-of-mass energies $\sqrt{S} = 200$ and 500 GeV. This would allow to confirm (or disprove) the observed energy dependence in Figure ?? and to test the conjectured spin independence of S_{NP}. Such measurements could also resolve remaining small tensions between the E288 and E605 low-Q Drell-Yan data observed in the global analysis in [??]. Scattering on alternative targets, like Helium-3, may additionally test the flavor dependence of S_{NP}.

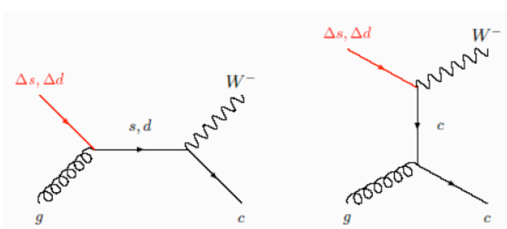
It is important to note that these measurements will be instrumental in identifying detailed features of k_T-factorization and also further contraining non-perturbative uncertainties in high-energy collider experiments aiming at a precision determination of the W-boson mass like the TeVatron and the LHC. Here uncertainties in S_{NP} currently contribute the largest systematical error.

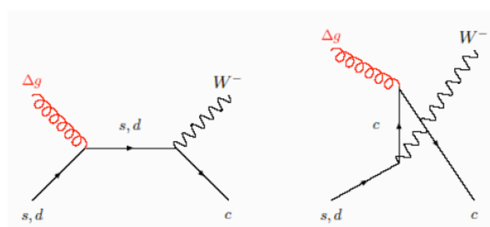
2.4 Determination of the strange polarization from associated W-boson plus charm quark production (K. Sudoh & H. Yokoya)

Further fundamental questions about the structure of the polarized nucleon concern the *polarization of strange quarks* which is very difficult to access experimentally. The polarized DIS measurements point to a sizable negative polarization, in line with other observations of significant strange quark effects in nucleon structure. Recent results from studies of semi-inclusive deep-inelastic kaon production at HERMES are consistent, within large errors, with a vanishing strange polarization. This could be investigated in more detail at RHIC, in particular, through measurements of the polarizations of produced Λ and $\overline{\Lambda}$-baryons (which carry valence (anti-)strangeness), see Section XX, and with sufficient luminosity perhaps through spin asymmetries in associated W-boson and tagged charm quark production.

The Λ and $\overline{\Lambda}$ studies might even help to detect any difference between strange and anti-strange polarizations in the proton. Recently, in the unpolarized case, the asymmetry between strange and anti-strange distributions has attracted much attention, due to its interest for nucleon models, but also due to its possible implications for an explanation of the ~3σ "anomaly" in the Fermilab-NuTeV measurement of the Weinberg angle.

At lowest order, $O(\alpha_s \alpha_{ew})$, and considering, as in Section XX.1 only singly polarized proton-proton collisions at RHIC, associated W^--boson and charm production proceeds through the following processes:





and similarly for W^+ and anti-charm production.

To extract information about Δs one has to disentangle contributions from $\Delta s\, g$ (signal) and $\Delta g\, s$ (background) initial states. In addition, one has to properly take into account the CKM mixing between the initial state s and d quarks which further suppresses the signal. At $\sqrt{S} =$ 500 GeV the unpolarized total cross section for charm-associated W^--production is rather small, of the order of a few picobarn, and even smaller for W^+-boson plus anti-charm quark production. Taking also into account that the charm quarks (and the W-boson) have to be tagged experimentally, makes these measurements very challenging, even with the luminosities that might be achievable at phase-II of RHIC.

The main idea to separate signal from background is to look at different rapidities, like for the flavor and quark/anti-quark separation. Of course, one has to assume that by the time such a measurement can be performed, Δg and $\Delta d\,(\Delta\bar{d})$ are suffciently known from other measurements at RHIC. The relevant single-spin asymmetry reads

$$A_L = \frac{d\Delta\sigma_{\Delta gs} + d\Delta\sigma_{\Delta sg}}{d\sigma_{gs} + d\sigma_{sg}} \approx \frac{\Delta g(x_a)\cdot s(x_b) + \Delta s(x_a)\cdot g(x_b)}{g(x_a)\cdot s(x_b) + s(x_a)\cdot g(x_b)}$$

Thus for large and negative rapidities y_W of the W-boson $x_a \propto e^{y_W}$ is large and $x_b \propto e^{-y_W}$ is small and vice versa for large and positive rapidities. This is illustrated in Figure XX for $\sqrt{S}$ = 500 GeV, assuming an integrated luminosity of 800 pb^{-1}, a beam polarization of 70%, and a charm detection efficiency of 10%. Such a luminosity might be just sufficient to determine the sign of the strange quark polarization from measurements at large and positive y_W. For W^+-production the situation is even less promising; see also Figure XX.

