RHIC Spin--To Study the Spin Structure of the Proton

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The RHIC Spin program, colliding polarized protons at high energy, is about studying the internal structure of the proton. We probe this structure, the polarizations of the quarks and gluons in a polarized proton, using the quarks and gluons of the other colliding proton. With the collider, we achieve high energy where the collisions are understood by perturbative QCD. The program follows a series of important experiments using electrons and muons to probe the proton. These experiments, initiated at SLAC, have shown that the quarks and anti-quarks in the proton carry very little of the proton spin on average, a surprise. RHIC, with its strongly interacting probes, is directly sensitive to the gluons in the proton, and is in the process of measuring the gluon's contribution to the proton spin. I describe why, how, and what we are learning, and our future program.

1. A HISTORY—FROM QUARKS TO SPIN STRUCTURE

A short history of the strong interaction might begin in the mid 1960s, when "quarks" were introduced to begin to understand the zoo of strongly interacting particles that had been discovered from accelerator experiments. The "color" quantum number was needed to describe the Omega^-, a state of three strange quarks, each with the same spin ½ adding to a total spin of 3/2. In the later 1960s, an experiment at SLAC showed that these "quarks" were real. In the early 1970s the theory of QCD was developed with quarks, "gluons", and color charge; perturbative QCD could be used for precise calculations for hard scattering. From the 1980s to the present, e-p and pbar-p colliders have carried out beautiful precision tests of perturbative QCD predictions, **unpolarized**. In this "history" I have not attempted to give references—the history has been presented in many reviews.

The history of **polarized** studies of the strong interaction is also closely tied to SLAC. In the 1960s a polarized electron source, PEGGY, was developed at Yale by Vernon Hughes and his group. The source was brought to SLAC to initiate a program of exploring the structure of the proton with polarized beam and target. A polarized electron probes a polarized proton through the absorption of polarized photons of known helicity. Quarks in the proton with the opposite helicity of the photon flip spin when the photon is absorbed. Quarks with the same helicity cannot absorb the photon. Thus one accesses the spin structure of the proton. The first results showed a strong correlation of the quark spins with the proton spin. This was expected from the simple quark model of the proton of the time (1970s) [1]. These experiments studied quarks which carried a large fraction of the momentum of the protons. Later, in 1988, an experiment with polarized muons at CERN (EMC) reported this correlation for lower momentum fraction quarks [2]. The EMC experiment discovered that little of the proton spin was carried by the quarks, on average, a major surprise. Experiments with electron and muon probes continue to this day [3,4,5,6]. These experiments have confirmed this basic conclusion from EMC.

In 2001 a new technique was introduced: measure the proton spin structure with strongly interacting probes which can interact directly with the gluons as well as the quarks in the proton, by colliding beams of polarized protons at the Relativistic Heavy Ion Collider at BNL [7,8].

2. POLARIZED SCATTERING

Figure 1 depicts the scattering of a polarized lepton from a polarized proton. By comparing the difference in scattering cross sections for leptons with the same helicity as the proton, and for unlike helicity, the polarized proton structure function g_1 can be measured. g_1 is the difference between the number density of quarks (and anti-quarks) with spins parallel vs. anti-parallel to the proton spin. The ratio of this difference to the unpolarized cross section is the asymmetry A_1^p. It is the measurement of A_1^p by the EMC collaboration at CERN that first indicated that the quarks and anti-quarks carry little of the proton spin on average, with this result shown in Fig. 2. Subsequent experiments confirmed this observation, with greater precision.

