The science case for RHIC Spin

Spin is one of the most fundamental concepts in physics, deeply rooted in Poincaré invariance and hence in the structure of space-time itself. Despite its both quantum-mechanical and relativistic nature, spin plays a role in everyday applications such as magnetic resonance imaging. Except for the Higgs, all elementary particles we know today carry spin, among them the particles that are subject to the strong interactions: The spin-1/2 quarks and the spin-1 gluons. Spin, therefore, plays a central role also in our theory of the strong interactions, *Quantum Chromodynamics (QCD)*, and to understand spin phenomena in QCD will help to understand QCD itself. To contribute to this understanding is the primary goal of the spin physics program at RHIC.

Proton and neutron, which make up all nuclei and hence most of the visible mass in the universe, themselves carry spin-1/2. As has been known for over eight decades now, they also possess internal structure. This insight came directly due to spin, through the measurement of a very unexpected "anomalous" magnetic moment of the proton. In fact, there is an important lesson to be learned from this discovery: Measuring the magnetic moment of the proton was not viewed as an important step at the time, because the answer was already assumed to be "known" to fairly high precision. However, this turned out to be false– and as a result we learned that the proton has substructure. This was just the first of numerous surprises related to spin in strong interaction physics, arguably culminating in the proton "spin crisis" uncovered by the EMC experiment in the late 1980s. The EMC discovery that quarks and antiquark spins provide only little of the proton spin, once again, proved previous expectations to be incorrect and showed that the proton substructure was much richer than we had imagined.

Our modern view of the proton is that of a complex system of quarks and transient quark-antiquark pairs, bound together by gluons (see Fig. 1). The study of the inner structure of such systems that are composed of quarks and gluons is at the heart of investigating confinement in QCD. Spin plays a dual role in this context, both as a mere tool for uncovering properties of the strong interactions, but foremost for proton structure in its own right. In a broad sense, RHIC investigates how spin phenomena in QCD arise at the quark and gluon level. A particularly important question, and a key focus ever since the EMC measurements, is how quarks and gluons conspire to provide the proton's spin-1/2 through their spin and orbital angular momentum contributions.

RHIC addresses these topics in various complementary ways, making use

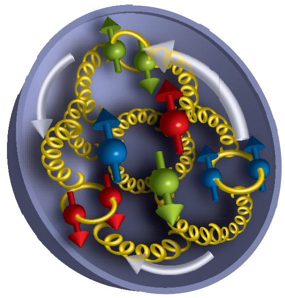

Fig. 1 — Proton built from quarks, quark-antiquark pairs, and gluons.

of the tremendous versatility of the machine which makes both longitudinal and transverse polarization of the protons relative to their momenta readily available. The focus at RHIC spin is on the following topics:

How do gluons contribute to the proton spin? Polarization of gluons in the proton has long been considered as a source for major contributions to the proton spin. Indeed, latest data from RHIC's 2009 run with longitudinal polarization have, for the first time, provided evidence that gluons do show a preferential alignment of their spins with the proton's spin. This is milestone for the field, offering new clues on the proton spin decomposition and on the nature of the strong force fields inside a proton.

What is the "landscape" of the polarized sea in the nucleon? In order to understand the proton helicity structure in detail, one needs to learn about the quark and anti-quark densities, $\Delta u, \Delta\bar{u}$, $\Delta d, \Delta\bar{d}, \Delta s, \Delta\bar{s}$, *individually.* This is expected to provide insight into the question of why it is that the total quark plus antiquark contribution to the proton spin was found to be so small. It is also important for models of nucleon structure which generally make clear qualitative predictions about, for example, the flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ in the proton sea. Such predictions are often related to fundamental concepts such as the Pauli principle. At RHIC one uses a powerful technique based on the violation of parity in weak interactions. The $W^{\pm}$ bosons naturally select left quark handedness and right antiquark handedness and hence are ideal probes of nucleon helicity structure. Data from RHIC have now reached the precision needed for obtaining meaningful constraints on the distributions. Comparison with data from semi-inclusive lepton scattering offers tests of basic concepts of high-energy perturbative QCD, such as factorization.

Transverse-spin phenomena in QCD. The past decade has seen tremendous activity and progress, both theoretically and experimentally in this area. Among the quantities of particular interest are parton distribution functions that may be accessed in spin asymmetries for hard-scattering reactions involving a transversely polarized proton. These distributions, known as "Sivers functions", express correlations between a parton's transverse momentum inside the proton, and the proton spin vector. As such they contain information on orbital motion of partons in the proton. It was found that the Sivers functions are not universal in hard-scattering reactions. This by itself is nothing spectacular; however, closer theoretical studies have shown that the non-universality has a clear physical origin that may broadly be described 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 will act in different ways on the parton (see Fig. 2). 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 processes. This is a fundamental prediction about the nature of QCD color interactions, directly rooted in the quantum nature of the interactions and akin to the Aharonov-Bohm effect in Electrodynamics. It tests *all* concepts for analyzing hard-scattering reactions that we know of. Studies have begun at RHIC aiming at verifying this prediction, which would be a milestone for the field of hadronic physics.

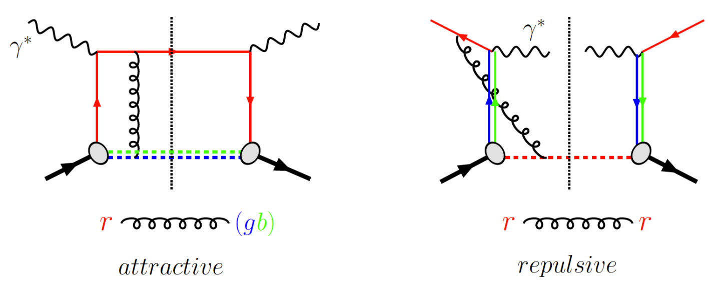

Fig. 2 — Final-state and initial-state color interactions in lepton scattering and the Drell-Yan process.