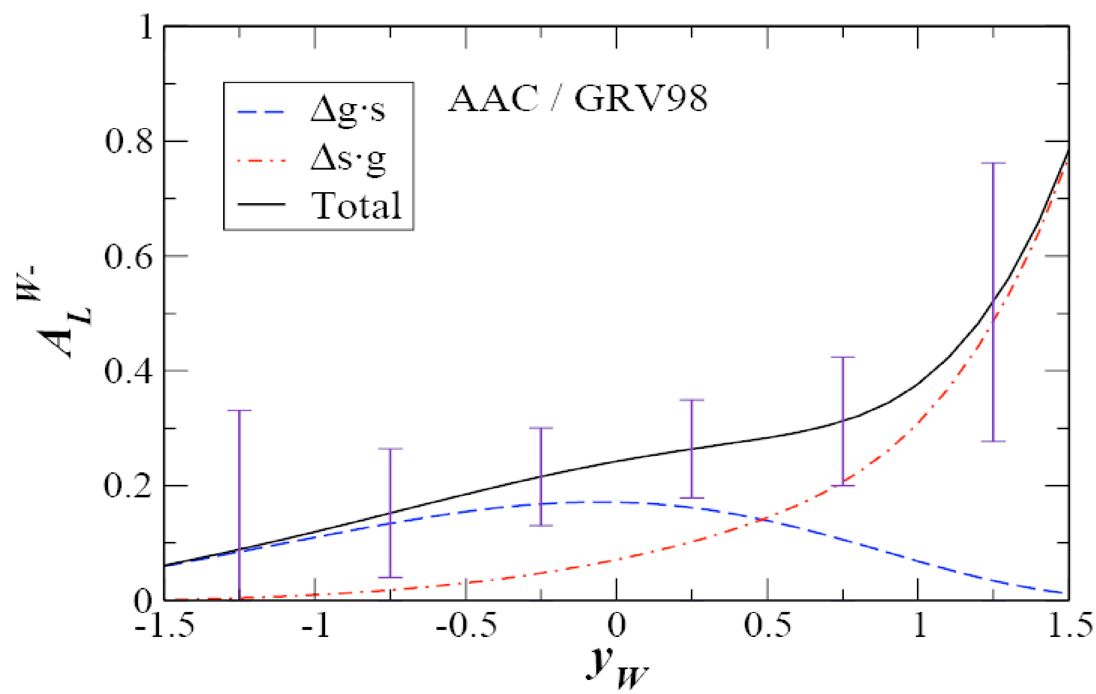


Figure XX: *Contributions from* $\Delta g\ s$ *(background; dashed line) and* $\Delta s\, g$ *(signal; dot-dashed line) initiated processes to the single-spin asymmetry as a function of rapidity* y_W *of the* W^-*-boson. The projections of the statistical accuracy are for 800* pb^{-1}*, 70% beam polarization, and 10% detection effiency.*

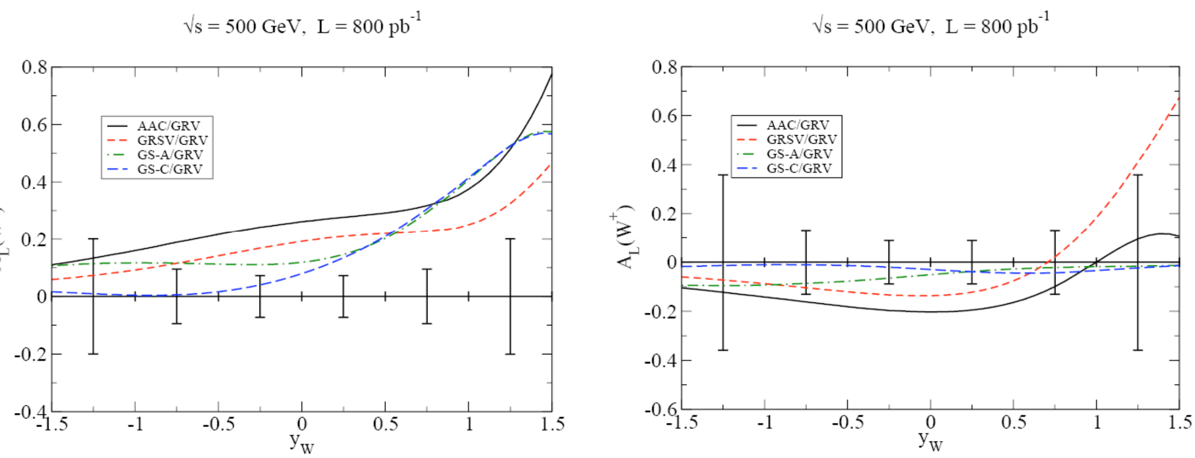


Figure XX: *Single-spin asymmetry for* W^- *plus charm* **(left)** *and* W^+ *plus anti-charm* **(right)** *production as a function of rapidity* y_W *of the W-boson for different sets of polarized parton densities. The projections of the statistical accuracy are for 800* pb^{-1}*, 70% beam polarization, and 10% detection effiency.*

2.5 Remarks on possible SUSY searches at RHIC (D. Maitre)

Supersymmetry is a framework allowing for a very large variety of different models with very different phenomenology. The most simple and most studied one being the MSSM which is obtained by imposing certain constraints on the realization of supersymmetry and by making assumptions on the relative magnitude of some parameters. The TeVatron has extensively searched for MSSM particles and set lower mass bounds for the squarks (250 GeV) and gluino (195 GeV). These bounds clearly do not allow their detection at RHIC. There are nevertheless other less restrictive models other than the MSSM. Provided these models are realized in nature, the mass bounds can be significantly weaker and squarks and gluinos might be produced also at RHIC. For these more exotic models the additional spin information from RHIC could valuably contribute to the understanding of this model. Most of these more general models still have the property that the production rates of the SUSY particles is governed by the strong coupling and the mass of the particles. Figure XX shows the mass range accesble at RHIC assuming a center-of-mass energy of 500 GeV, an integrated luminosity of 800 pb^{-1}, and 70% beam polarization.