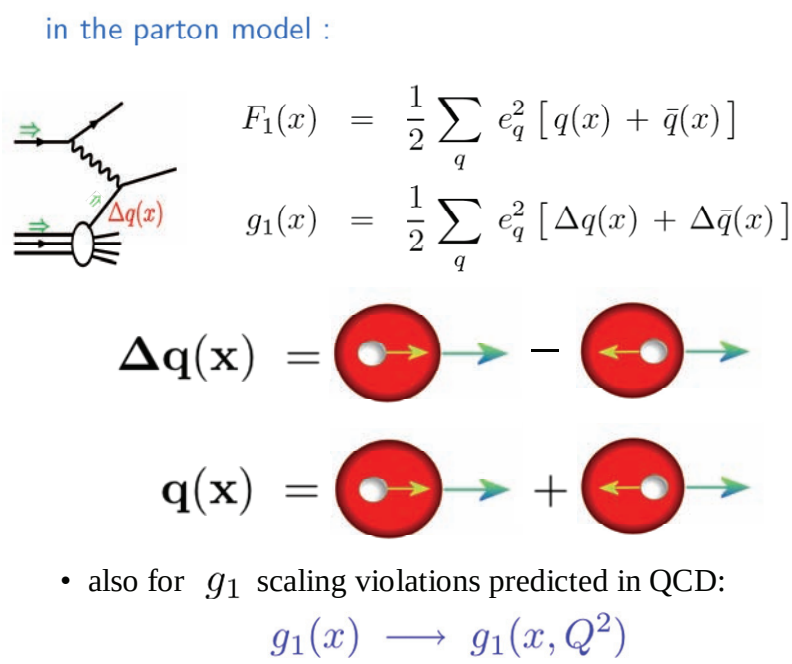
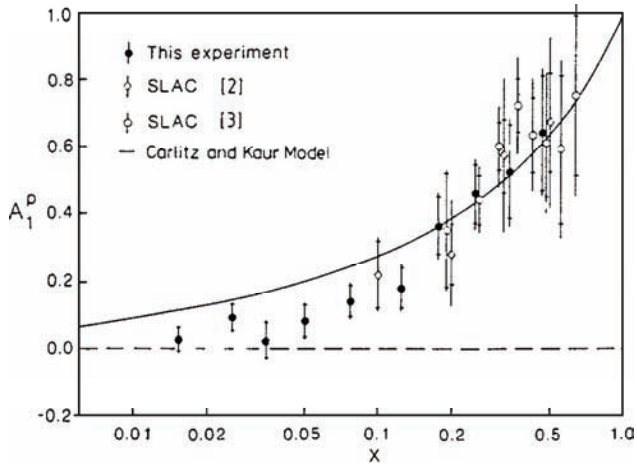


Figure 1: A polarized lepton scattering from a polarized quark. These polarized deeply inelastic scattering experiments probe the quark plus anti-quark spin contribution to the proton spin, measuring the polarized structure function g_1. Delta q represents the quark density with helicity the same as the proton minus the quark density with helicity opposite to the proton.

Figure 3 presents the proton spin sum rule, breaking down the contributions into quark and anti-quark spin (Delta Sigma), gluon spin (Delta G), and orbital angular momentum (L) from quarks and gluons. RHIC spin probes the proton structure with a process similar to that of deeply inelastic scattering (DIS), shown in Fig. 1. Fig. 3 shows the collision of two polarized protons, with a quark from one proton interacting with a gluon from the other proton, in an inclusive process where the scattered quark fragments into a pion. Just as the absorption of the photon in DIS distinguishes between like and unlike helicities for the photon and quark, the quark-gluon interaction in Fig. 3 is significantly stronger for like helicity quark and gluon than for unlike helicity, 4/1 for pion production at mid-rapidity (90 degrees from the axis of the colliding beams).

EMC at CERN: J. Ashman et al., NPB 328, 1 (1989):
polarized muons probing polarized protons



$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$ "proton spin crisis"

Figure 2. The European Muon Collaboration measurement of polarized muon-polarized proton scattering [2].

Measuring the proton spin structure with polarized proton probes

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Quarks contribute only 20%!

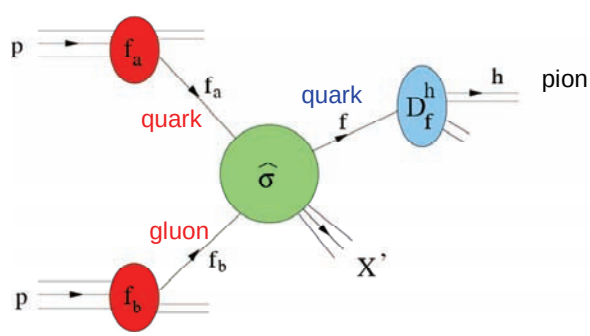
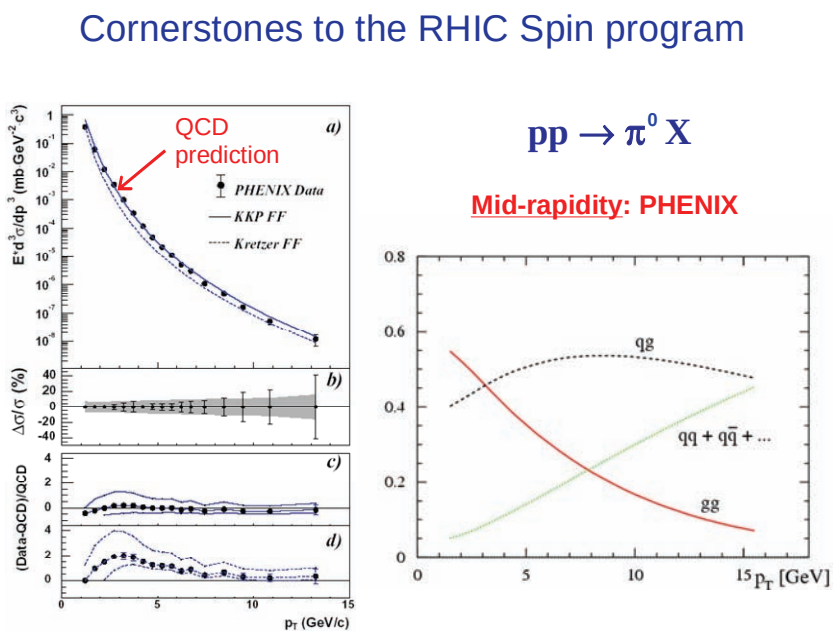


