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SPIN PHYSICS AT RHIC

M. J. TANNENBAUM
Brookhaven National Laboratory *
Upton, NY 11973 USA

Abstract

Operation of RHIC with two beams of highly polarized protons (70%, either longitudinal or transverse) at high luminosity $\mathcal{L} = 2 \cdot 10^{32}$ cm^{-2} sec^{-1} for two months/year will allow the STAR and PHENIX detectors to perform high statististics studies of polarization phenomena in the perturbative region of hard scattering where both QCD and ElectroWeak theory make detailed predictions for polarization effects. The collision c.m. energy, $\sqrt{s} = 200 - 500$ GeV, represents a new domain for the study of spin. Direct photon production will be used to measure the gluon polarization in the polarized proton. A new twist comes from W-boson production which is expected to be 100% parity violating and will thus allow measurements of flavor separated quark and antiquark (u, $\bar{u}$, d, $\bar{d}$) polarization distributions. Searches for parity violation in strong interaction processes such as jet and leading particle production will be a sensitive way to look for new physics beyond the standard model, one possibility being quark substructure.

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Abstract

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1 Spin Physics and RHI Physics are Complementary

The structure of the nucleon, including its spin structure, are fundamental issues of the utmost significance. To quote from a recent article in Physical Review C[1] "The nucleon-nucleon (NN) interaction is fundamental to nuclear physics. NN data serve as tests of the strong interaction and as input to microscopic models of the nucleus." One of the principal objectives of the Heavy Ion program at RHIC is to study nuclear matter under extreme conditions of high temperature and density, the domain of non-perturbative QCD. As QCD is a gauge theory of the strong interactions in which helicity plays as fundamental role[2, 3, 4] as "charge", the complementarity of Spin Physics and RHI Physics is evident.

2 Spin Physics at BNL—a long tradition

BNL has a long and distinguished history in spin physics. In fact, Sam Goudsmit, the co-originator of the concept of spin[5], was one of the early BNL senior staff members and chairman of the Physics Department throughout most of the 1950's[6]. Other highlights include the neutrino helicity measurement[7], major contributions to the physics of the acceleration and storage of polarized beams[8], the AGS spin physics program[9], the 1982 International Spin Symposium[10], and the theory of the systematics of $W^{\pm}$ production at hadron colliders including parity violation effects[11].

2.1 How we were able to get Polarized Protons at RHIC

In the early 1980's, the first Snowmass meeting[12], the transition from ISABELLE to the 'CBA'[13, 14] and the AGS spin program stimulated lots of thinking about spin physics at hadron colliders. Work continued intermittently until January 1990 when the approval of RHIC caused a renaissance. This led to the Polarized Collider Workshop[15] at Penn State in November 1990 where the RHIC Spin Collaboration (RSC), a collaboration of accelerator physicists, theoretical physicists and experimental physicists with a common interest in spin, was formally initiated.

A proposal (R5) was submitted to the BNL HENP Program Advisory Committee in September 1992, for a program of Spin Physics using the RHIC Polarized Collider[16, 17], which included a general section—covering an overall view of the physics and a detailed conceptual design for the spin rotators, siberian snakes, and polarimeters which would be necessary to operate RHIC with polarized protons—followed by specific proposals by PHENIX and STAR for experiments to survey spin phenomena using the two major heavy ion detectors[18]. After 3 additional PAC presentations (for spin only), several technical reviews and a major external spin physics review in June 1995, the project "came onto the mass shell" in September 1995 with the signing of the BNL-RIKEN Agreement on Spin Physics—RIKEN, The Institute of Physical and Chemical Research, a non-profit research institute supported by the Science and Technology Agency of Japan, will provide \$20M for the accelerator components and a second muon arm in PHENIX to implement the BNL-RIKEN RHIC/Spin program.

Over this long period, we were fortunate to receive many positive reviews. One my favorites is from the June 1993 Technical Review, *"The proposal has the flavor of the application of an ingenious technological invention (siberian snakes) to make possible exciting physics research (polarization physics) reminiscent of the application of stochastic cooling to obtain $\bar{p}p$ beams for W and Z in the CERN SPS."*[a]

3 Why RHIC?

The use of RHIC to study the interactions of highly polarized protons ($\geq$ 70%), with a luminosity in excess of $2 \cdot 10^{32}$ cm^{-2} s^{-1}, and c.m. energy from 50 to 500 GeV, with dedicated operation for two months a year, will open up a totally new field in elementary particle physics and fill a vital gap in the world's accelerators. Both longitudinally and transversely polarized protons will be provided at the interaction regions, and frequent polarization sign reversal will allow the systematic errors to be minimized (see Fig. 1). This facility would be unique in the ability to perform parity-violating measurements with hadrons and polarization tests of QCD including polarized structure function measurements of gluons and flavor-separated

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[a] In case you forgot, that project got the Nobel Prize.

quarks and anti-quarks. Polarization will be exploited to test fundamental symmetries in strong interactions and to search for new effects beyond the standard model.

