The Whole Story Behind a Half:
The Quest to Understand the Proton's Spin

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(Dated: August 4, 2008)

I. INTRODUCTION

Spin is a fundamental quantum mechanical property of all particles. It has been known for 80 years that the proton's spin is quantized as $\frac{1}{2}\hbar$, which is the same as for the electron. However, unlike the electron, still believed to be a point particle, the proton is known to be composite, made up of subnuclear particles called quarks and gluons, all of which have their own spin values. Since a surprising measurement in the late 1980's revealed that the proton's subcomponents did not build up its spin as expected, there has been an ongoing quest to unravel this puzzle, which remains unresolved to this day. [1]

II. PROTON STRUCTURE

Despite the proton's role as one of the fundamental building blocks of everyday matter, there remains a great deal that we do not understand about its internal structure. After a half century of research, the proton has proven to be an extremely rich and complex entity.

About a century ago the atomic nucleus, made of protons and neutrons, was discovered by the well-known Rutherford scattering experiment, in which beams of alpha particles were scattered off of gold foil and a surprising number bounced back at large angles, revealing a hard core within the atom. In analogous experiments in the 1960's in which beams of electrons were scattered inelastically off of proton targets, a surprising number of the electrons bounced back at large angles, revealing in turn some kind of hard subcomponents within the proton. These hard subcomponents within the proton have come to be known as "quarks," or slightly more generally, "partons." There are six known quarks: up, down, charm, strange, top, and bottom. Quarks, like the proton, have spin quantized as $\frac{1}{2}\hbar$.

In the simplest model of the proton, it is comprised of three so-called "valence" quarks, but these quarks are not free within the proton. They are bound by force-carrier particles known as gluons, messengers of the strong force, which is also responsible for binding together the protons and neutrons within atomic nuclei. Over the very short distance of an atomic nucleus, the strong force dominates over the electromagnetic force, which would otherwise cause the nucleus to break apart due to the repulsion between all the positively charged

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[1] Prepared for the 2008 Sambamurti Memorial Lecture, delivered on July 22, 2008 at Brookhaven National Laboratory.

protons. As the electromagnetic force acts on particles which carry electromagnetic charge, the strong force acts on particles which carry "color" charge. Quarks and gluons can never be observed directly in the laboratory; they are *confined* to composite, color-neutral particles. A color-neutral particle, observable in the laboratory, can be formed by combinations of three quarks (red, green, and blue), known as baryons and including the proton and neutron, or combinations of two quarks (a red-antired, green-antigreen, or blue-antiblue pair), known as mesons. Quantum chromodynamics (QCD), developed in the 1970's, is the underlying theory describing the strong force.

If the individual quarks and gluons within the proton cannot be observed directly, how can the internal structure of the proton be studied? A tool of the trade for half a century now has been the technique of deep inelastic scattering, in which one shoots a beam of electrons onto protons, breaking them up, and then observing the final products in the laboratory. It is possible to probe the quarks within the proton using beams of electrons thanks to the fact that quarks carry not only color charge but also electromagnetic charge. Quarks are the only known particles to carry *fractional* electromagnetic charge, with the charges of the proton and neutron understood in terms of the three-quark valence model of the nucleon.

After decades of research on the proton's momentum structure, the picture that has coalesced is one of three valence quarks, each carrying on average more than approximately 10% of the proton's momentum, but at lower momentum fractions there exists a wealth of gluons and sea quark-antiquark pairs. Gluons are now known to carry about half of the total momentum of the proton.

The angular momentum, i.e. spin, structure of the proton remains much less well understood. For many years it was assumed that the proton's spin of $\frac{1}{2}\hbar$ was due effectively to the spins of the three spin-$\frac{1}{2}\hbar$ valence quarks, with two oriented in one direction and one in the other. In the late 1980's, however, the EMC experiment at CERN discovered that only $14 \pm 23\%$ of the proton's spin was carried by quarks [1]. This surprising result became known as the proton spin crisis. Subsequent experimental work has continued to explore this problem for two decades, yet there remains much to be understood. In particular, the magnitude and even sign of the gluon spin's contribution to the spin of the proton remains to be determined, the flavor breakdown of the sea quarks' contributions, i.e. how much is carried by up and antiup sea quarks versus down and antidown, is largely unknown, and the contribution from orbital angular momentum of both quarks and gluons has yet to be probed.