Figure 3: The proton spin sum rule, with the proton spin ½ built from quark and anti-quark contributions (Delta Sigma), the gluon contribution (Delta G), and contributions from orbital angular momentum. Our present understanding is that the quarks and anti-quarks contribute about 20% of the proton spin on average. One RHIC approach to measuring the gluon contribution is shown in the bottom half of the figure, with two protons colliding through the hard scattering of a quark and gluon, inclusively producing a pion.

Perturbative QCD predicts the cross section and spin-dependence for high-p_T processes at RHIC through assumed factorization, where the cross section is calculated as a convolution of parton distribution functions (pdf) for quarks and gluons in the proton, with the spin-dependent subprocess hard scattering cross section, and with the fragmentation of the scattered quark or gluon to a pion (D). Spin independent pdfs, obtained from other experiments such as e^+e^- collisions and DIS, are used to predict the cross section for pion production. The prediction and data from the PHENIX experiment at RHIC [9] are shown in Fig. 4. pQCD describes the unpolarized cross section well, vs. p_T of the pion, over eight orders of magnitude in cross section. These comparisons are a necessary demonstration that the subprocesses are understood. From the polarized cross section, we use pQCD to obtain the polarized gluon and quark densities in the polarized proton.



Physical Review Letters **91**, 241803 (2003)

Figure 4: The pion cross section measured at RHIC with the perturbative QCD prediction at NLO, calculated by W. Vogelsang. The right panel displays the contributions of the different subprocesses, according to the pQCD calculation.

3. RHIC

The RHIC spin program emphasizes:

- Direct measurement of polarized gluon distribution using multiple probes
- Direct measurement of anti-quark polarization using parity violation of W boson production
- Studies of the transverse spin structure of the proton

The RHIC polarized proton collider layout is shown in Fig. 5 [8]. An 80% polarized proton source (H^-, to greatly improve the injection efficiency) feeds a series of accelerators. The AGS accelerates the protons to 24 GeV, prior to

injection into the two counter-rotating accelerator/storage rings of RHIC, indicated by blue and yellow rings. In my lecture I emphasized the great difficulty in maintaining the beam polarization through the acceleration process. The anomalous magnetic moment of the proton is large, 1.79 nuclear magnetons, and the proton spin precesses a large number of times each pass around the AGS or RHIC. For example, at RHIC at 100 GeV the non-vertical component of the proton spin will precess 179 times per turn, around the vertical guide field of RHIC. When horizontal magnetic fields are also present, which must be present to keep the RHIC beam focused vertically, precession of the spin around the horizontal fields and around the guide field can be in phase. This condition, a spin resonance, can completely depolarize the beam if nothing is done. An elegant solution to avoid this depolarization is to reverse the horizontal components of the proton spin each turn in RHIC, so that the spin resonance condition does not build up. Two "Siberian Snakes" [10], sets of magnets that manipulate the spin but leave the proton beam on axis, achieve this. The beam polarization at 100 GeV in the 2006 RHIC run was 60%, a remarkable achievement. There are many other important and elegant additions to the RHIC complex to allow the collision of polarized protons at high energy. RHIC is the world's first, and only, polarized proton collider.

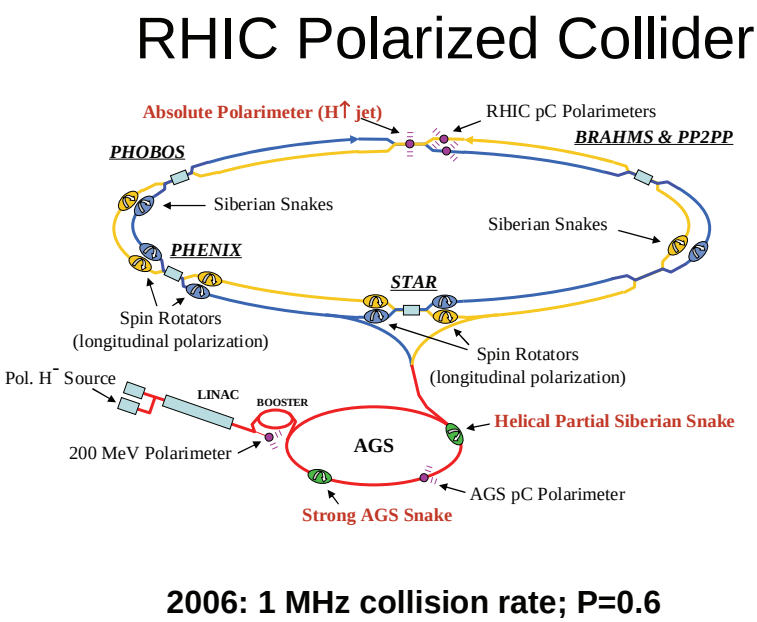


Figure 5: The layout of the RHIC polarized proton collider.