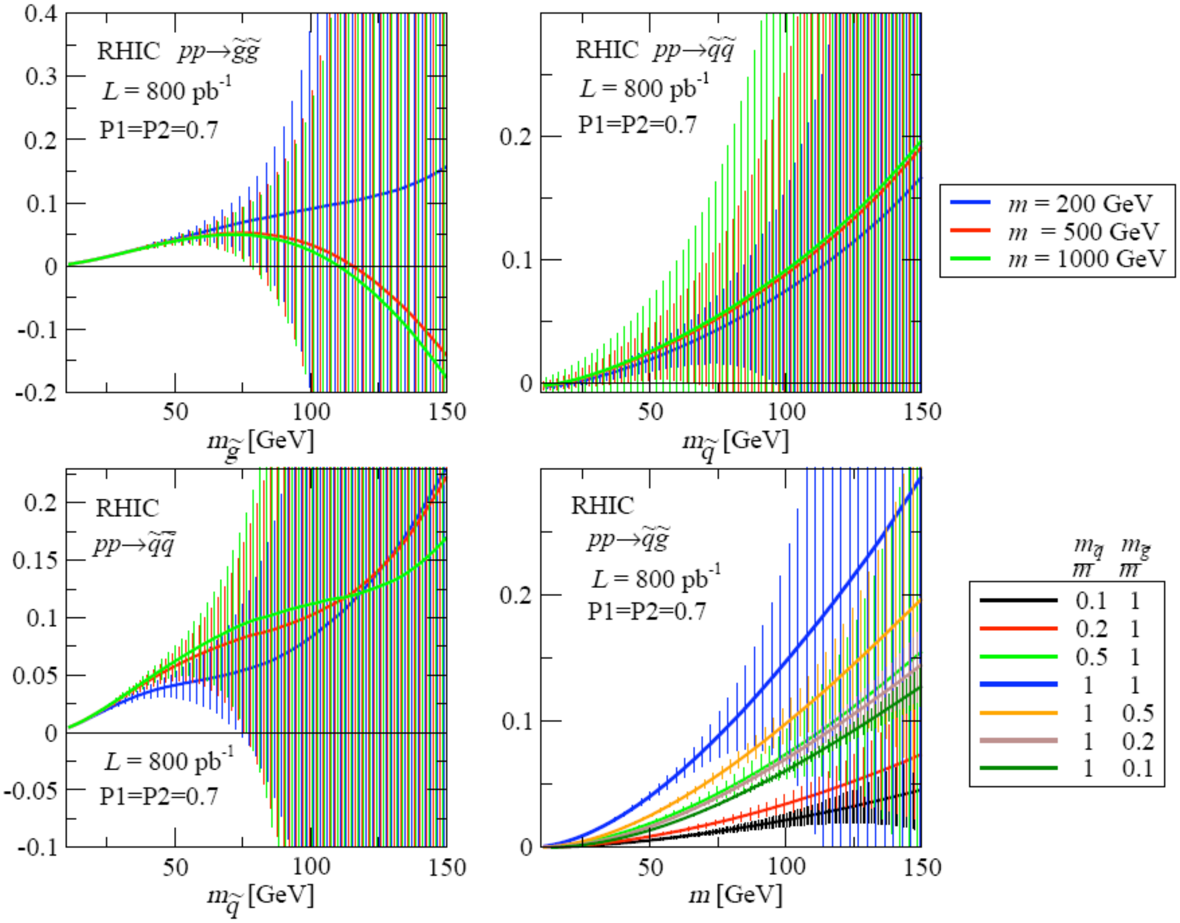


Figure XX: *Spin-asymmetry for the production of SUSY particles as a function of the masses of the squarks and gluino. The projections of the statistical accuracy are for 800* pb^{-1} *and 70% beam polarization.*

3 Physics opportunities in heavy flavor production at RHIC

Heavy D and B mesons and heavy quarkonia, in particular the J/Ψ, are a versatile laboratory for quantitative tests of QCD and the interplay of perturbative and non-perturbative phenomena. Measurements of heavy probes like the J/Ψ will foster our understanding of the quark-gluon plasma in heavy-ion collisions and, thanks to the dominance of the gluon-gluon fusion channel, $gg \to Q\overline{Q}$, the (polarized) gluon distribution of the nucleon. High luminosities as envisioned in phase II of RHIC would allow for precision studies of heavy flavor production. Apart from sufficient luminosity, planned vertex detectors for both PHENIX and STAR are essential to select these events based on displaced vertices.

On the theory side, "open" charm and bottom production is described in the standard factorized framework of perturbative QCD, and hard scattering cross sections have been computed up to NLO accuracy both for unpolarized and polarized proton-proton collisions. Since a long-standing discrepancy between bottom production rates at the TeVatron and NLO QCD theory has been resolved recently, open heavy flavor production is expected to be a reliable tool to further our knowledge of the spin structure of the proton at RHIC. Detailed quantitative theoretical simulations for RHIC focussing on Δg are currently under way, including also studies of $Q\overline{Q}$ correlations and the $Q-\overline{Q}$ charge asymmetry.

The decay of heavy-flavor mesons dominates the inclusive production of leptons in the range of 2-10 GeV, so that highest statistics measurements of heavy flavor production will be made via inclusive electron and/or muon spectra. Figure XX shows PHENIX projections of double-spin asymmetry A_{LL} uncertainties attainable via inclusive electron detection at mid-rapidity.

The focus in studies of heavy quarkonia like the J/Ψ is primarily to understand the underlying production mechanisms better. The factorization formalism of non-relativistic QCD (NRQCD) provides a rigorous theroretical framework for the description of heavy quarkonium production and decay. In particular, this formalism predicts the existence of color-octet (CO) processes. This means that the $Q\overline{Q}$ pairs are produced at short distances in CO states and subsequently evolve into physical, color-singlet quarkonia by non-perturbative emission of soft gluons. The biggest triumph of this formalism was that it was able to correctly describe the cross section for inclusive charmonium production at TeVatron, which had turned out to be more than one order of magnitude in excess of earlier theoretical predictions based on the so-called color-singlet model (CSM). Also recent PHENIX data for J/Ψ production in unpolarized pp collisions can be explained by the same mechanism. This is in line with results obtained in electroproduction at HERA and photoproduction at LEP2.

There are, however, other aspects of quarkonium production which are much less understood. In particular, polarized heavy quarkonium production at TeVatron energies is not explained satisfactorily by the NRQCD color-octet mechanism despite its successes for other channels. With the possibility of polarized pp collisions, RHIC offers a wide variety of *unique* measurements with respect to quarkonium production to shed some light on the underlying production mechanisms: in unpolarized pp collisions one can study the energy dependence of quarkonium production; in polarized pp collisions one can study both the production of unpolarized quarkonia and, for the first time, the spin transfer to polarized quarkonia. LO NRQCD estimates of charmonium production at RHIC for all specific polarization states have to obtained recently. Further simulations including also detector simulations are, however necessary.