III. THE RELATIVISTIC HEAVY ION COLLIDER

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is the first and only polarized proton collider in the world. A schematic diagram of the collider complex can be seen in Fig. 1. As a polarized proton-proton collider, it brings several advantages with respect to earlier polarized experiments, which have utilized stationary proton targets and electromagnetic beams to probe them. By colliding two beams rather than one beam against a stationary target, higher center-of-mass energies can be achieved, allowing the use of different theoretical techniques, and offering the ability to probe the proton via the production of heavier final-state particles ($E = mc^2$). By using other protons to probe the proton rather than an electromagnetic beam, one gains direct access to gluons, which do not couple electromagnetically. However, probing a composite system with another composite system is also more complex than probing it with a beam of elementary particles such as electrons; therefore, at RHIC we rely on the existence of previous measurements in simpler systems to be able to interpret our results. An overview of the RHIC spin program as originally planned can be found in [2].

IV. THE PHENIX EXPERIMENT

The PHENIX experiment is one of two large experiments at RHIC studying the spin structure of the proton, with more than 500 participants from 14 different nations. PHENIX has a broad spin physics program. The principal areas of investigation are the gluon spin contribution to the spin of the proton (ΔG), flavor separation of the sea quark polarization ($\Delta\bar{u}$, $\Delta\bar{d}$), and study of the transverse spin structure of the proton, which cannot be derived from the proton's longitudinal spin structure. PHENIX can probe ΔG through measurement of double-longitudinal spin asymmetries, i.e. looking at the difference in the rate of production of a final state particle when the colliding protons have the same versus the opposite spin directions.

One of the main channels sensitive to the gluon polarization is production of pions, the lightest mesons, for which results have already been published [3]. The latest preliminary

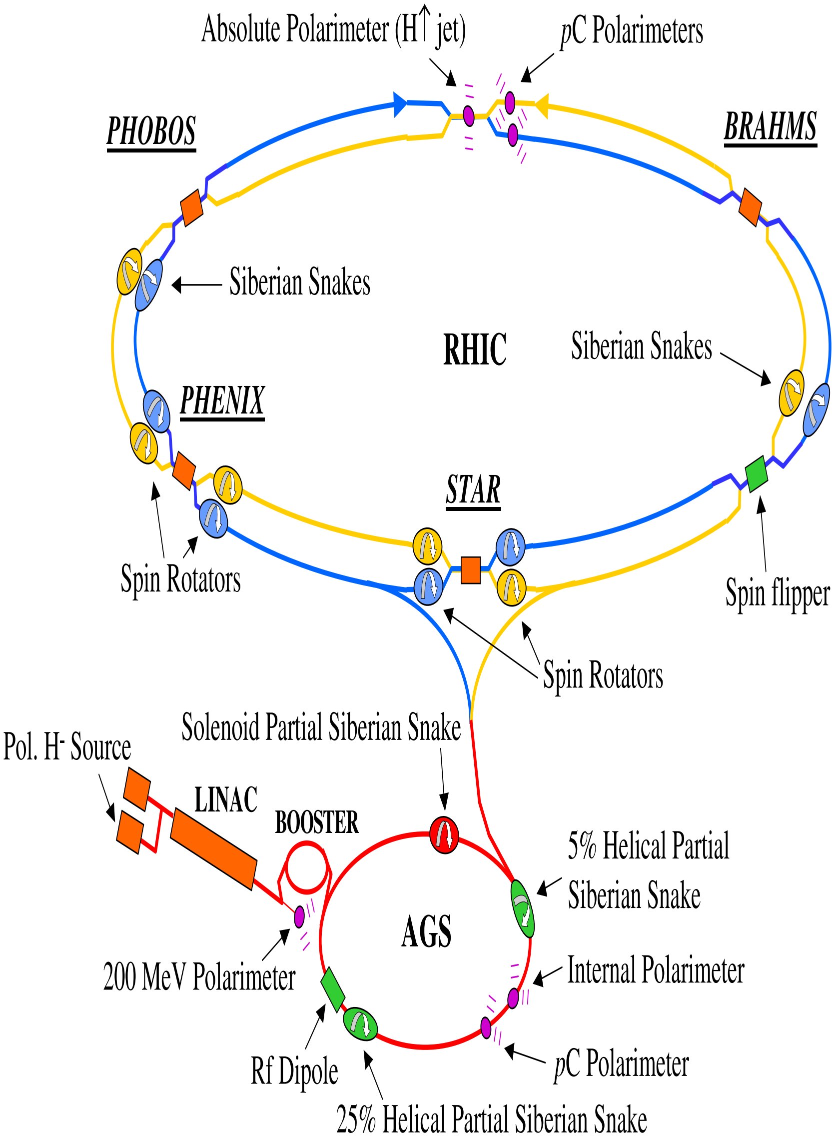

FIG. 1: The RHIC accelerator complex.