The experiments compare beam helicity-dependent (or transverse spin-dependent) rates or cross sections for a variety of processes, such as pion production discussed above. At RHIC we have exquisite control of the systematic uncertainties for these beam spin-dependent measurements through loading the RHIC rings with a large number of "bunches" of protons with different spin orientations, for each ring. A proton bunch will contain 1-2 x 10^11 protons in a roughly 60 cm long packet. There are typically 110 bunches in each RHIC ring, with the bunches 30 meters apart. The rings are loaded with alternate spin sign bunches (or alternate pairs of bunches). The RHIC collisions, where the

same bunches collide on each pass, then include (++, +-,-+, and --) collisions. RHIC timing signals keep track, and the experiments collect data on all spin combinations at once. This is illustrated in Fig. 6.

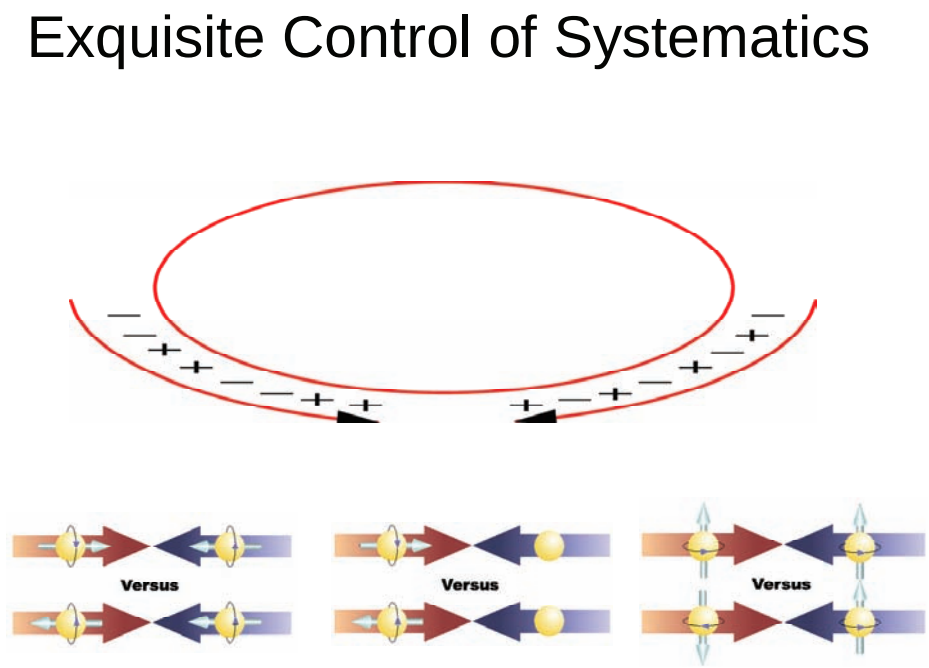


Figure 6: At RHIC, the opposing rings are loaded with bunches of protons with alternating polarization signs. Data are taken by the experiments with all spin combinations at the same time, with RHIC timing signals used to determine the spin signs of the beams for each event. Experiments with spin rotators, STAR and PHENIX, collide either longitudinal or transversely polarized beams; the BRAHMS experiment collides only transversely polarized beams.

4. RHIC EXPERIMENTS AND SPIN MEASUREMENTS

The STAR, PHENIX, and BRAHMS detectors were presented in Jamie Nagle's lecture on heavy ion physics. In general, these detectors, designed for gold-gold collisions in RHIC with very high multiplicity per event and very low collision rates, work well for the polarized proton collisions with low multiplicity and high collision rates. The experiments have also added capabilities specifically emphasizing spin. Spin rotators around STAR and PHENIX allow measurements with longitudinal polarization. The stable spin direction in RHIC is vertical, and all experiments have access to transverse spin collisions.

There are three types of measurements that are the main focus of RHIC. The two-spin longitudinal asymmetry, A_LL, for various processes can be very sensitive to the gluon polarization in the proton. A one-spin longitudinal asymmetry, A_L, is parity-violating, and will be used with W boson production to measure the polarization of the anti-u and anti-d quarks in the proton. A one-spin transverse asymmetry, A_N, is a left-right asymmetry that can be sensitive

to the degree of polarization of the quarks in a transversely polarized proton and to the orbital angular momentum of quarks and gluons in the proton. In addition to these three, measurements are also underway on spin transfer, comparing the beam spin and the spin of self-analyzing produced particles such as Lambda and anti-Lambda.