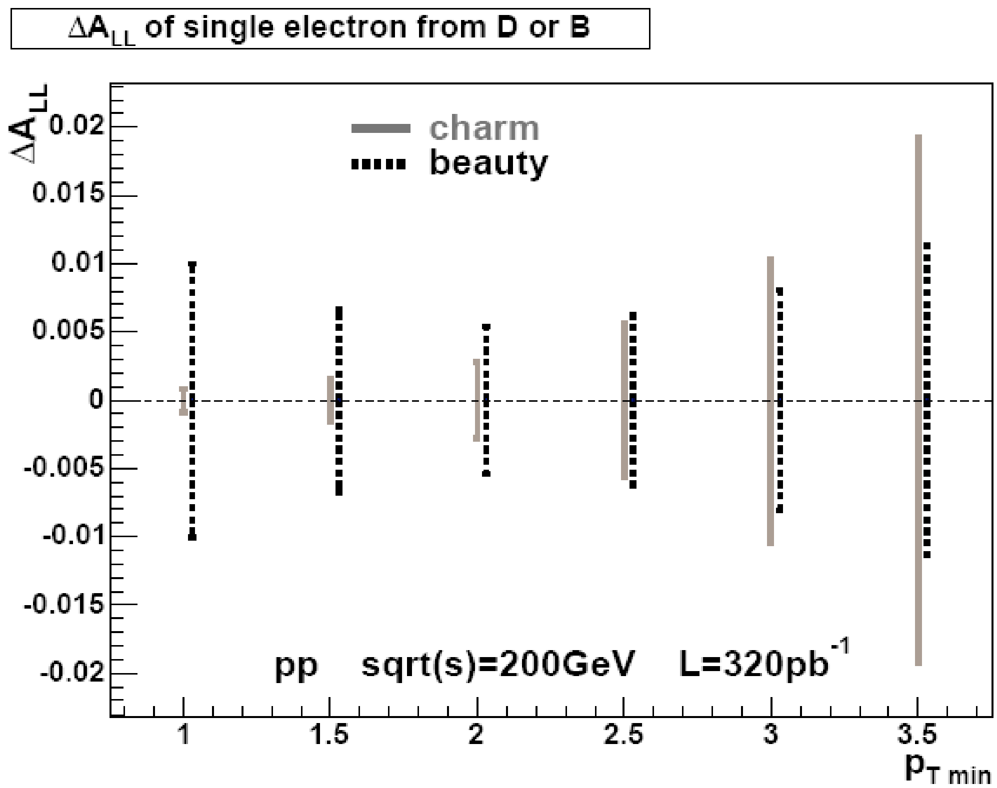


Figure XX: *Projected uncertainties in the double-spin asymmetry* A_{LL} *for heavy flavor production at PHENIX with a proposed vertex detector.*

Before the advent of the NRQCD factorization formalism, heavy quarkonium production at RHIC and other polarized experiments was believed to provide reliable information on the spin-dependent gluon distribution. At present, however, we are faced with the potential problem that NRQCD predictions at the lowest order come with considerable normalization uncertainties, partly due to the introduction of several CO matrix elements as additional input parameters. In fact, the relevant CO matrix elements have only been determined through LO fits to experimental data and come with appreciable theoretical uncertainties. Thus, it must be carefully clarified first if heavy quarkonium production is a useful tool for a precision determination of Δg. New data from RHIC in the future would certainly boost further theoretical developments in the field of NRQCD.
Figure XX shows the NRQCD and CSM predictions for unpolarized J/Ψ cross sections at RHIC, differential in transverse momentum and rapidity (upper panel). Also shown are the double-spin asymmetries for unpolarized J/Ψ production for various different assumptions about Δg in NRQCD and the CSM in the middle and lower panel, respectively. The shaded bands indicate the uncertainties in the theoretical estimates. It turns out that the spread in the predictions due different assumptions about Δg usually exceeds the uncertainties from other sources in the NRQCD and CSM approaches. However, studies of the expected experimental accuracy for such measurements at PHENIX and STAR are still lacking at the moment.

Theoretical expectations in LO NRQCD for the production of polarized J/Ψ and Ψ' in polarized pp collisions at RHIC can be found in [XX].

