1 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 [1]. 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 RHIC Spin Plan [2], 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 [3]. 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, following 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 calculations.

Published RHIC results [4, 5] indicate that the gluons in the proton are relatively little polarized in the range $0.03 \lesssim x \lesssim 0.2$ so far accessible at RHIC. Complementary results from lepton scattering made by the HERMES and COMPASS experiments [6] are consistent with this finding. Recent RHIC data collected during Run 6 [7, 8] 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 [9]. 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, anti-quark, 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 $0.03 \lesssim x \lesssim 0.2$, 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, $0.03 \lesssim x \lesssim 0.2$. 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. As we will describe in this document, planned measurements at RHIC should well allow to fulfill these goals. Studies of di-jet coincidences at central and forward angles allow precision mapping of $\Delta g(x, Q^2)$ over a broad range in x. Measurements at RHIC's higher pp center-of-mass energy of 500 GeV, both for inclusive channels and for coincidences, will be important for reaching lower x.

Measurements of the polarized quark and anti-quark flavor structure in the proton.
It has long been recognized that $W^\pm$ boson production at RHIC provides unique and clean access to the individual polarizations of the quarks and anti-quarks in the colliding protons. The W bosons of the weak interactions are 100% parity-violating, as they couple only to left-handed quarks and right-handed anti-quarks, which provides a natural probe of polarization. At the same time, the scale in W production is set by the large W mass, which will provide a very large lever arm in QCD evolution, with $Q^2 \approx 6400$ GeV^2, vs. $Q^2 \sim 1 - 10$ GeV^2 in present polarized DIS.

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 beautiful measurement. It becomes possible in the first place thanks to the fact that $\Delta u/u$ and $\Delta d/d$ are known from DIS measurements to be large in the valence region $x \gtrsim 0.1$, which leads to predicted large and observable single-spin asymmetries at RHIC when the W decay lepton is produced in the forward direction of the polarized proton. We also note in this context that the valence region probes the presence of non-vanishing orbital angular momentum components in the nucleon wave function [10]. The measurements at RHIC in this regime will thus offer interesting comparisons with those performed at the Jefferson Laboratory [11], but at much higher scales.

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 [12, 13, 14]. 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 $\Delta\bar{u} \geq 0$, $\Delta\bar{d} \leq 0$ [12], 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 [15]. They are included in the new global analysis [9] 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 in fact 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 the possibilities offered by W production at RHIC in detail in this document, and also the challenges that are involved.

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 [17, 18, 19], demonstratively in the hard scattering regime, along with results from DIS [20, 21] and e^+e^- annihilation [22], 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" [23], 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 [24, 25, 26]. 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 [24, 25, 26]. Beyond color-singlet processes, the non-universality manifests itself in more complex, but calculable, ways. It has been predicted [28] 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 [29, 30].

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 [20, 21], 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 [31, 32], 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 [32]. The transversity densities also determine the fundamental tensor charge of the nucleon [32, 33]. 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 [20] with dedicated determinations of the Collins fragmentation functions in e^+e^- annihilation [22], to obtain a first glimpse at the valence transversity distributions [34]. Transversely polarized pp scattering at RHIC offers access to the transversity distributions. Two fragmentation effects, the Collins mechanism and Interference Fragmentation, provide excellent probes. We will discuss these planned measurements in this document.

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