The longitudinal 2-spin asymmetry A_LL is illustrated in Fig. 7. It consists of comparing cross sections for like versus unlike helicities, producing for example pions, normalized by the unpolarized cross section and by the beam polarization values. The beam polarization is obtained from separate measurements at the 12 o'clock intersection region of RHIC (see Fig. 5, top of the figure) where the scattering of each polarized beam is compared to the scattering of the beam from a highly polarized (92%) atomic hydrogen gas target.

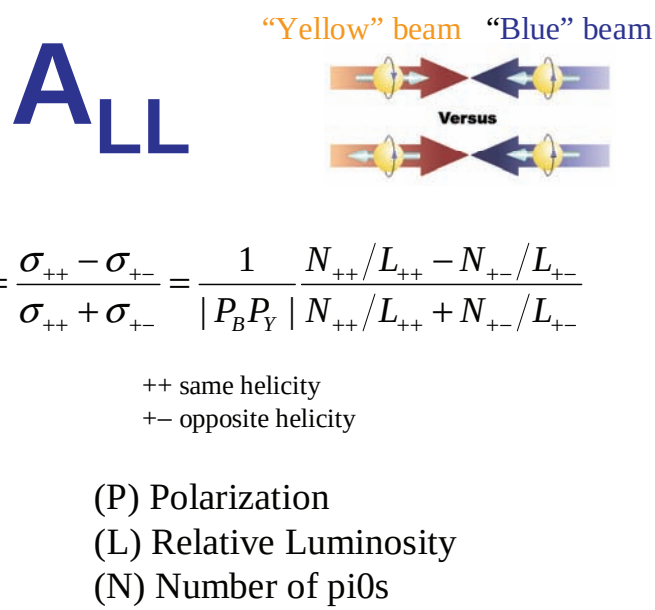


Figure 7: The double beam helicity asymmetry A_LL. For many RHIC probes, this asymmetry is proportional to the gluon polarization. For this example, where N is explicitly the number of pi^0 observed, the asymmetry is generated by gluon-gluon scattering and by quark-gluon scattering, and A_LL is quadratic in gluon polarization in the proton.

Figure 8 shows recent results for the asymmetry A_LL for pi^0 and for jet production. These measurements are proportional to the polarizations of the interacting gluons and quarks (Fig. 3 and 4). The curves indicate the asymmetry for different levels of gluon polarization, with the filled region representing the range of gluon polarizations that have been speculated after the EMC surprise. The results shown in the left panels [11,12] exclude the maximum curves. The maximum curve represents very large gluon polarization, suggested shortly after the EMC result. The suggestion was, to support the view that the quarks must carry the spin of the proton, that a very large gluon polarization would mask the quark contribution to the spin. The masking would come from quark-anti-quark pairs generated from the polarized

gluons, that would decrease the overall polarization of the quarks and gluons, as measured by DIS. This is ruled out, by RHIC data, and also by DIS data from the COMPASS experiment at CERN. We expect that over the next years, we will determine the gluon polarization.