result for neutral pions, compared to theoretical predictions assuming different values of ΔG, is shown in Fig. 2. The small asymmetry suggests that within the range of gluon momentum fraction to which we are sensitive, the magnitude of the gluon polarization is not large. There are also two other species of pions, carrying positive and negative electromagnetic charge. There exists a theoretical prediction for the order of the pion asymmetries depending on the sign of the gluon spin contribution to the proton spin. If the gluon spin contribution is positive, the positive pion asymmetry should be greater than that of the neutral pion, and the neutral pion asymmetry in turn greater than that of the negative pion. Preliminary results for all three pion species from the data taken by PHENIX in 2006 can be seen in Fig. 3. The statistical uncertainties are not yet small enough to clearly determine the ordering; however, we hope that the large polarized data set anticipated for 2009 will allow us to draw a conclusion.

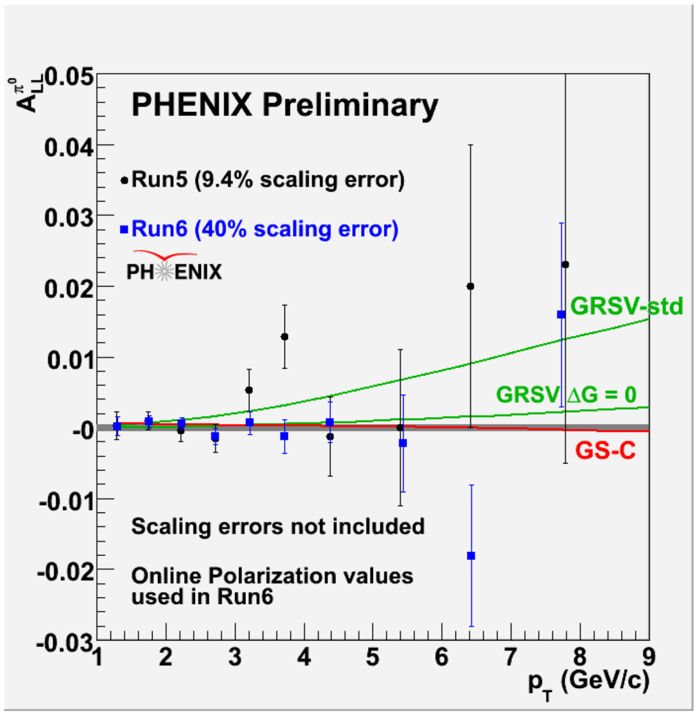

FIG. 2: Preliminary PHENIX results on the double-longitudinal asymmetry of neutral pion production versus transverse momentum, compared to theoretical calculations assuming different values of ΔG.

No single measurement can fully determine the spin structure of the proton; a wide variety of measurements covering different kinematic regions and sensitive to different subcomponents within the proton is necessary. All available world data is then combined into global analyses, which seek a common description of proton structure that can simultaneously fit all existing measurements. Figure 4 shows the resultant gluon spin distribution, as a function of the momentum fraction of the proton carried by the gluon, obtained from a number of global fits. The wide range in magnitude and uncertainty regarding the sign can be seen. The most recent fit, DSSV [4], indicated by the dashed line, is the first to include data from RHIC on an equal footing with data from all previous experiments.