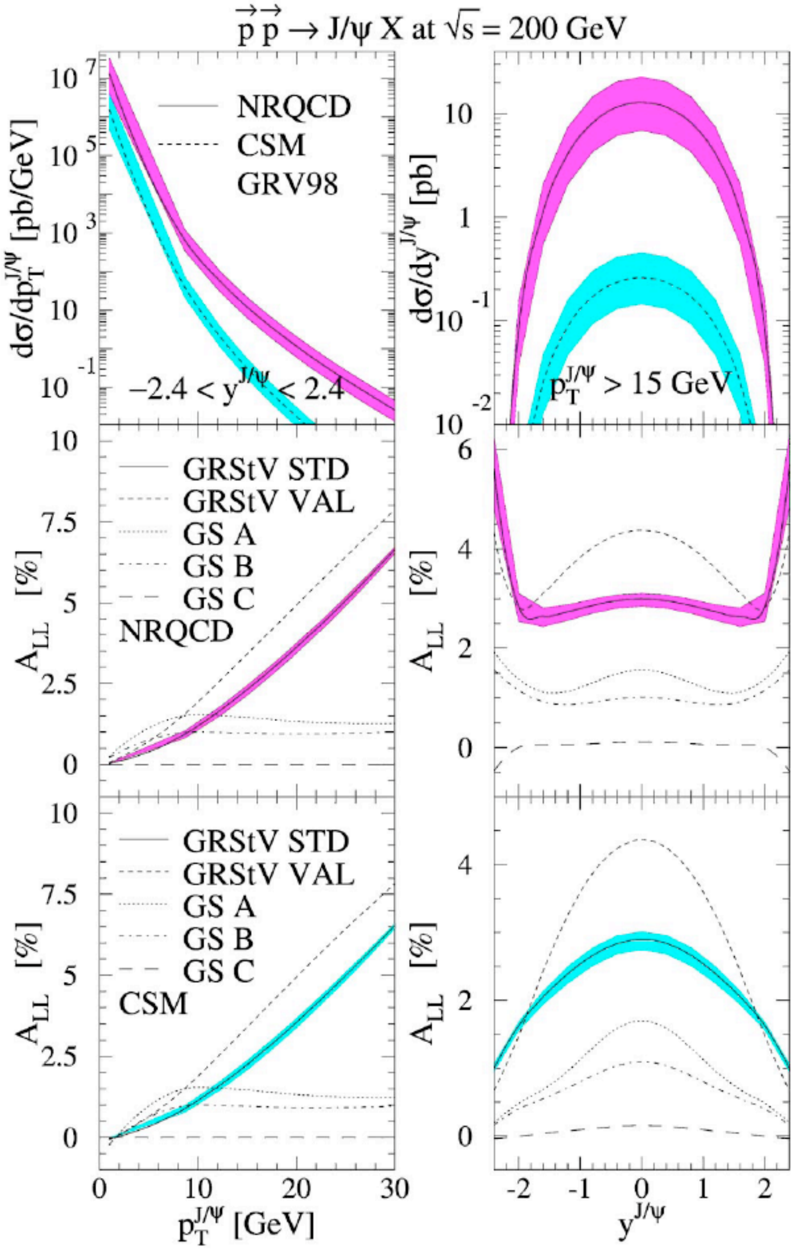


Figure XX: *The unpolarized* p_T *and rapidity differential cross sections (upper panel) and the double-spin asymmetries (middle and lower panel) for inclusive* J/Ψ *production at RHIC in the framework of NRQCD and the CSM. The shaded bands indicate the theoretical uncertainties in the NRQCD and CSM results. In the case of* A_{LL} *these uncertainties are compared to the spread due to different assumptions about* Δg.

4 Physics opportunities with hyperon polarization at RHIC

The polarizations of hyperons, in particular the Lambda (Λ), have been widely used in high energy reactions for their self spin-analyzing parity violating decay. Hyperon polarization measurements alllow the study of spin transfer in fragmentation. Significant non-zero transfers have been observed. In polarized proton-proton collisions these measurements provide in addition selective sensitivity to the spin structure of the nucleon. For example, the spin transfer to strange and inclusive charmed hyperons has been proposed as a probe for the polarized gluon distribution of the proton.[1,2] Strange hyperons may also provide sensitivity to strange quark polarization.

4.1 Λ_c and gluon polarization (K. Sudoh et al)

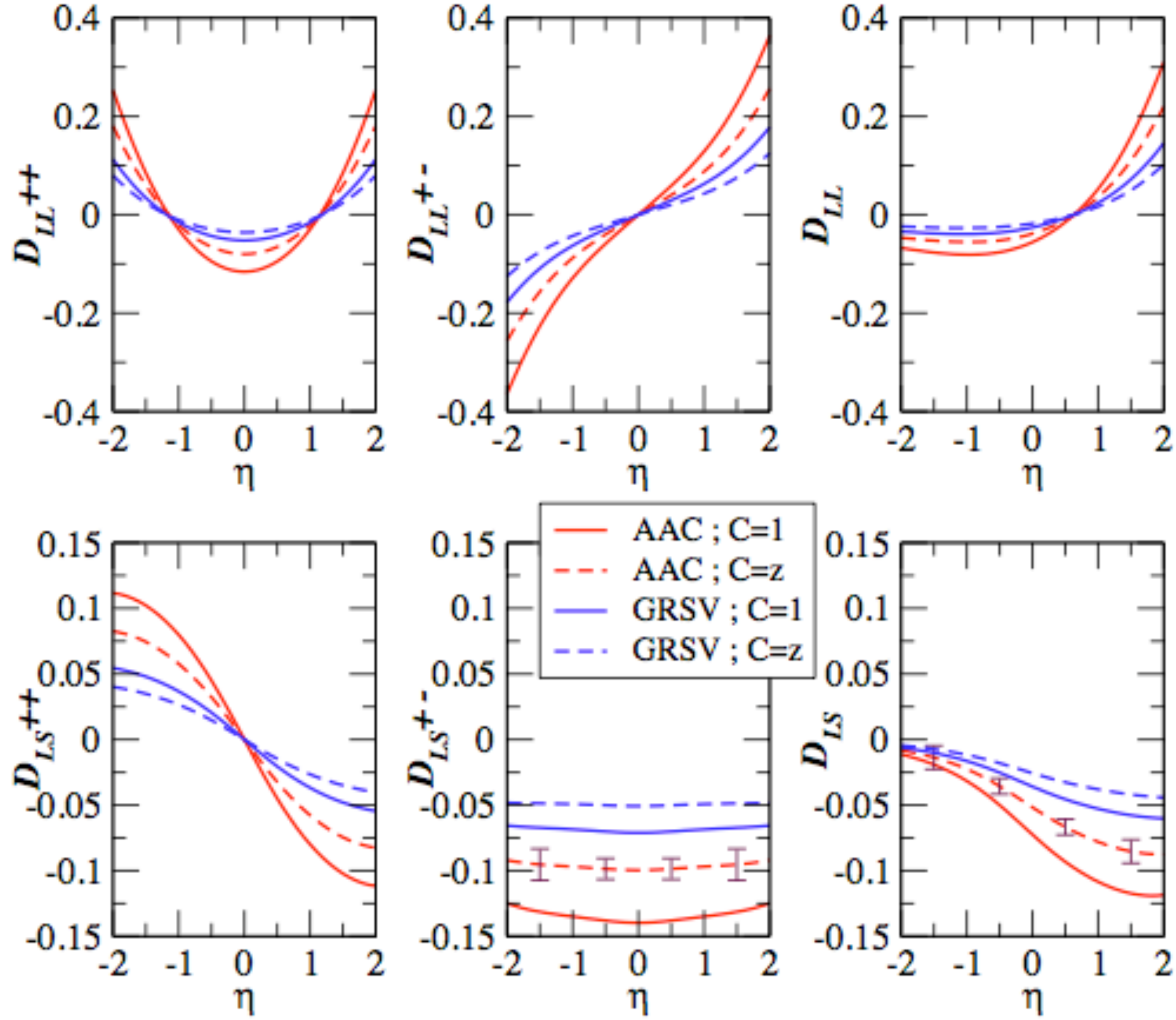
The Λ_c^+ consists of a heavy charm quark and anti-symmetrically combined light up and down quarks. Its spin is carried mostly by the charm quark spin, which is unlikely to have flipped in the fragmentation process. In proton-proton collisions gluon-gluon fusion dominates heavy quark production. The contributions to Λ_c^+ production from light-quark fragmentation are negligibly small, unlike in the case of ordinary Λ production. A measurement of helicity-to-helicity transfer in Λ_c^+ production thus gives rather direct information about gluon polarization in the nucleon and/or the polarized fragmentation function.