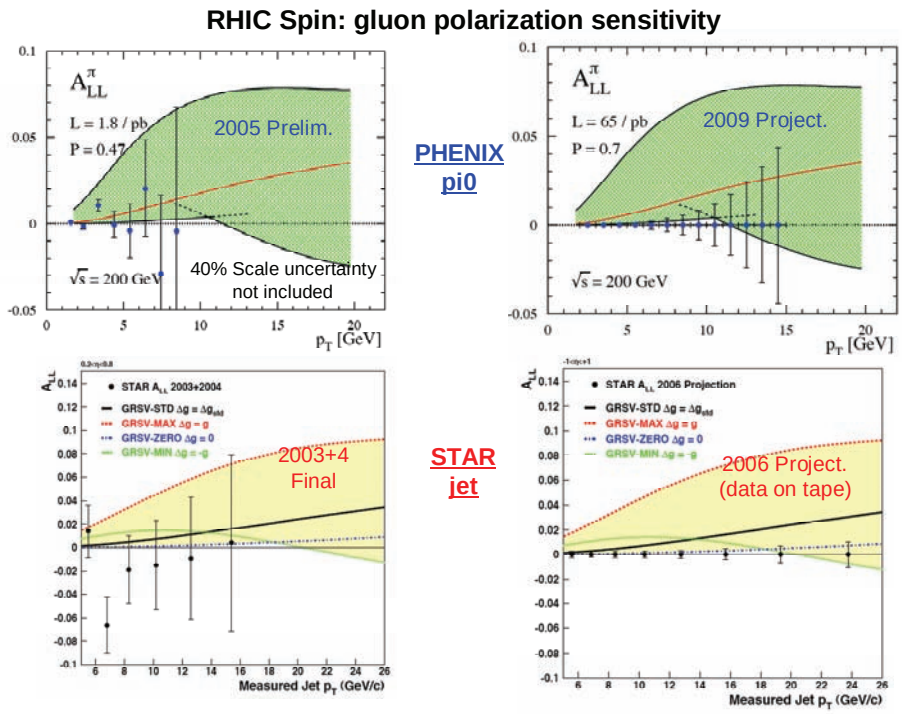


Figure 8: The left panels show the measurements of the 2-spin longitudinal asymmetry A_LL for production of pi^0 (top, by PHENIX), and for production of jets (bottom, STAR). Filled region indicates a range of speculations on gluon polarization. The right panels show expected sensitivity by the end of 2009 (top, PHENIX) and from the RHIC spin run in 2006 (bottom, STAR).

Future measurements at RHIC on gluon polarization include data on pi^0 and on jets with much greater precision, from the 2006 run and our future runs. With greater integrated luminosity, we will measure asymmetries with many other probes, including direct photon production. Photon production is very clean theoretically, with quark-gluon scattering the dominant subprocess. The probe is particularly attractive because the asymmetry directly measures the gluon polarization: at lowest order, the asymmetry is a product of the gluon polarization with the DIS asymmetry A_1^p (known and large at high x—see Fig. 2) and the hard scattering asymmetry (calculable and large). A measurement of the direct photon cross section by PHENIX will be published shortly [13], confirming that the process is well understood. Further, photon + jet and other 2 particle or 2 jet correlation asymmetries will be measured (by the STAR experiment). The correlation measurements constrain the kinematics of the participating quarks and gluons.

A very elegant measurement of identified anti-quark polarizations in the proton will use parity-violating production of W bosons at RHIC. This requires running RHIC at 500 GeV, planned for 2009 and later. W bosons are produced with maximal parity violation. At RHIC, Ws will be produced through q + qbar→ W with a quark from one proton and anti-quark from the other colliding proton, W^+ from u-dbar and W^- from d-ubar. By controlling the helicity of one

proton, and averaging over the spin states of the other proton, we plan to measure the single helicity asymmetry A_L, for leptons produced at very large p_T, the signature of W bosons. This asymmetry violates parity. The kinematics can be arranged, by selecting backward Ws, so that the quark from the unpolarized proton is at large x (momentum fraction), strongly selecting for a quark over anti-quark from the x-dependence of the parton distributions, and the anti-quark (at low x) comes from the polarized proton. Backward Ws are produced backward from the polarized beam. The degree of observed parity violation is then directly the observed parity violation, A_L, neglecting background and the mixing of incorrect assignments of quark/anti-quark to the unpolarized proton/polarized proton. In addition to measuring the anti-u and anti-d quark polarizations directly for the first time, the A_L for W^+, with the u-quark from the polarized proton beam, is expected to reach A_L=0.7. This huge parity-violating signal would confirm our understanding of the production, the previously measured u-quark polarization from DIS (related to A_1^p in Fig. 2), and the expected maximal parity violation from the weak interaction.