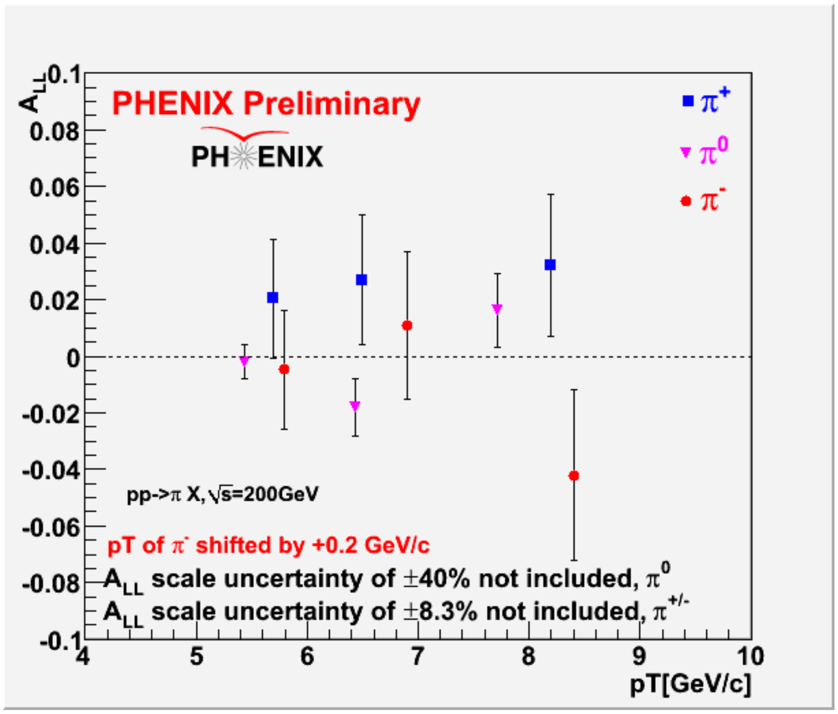

FIG. 3: Preliminary PHENIX results on the double-longitudinal asymmetry in neutral and charged pion production versus transverse momentum.

V. CONCLUSIONS

So far data from the RHIC spin program, in conjunction with other world data, suggest that the gluon spin contribution to the proton spin is small, not enough to account for what is "missing" from the quarks' contributions. The proton spin crisis continues! More precise data covering a wider kinematic range will be important to confirm this. If it is indeed the case that the gluon plus quark spins within the proton are not enough to account for the total of $\frac{1}{2}\hbar$, the remainder must lie in the orbital angular momentum of both the quarks and gluons. However, we do not yet know how to make any kind of direct measurement of orbital angular momentum within the proton, leaving the field open for new ideas.

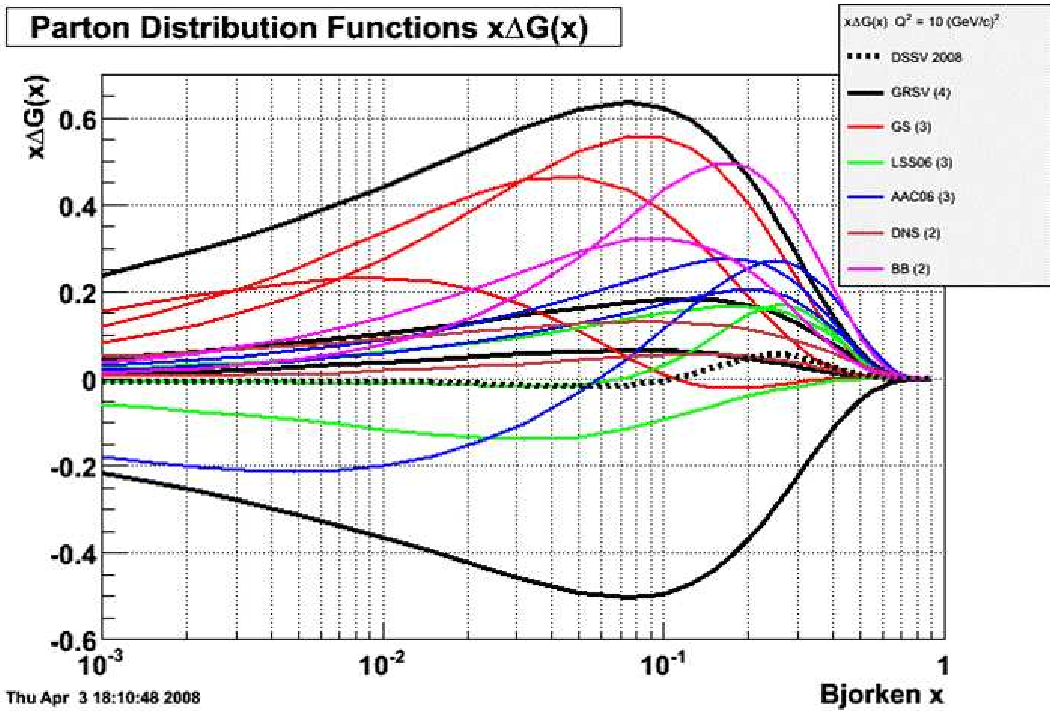

FIG. 4: The gluon spin distribution versus momentum fraction, as obtained from a number of global fits. The dashed line represents the most recent fit, which includes RHIC data.

Acknowledgments

The author wishes to gratefully acknowledge the family of Aditya Sambamurti for the opportunity to deliver this lecture in commemoration of his work.

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