The self-analyzing decay and the availability polarization in both proton beams at RHIC offers an attractive variety of spin observables. The “ordinary” spin transfers D_{LL} and D_{LS} can be measured, as well as the transfers for parallel (++) and anti-parallel helicities (+-) of the proton beams. Their measurements allow the construction of the double longitudinal spin asymmetry,

$$A_{LL} = \frac{2D_{LL,S} - D^{++}_{LL,S} - D^{+-}_{LL,S}}{D^{++}_{L,LS} - D^{+-}_{L,LS}}$$

in a way that is free from experiment systematic uncertainty caused by the relative luminosity measurement.[3] The statistical uncertainty with this approach is typically larger than that in a direct measurement of the double longitudinal spin asymmetry. However, the technique is complementary and eliminates systematic uncertainty from a source that is common to most, if not all, other spin measurements.

Figure ZZ shows leading order estimates of the spin transfers D in inclusive Λ_c^+ production in the range of 2-5 GeV/c for two sets of polarized parton distribution functions and two models for the spin transfer in fragmentation. The projected uncertainties on the data points were obtained for an integrated luminosity of 320pb-1 and 70% beam polarization in the decay channel $\Lambda_c^+ \rightarrow \Lambda^0 \pi^+$ for an assumed reconstruction efficiency of 10%. Measurements for the in plane (LS) spin transfer are seen to form viable candidates at projected RHIC-II luminosities.



4.2 Anti-Lambda polarization and the anti-strange sea (Q. Xu et al)

Most of our knowledge of the flavor decomposition of the proton spin originates from deep-inelastic scattering (DIS) measurements. Polarized inclusive DIS data, combined with hyperon beta decay measurements, indicate that the strange sea in the nucleon is negatively polarized. Recent semi-inclusive DIS data may indicate a different outcome[4]. The semi-inclusive data do not rely on hyperon decay measurements and flavor-symmetry assumptions, but cover a smaller kinematic range than the inclusive DIS measurements. In addition, some aspects of the analysis have come under discussion[5]. Existing data from elastic neutrino scattering lack the precision to distinguish.

Measurements of the longitudinal polarization of anti-Lambda's produced at large transverse momenta in longitudinally polarized proton collisions may provide a window at RHIC on the polarization of anti-strange quarks in the nucleon[6]. The anti-Lambda consists of an anti-strange quark and of the light up and down anti-quarks, which contribute at best only a small fraction to the anti-Lambda's spin. The large p_T production has a leading contribution from (anti-) quark fragmentation, at central rapidity mostly from strange anti-quarks. Feed-down contributions from decays of heavier hyperons are expected to be relatively small.