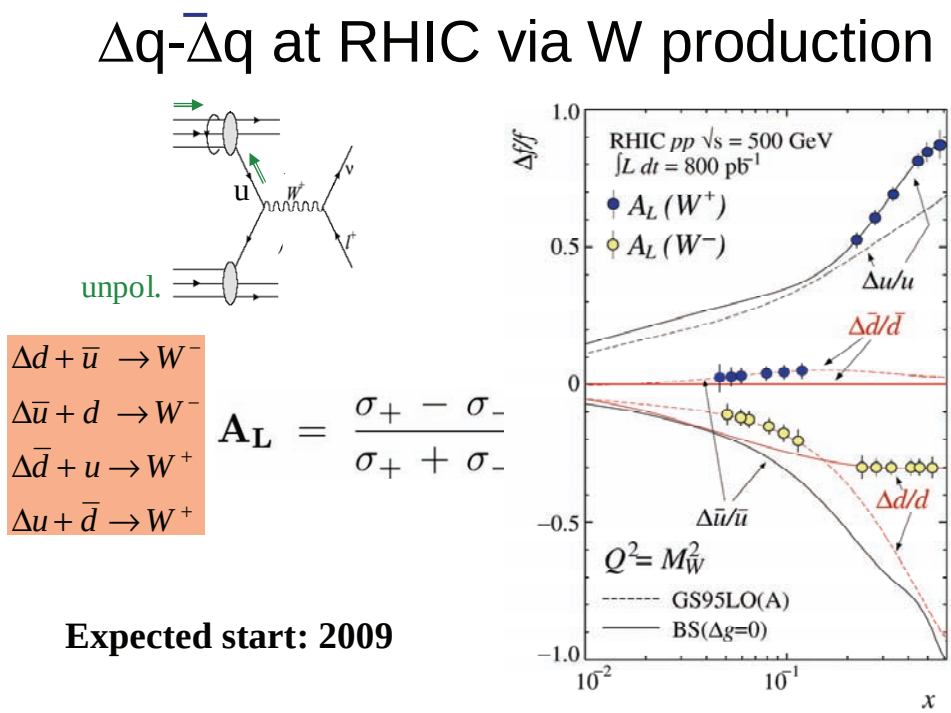


Figure 9: Parity violating W boson production at RHIC. The diagram shows a positive helicity proton colliding with an unpolarized proton. A W^+ boson is produced, with the u-quark from the polarized proton, and the dbar-quark from the unpolarized proton. For this case, the single spin asymmetry A_L is expected to be about 0.7, and be directly the polarization of the u-quark in the proton at large x, shown in the right panel.

Fig. 9 shows the expected parity violation sensitivities, for u, d, ubar and dbar quarks in the polarized proton. The ubar and dbar polarization curves are used to indicate a suggested range of anti-quark polarizations. Measurements have shown that the unpolarized numbers of ubar and dbar anti-quarks in the proton are not equal in the proton, with dbar reaching twice the number of ubar [14]. This difference inspired the model used in Fig. 9 [15]. At this time, prior

to these planned RHIC measurements, the HERMES experiment has used semi-inclusive production of charged pions in DIS to access the anti-quark polarization, assuming equal polarization for ubar and dbar [16].

5. TRANSVERSE SPIN

Transverse spin is a very hot topic at this time. I will not have time to do it justice here. Historically, I was fortunate to be involved in an early measurement at Fermilab, where we found that Lambda hyperons were produced polarized, a great surprise [17]. At the time, spin effects were expected to be very small at high energy, in the perturbative QCD regime. I believe that it was only with the measurement of the cross section for pion production by STAR at RHIC, which was described well by pQCD [18] in the same region where they observed a large transverse spin asymmetry, that the subject warmed up. Fig. 10 shows the published transverse asymmetry [18]. Since then, large asymmetries have been measured in semi-inclusive DIS at HERMES [19], and very large asymmetries were measured with high precision for pions [20] and pions, kaons, and anti-protons [21] at RHIC. The asymmetries are opposite sign for pi^+ and for pi^-, very similar to an earlier result from Fermilab [22]. These asymmetries are large: production to the left, from the polarized beam direction and for spin up, is twice as large as production to the right at large x_F.

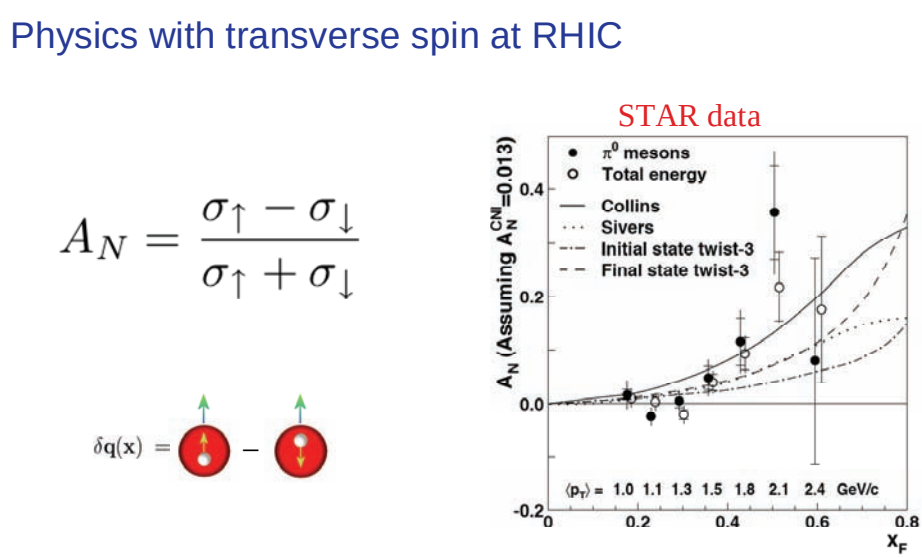


Figure 10: Transverse asymmetry for pi^0 production at RHIC, versus x_F [18]. The curves are predictions from models to observed asymmetries at lower energy.

The physics issues addressed by transverse spin are the degree that the quarks in a transversely polarized proton are polarized (delta q in the figure, and the Collins curve), the degree that the asymmetry may come from an orbital angular momentum of the quarks in the proton (Sivers in the figure), and a correlation between the quarks and gluons in the

proton (twist 3 in the figure). Data were taken in 2006 by STAR to distinguish between these. Another very interesting issue is whether a fragmenting polarized quark might create particles with an orbital angular momentum. This was suggested by Collins and Heppelmann [23] and has been observed to be a large effect by the Belle experiment at KEK [24].

6. PLANS

The "initial" RHIC spin program is planned through 2012. We will focus on measuring the gluon polarization in the polarized proton and transverse spin structure until 2009 at root(s)=200 GeV, and then move to root(s)=500 GeV. There we will measure parity-violating W boson production, and also gluon polarization where the higher energy provides access to the gluon polarization at lower momentum fraction. There are several new detectors planned for the RHIC experiments. A large forward spectrometer is being built now for STAR, new forward electromagnetic calorimeters have been installed for PHENIX, micro vertex detectors are planned for both experiments, improved capabilities for trigger and tracking are needed for both experiments for the W physics. An endcap calorimeter is planned for PHENIX. Finally, it is hoped that a polarized electron-polarized proton collider (and electron-heavy ion collider) will be built based at RHIC beginning in 2012. This is an extensive and exciting program, to understand with precision measurements the helicity structure and the transverse spin structure of the proton.

I would like to close with Fig. 11, which is taken from the RHIC Spin Plan, prepared for the Department of Energy two years ago [25]. We are on track with this plan.

Spin is one of the most fundamental concepts in physics, deeply rooted in Poincare invariance and hence in the structure of space-time itself. All elementary particles we know today carry spin, among them the particles that are subject to the strong interactions, the spin ½ quarks and the spin 1 gluons. Spin, therefore, plays a central role also in our theory of the strong interactions, 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.

Figure 11: from the Research Plan for Spin Physics at RHIC (2005), http://spin.riken.bnl.gov/rsc/.

Ackowledgements

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References

[1] M.J. Alguard *et al*., Phys. Rev. Lett. **37**, 1261 (1976).

[2] J. Ashman *et al*. [European Muon Collaboration, CERN], Phys. Lett. **B206**, 364 (1988).

[3] B. Adeva *et al*. [SMC, CERN], Phys. Rev. **D58**, 112002 (1998).

[4] K. Abe *et al*. [E154 Collaboration, SLAC], Phys. Rev. Lett. **76**, 587 (1996).

[5] A. Airapetian *et al*. [HERMES, DESY], **hep-ex**/0609039 (to be published).

[6] V.Yu. Alexakhin *et al*.[COMPASS, CERN], **hep-ex**/0609038 (to be submitted to PLB).

[7] G. Bunce, N. Saito, J. Soffer, and W. Vogelsang, Ann. Rev. Nucl. Part. Sci. 2000 **50**, 525 (2000).

[8] I. Alekseev *et al*., Nucl. Instr. Meth. **A499**, 392 (2003).

[9] S.S. Adler *et al*. [PHENIX, RHIC], Phys. Rev. Lett. **91**, 241803 (2003).

[10] Ya.S. Derbenev and A.M. Kondratenko, Sov. Phys. JETP **37**, 968 (1973).

[11] S.S. Adler *et al*. [PHENIX], Phys. Rev. **D73**, 091102 (2006); K. Boyle *et al.* [PHENIX], **nucl-ex**/0606008.

[12] B.I. Abelev *et al*.[STAR, RHIC], **hep-ex**/0608030 (to be published in Phys. Rev. Lett.).

[13] S.S. Adler *et al*. [PHENIX], **hep-ex**/0609031 (to be published in Phys. Rev. Lett.).

[14] P. Amaudruz *et al.*, Phys. Rev. Lett. **66**, 2712 (1991); A. Baldit *et al.*, Phys. Lett. **332**, 244 (1994); E.A. Hawker *et al.*, Phys. Rev. Lett. **80**,3715 (1998); K. Ackerstaff *et al.*, Phys. Rev. Lett. **25**, 5519 (1998).

[15] C. Bourrely and J. Soffer, Nucl. Phys. **B445**, 341 (1995).

[16] A. Airapetian *et al*. [HERMES], Phys. Rev. **D71**, 012003 (2005).

[17] G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113 (1976).

[18] J. Adams *et al*. [STAR], Phys. Rev. Lett. **92**, 171801 (2004).

[19] A. Airapetian *et al*. [HERMES], Phys. Rev. Lett. **94**, 012002 (2005).

[20] L. Nogach *et al*. [STAR], Kyoto Spin2006, http://www-nh.scphys.kyoto-u.ac.jp/SPIN2006/.

[21] J.H. Lee *et al*. [BRAHMS, RHIC], Kyoto Spin2006, http://www-nh.scphys.kyoto-u.ac.jp/SPIN2006/.

[22] D.L. Adams *et al*. [E704, FNAL], Phys. Lett. **B264**, 462 (1991).

[23] J. Collins, Nucl. Phys. **B396**, 161 (1993).

[24] R. Seidl *et al*. [BELLE, KEK], Phys. Rev. Lett. **96**, 232002 (2006).

[25] Research Plan for Spin Physics at RHIC (2005), http://spin.riken.bnl.gov/rsc/.