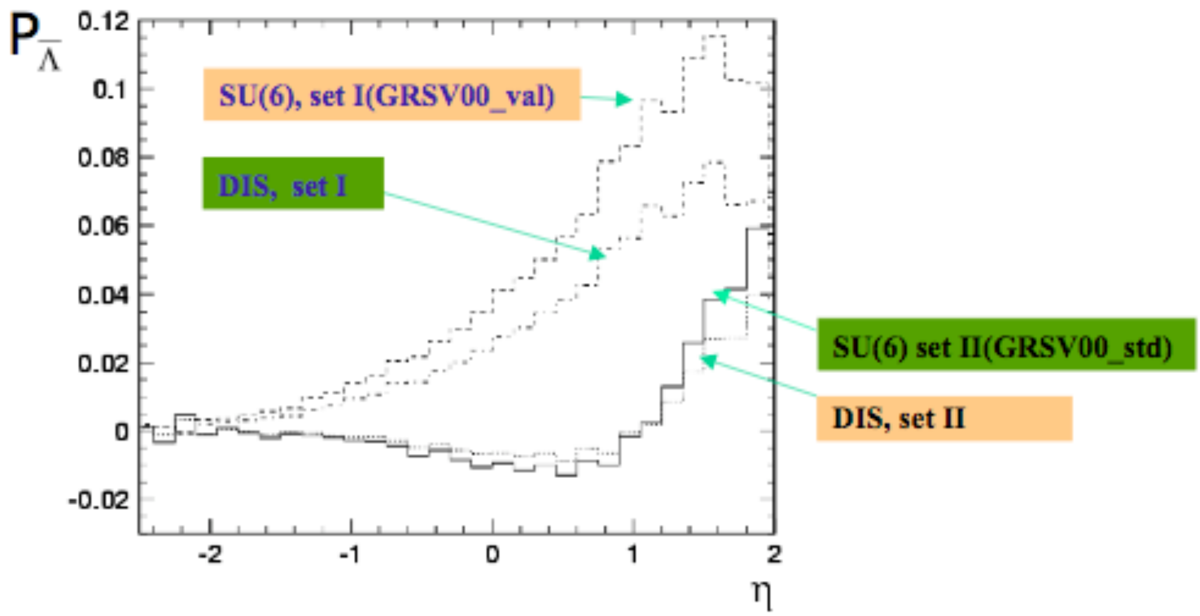


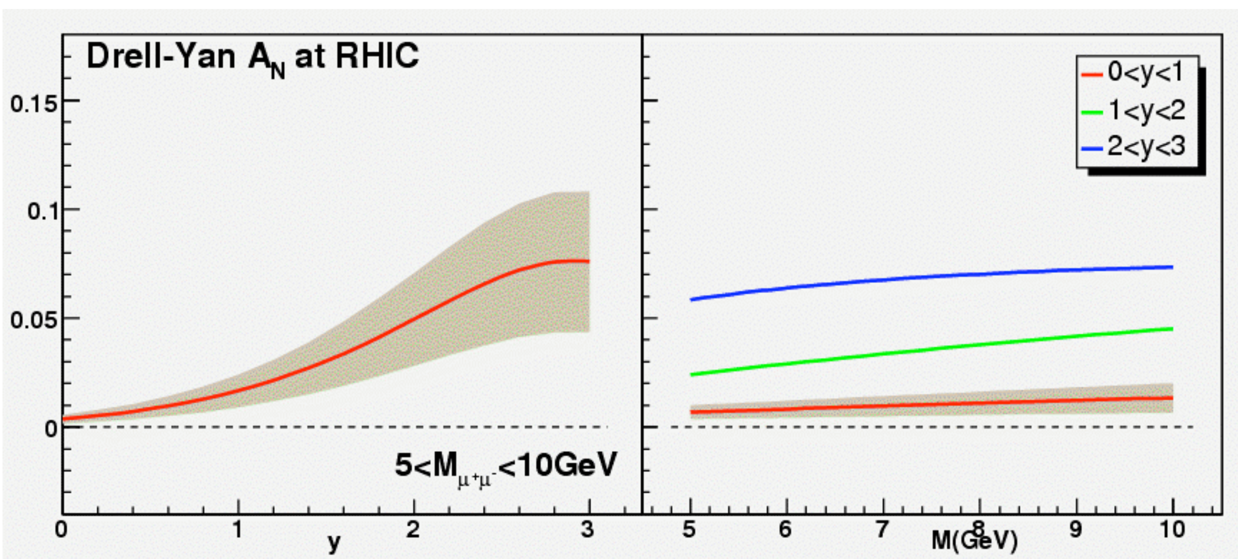
Figure AA shows the longitudinal anti-Lambda polarization for transverse momenta larger than 8 GeV/c in longitudinally polarized proton-proton collisions at a center of mass energy of 200 GeV versus pseudo-rapidity η. Positive η is taken along the direction of the polarized proton bean. The four evaluations are based on two different parton distribution functions that differ mostly in the strange quark distributions, and for two commonly used models to connect the spin of the fragmenting quark and that of the produced hadron. The polarization is seen to be sensitive mostly to the difference in parton distribution functions. The probed kinematic region in Bjorken-x ranges from about 0.05 to 0.25. The projected experimental uncertainties are at the level of 1% for future high luminosity (>100 pb^{-1}) running at RHIC.
Spin transfer measurements with transversely polarized protons are expected to give insight in the transversity distribution of strange anti-quarks. Future studies may yield suitable candidates to probe the strange quark distributions. At this time we note that the production the Λ has large contributions from up-quarks and form feed-down, which will considerably complicate the interpretation of its spin-transfer measurement. The Σ+ hyperon is expected to be sensitive primarily to the connection of the spin of the fragmenting quark and the produced hadron.

5 Physics opportunities in with transverse spins at RHIC

This section is under construction.

Single-transverse spin asymmetries (SSA) in hadronic processes have a ~30 year history. In recent years they have attracted renewed interest, both experimentally and theoretically. First measurements at RHIC extend the observations from the fixed-target energy range to the collider regime. Experimental studies in DIS show remarkably large SSAs in semi-inclusive hadron production. On the theoretical side, two mechanisms have been proposed to generate sizable SSAs in the QCD framework: the transverse momentum dependent parton distributions and the twist-three Qiu-Sterman mechanism. RHIC-II will provide opportunities to study these mechanisms in detail, and advance our understanding of the nucleon structure and QCD dynamics.

Transverse momentum dependent parton distributions and their roles in SSA physics. The transverse momentum dependent (TMD) parton distributions provide new insights into QCD and nucleon structure, and can be measured in various semi-inclusive processes including semi-inclusive DIS, Drell-Yan at low transverse momentum, and jet-jet correlations at hadron colliders. The gauge invariant definition of TMD parton distributions and the QCD factorization for semi-inclusive processes have been studied thoroughly in the last few years. One of the TMD distributions, the so-called Sivers function, describes the correlation between the quark's transverse momentum and the nucleon's transverse polarization vector. It contributes to the single spin asymmetries for the semi-inclusive production of hadrons in DIS, and Drell-Yan at low transverse momentum. The DIS data have been analyzed and predictions for single spin have been made for various processes at RHIC, including Drell-Yan, Di-jet, and jet-photon correlations. The asymmetries are expected to be sizable, of the order of 5-10%, in the forward rapidity region. Figure DY shows an example.



The **twist-three Qiu-Sterman mechanism** can also contribute to the single spin asymmetry in hadronic processes. This mechanism was previously applied only to inclusive hadron and direct photon production. Theoretical progress to advance the twist-three studies from a model perspective to a QCD theory for SSAs are in progress, in particular for the following processes: Drell-Yan at low and high transverse momenta, inclusive hadron/jet production, di-jet/di-hadron production, inclusive single lepton production, etc. Their measurement is certainly within the scope of future RHIC and RHIC-II measurements. Furthermore, the Drell-Yan measurement will connect the TMD picture and the twist-three mechanism.

6 Connections to eRHIC

The addition of a high energy, high polarization lepton (electron/positron) beam facility to the existing RHIC complex, able to collide with its hadron beam, would dramatically increase RHIC's capability to do precision QCD physics. Such a facility with 10 GeV/c polarized electrons/positrons has been proposed and is called eRHIC. There are many connections between the RHIC spin program and eRHIC. We categorize them in two groups:

- **Direct connections to RHIC Spin**: In these, the physics observables measured by the existing RHIC spin physics program will be measured in complementary kinematic regions, or in some cases augmented to complete the understanding of nucleon spin.
- **Indirect Connections to RHIC Spin**: These include measurements not possible with RHIC Spin, but of significance to understanding QCD with spin in general or nucleon spin in particular.

6.1 Direct Connections

Direct connections between RHIC Spin and eRHIC are made on three principal topics: the measurement of the polarized gluon distribution, the measurement of polarized quark-anti-quark distributions, and on transverse physics measurements.

For polarized gluon distribution measurements, eRHIC enables an increase in the kinematic range and precision, particularly at low x. At eRHIC the polarized gluon distribution will be measured using

a) the scaling violations of spin structure functions g_{1}^{p/n} and
b) di-jet and high p_{T} di-hadron production in the photon gluon fusion process.

The RHIC spin measurements discussed earlier in this document will be most significant in the medium-high x range, $x>10^{-2}$, while eRHIC will complement them with precision on low x, ($x<10^{-2}$) all the way to $x\sim 10^{-4}$.

RHIC Spin will be the first to measure in a model independent way the polarized quark and anti-quark distributions using single spin longitudinal asymmetry measurements in pp scattering at $\sqrt{s}$=500 GeV/c via ($W^{\pm}$) production. Analysis of these asymmetries will give us $\Delta u, \Delta \overline{u}, \Delta d, \Delta \overline{d}$ (see Sec. XX). The quark-anti-quark separation in such a way is not possible in fixed target DIS where the virtual γ is the propagator of the force which cannot differentiate between quarks and anti-quarks. However, at high enough energy, in DIS at eRHIC, virtual $W^{\pm}$ also get exchanged. If $\Delta q = u, \overline{u}, d, \overline{d}$ are known by early next decade from RHIC Spin, eRHIC will be able to continue this program by exploring the heavy quarks, i.e., identify the spin contributions from $\Delta c/\overline{c}$ and $\Delta s/\overline{s}$. Of course, traditional methods to get quark flavor distributions (quark-antiquark unseparated) using semi-inclusive DIS measurements of charged and neutral pions and kaons will also continue, with access to flavor separation at lower x than is possible in current fixed target DIS experiments.

Transversity is the last as yet unmeasured spin structure function, discussed in detail in Section XX. The measurements at RHIC with pp scattering will be made using measurements of Collins Fragmentation Function (CFF), Interference Fragmentation Functions (IFF) and if very large luminosities are achieved, also with Drell Yan (DY) processes. These measurements will be made in the center of mass energy range from 200 to 500 GeV. The eRHIC will make a complementary set of measurements, with high precision using CFF and IFF measurements, not unlike those made by the HERMES collaboration currently.

6.2 Indirect Spin Connections

In addition to the measurements eRHIC will do that will extend or complement the investigation of nucleon spin with RHIC Spin, there is another class of nucleon spin and other helicity related measurements that could also be made with eRHIC. A partial list includes:

- Measurement of spin structure functions g_{1} of the proton and neutron and the difference between them that tests the Bjorken spin sum rule. eRHIC will do this with accuracies that will for the first time start competing and challenging the experimental systematic uncertainties at the level of 1- 2%. Low x phenomena have been some of the most exciting aspects of the physics coming from unpolarized DIS measurements in the last decade, and eRHIC will probe low x kinematics for the first time with polarized beams
- eRHIC will be the only possible facility in the foreseeable future at which QCD spin structure of the quasi-real photon could be explored. The process employed for this investigation is that of photon-gluon fusion [XX].
- Deeply virtual Compton scattering (DVCS) for final state photons as well as other vector mesons measured using almost complete acceptance (4π) detectors has been suggested as a preliminary requirement towards the measurement of the Generalized Parton Distributions (GPDs). A series of different GPD measurements may be required eventually to extract the orbital angular momentum of the partons. This is the last part of the nucleon spin puzzle which we may have to address after the spin of the gluon is understood. Although the theoretical formulation is not yet ready, it is expected that by the time eRHIC comes on line, there will be a formalism available to take the measured GPDs and determine the orbital angular momentum of partons. These measurements at eRHIC will be complementary, at much higher energy scales, to those being planned at Jefferson Laboratory after its 12 GeV upgrade plan.
- Drell Hearn Gerasimov spin rule measurements presently underway at Jefferson laboratory and at the Mainz Microtron (MAMI) are mostly at low values of ν \cite{sdbath}. While the significance of the contribution the spin sum rule from high ν is small, absolutely no measurements exist beyond the value of $\nu > \approx 1$ GeV. eRHIC will extend direct measurements of the high ν component up to 500 GeV.
- Precision measurements of spin structure functions in very high x ~ 0.9 region could be part of the eRHIC physics program with specially designed detectors as has been discussed in [caldwell].

The physics programs with polarized proton beams at RHIC and eRHIC have much in the way of complementarity of physics measurements. It's also clear that success at eRHIC passes through a period of successful measurements and collider development by the RHIC spin program not only at $\sqrt{s}$=200 GeV/c but also at $\sqrt{s}$=500 GeV/c.

7 Conclusions

Conclusions will be added later.

References

[1] K. Ohkuma, K. Sudoh, and T. Mori, Phys. Lett. B491 (2001) 117.
[2] Q-H. Xu and Z-T. Liang, Phys. Rev. D70 (2004) 034015.
[3] V.L. Rykov and K. Sudoh, hep-ph/0412244
[4] A. Airapetian et al, Phys. Rev. D64 (2001) 112005.
[5] E. Leader and D.B. Stamenov, Phys. Rev. D67 (2003) 037503.
[6] Q-H. Xu, Z-T. Liang, and E.P. Sichtermann hep-ph/0511061.