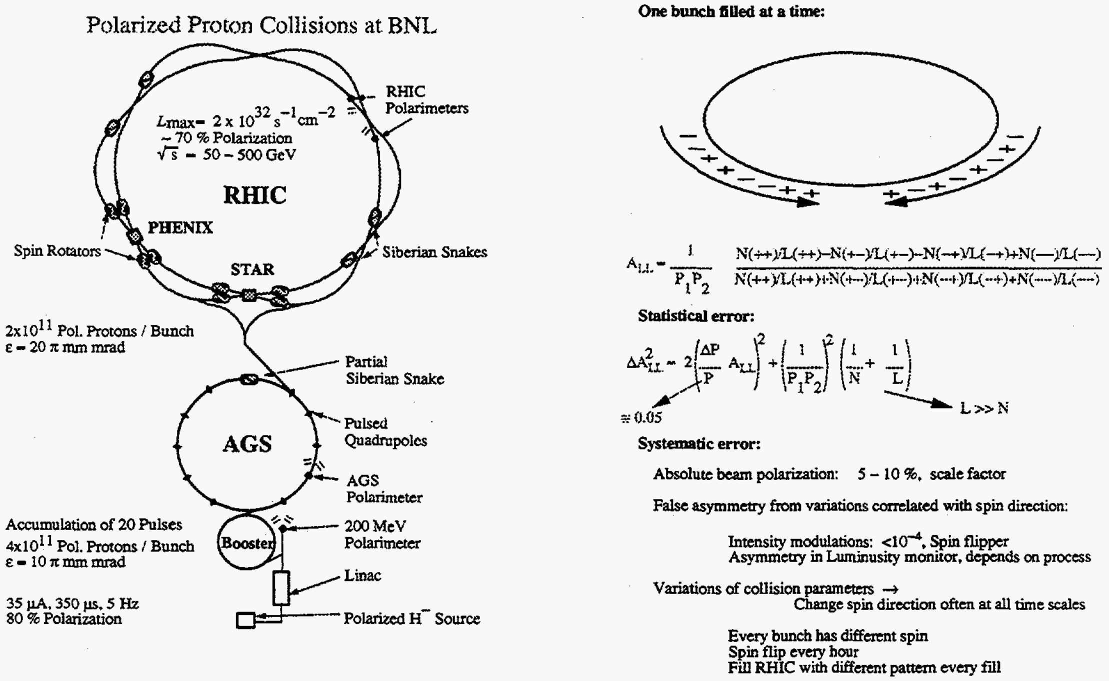

Figure 1: a) Scheme for Polarized Proton Collisions at RHIC. b) Scheme for bunch polarization to minimize systematic errors—figures from Tom Roser.

The simplest description of spin physics at RHIC would be proton structure physics, the exploration of the constituents of the proton with a resolution approaching 10^{-17} cm, corresponding to a mass scale of 2 TeV.[b] For many experiments, it would be preferable to run the machine at c.m. energy 200 GeV, rather than the nominal 500 GeV, to obtain the large values of Bjorken x, ($x > 0.3$), required to effectively transmit the polarization of the protons to the constituent quarks and gluons. Also, the existence of $p-p$ collisions in the energy range $\sqrt{s} = 200 - 500$ GeV will permit the study of some classical reactions like the total cross section and elastic scattering[19] as a complement and extension of the CERN and Tevatron $p-\bar{p}$ measurements.

RHIC offers an extraordinary combination of energy, luminosity and polarization. This facility would be unique in the ability to perform single-spin parity violating measurements both in $p-p$ and $p+A$ collisions, and two-spin parity violating measurements in $p-p$ collisions. Also, the utilization of polarized nuclei is possible in principle, and, for the cases of polarized d or ^{3}He, under active study.

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[b] The sensitivity to mass scales beyond the c.m. energy will be explained in due course.

4 Helicity Asymmetry measurements

Spin effects can be observed with fine precision since they involve the measurements of asymmetries. The effect of systematic errors in the detectors and accelerator can be minimized by frequent polarization sign reversal and careful preparation of the initial polarized beams to give equal luminosities in all polarization states (see Fig. 1b). The goal is to polarize the beams for all proton runs including the possibly extensive $\sqrt{s} = 200$ GeV comparison runs for the Relativistic Heavy Ion (RHI) program. Experiments not interested in polarization will obtain the spin-averaged result to a high accuracy.

4.1 A_{LL}—Parity Conserving Two-Spin Longitudinal Asymmetry

The polarization of a longitudinally polarized proton beam has two possible states, parallel to the momentum ('+' helicity) or opposite to the momentum ('−' helicity). In asymmetry definitions at RHIC, care must be taken to account for the possibility of large parity violating effects. We use the notation $\sigma^{++} = N^{++}/L^{++}$ for the measured cross section with both beams having '+' helcity, where N^{++} is the measured number of events for an integrated luminosity L^{++}, with analogous notation for the other helicity combinations.

The two-spin parity-conserving longitudinal asymmetry, A_{LL} is defined:

$$A_{LL} = \frac{1}{P_1 P_2} \frac{\sigma^{++} + \sigma^{--} - \sigma^{+-} - \sigma^{-+}}{\sigma^{++} + \sigma^{--} + \sigma^{+-} + \sigma^{-+}} \tag{1}$$

where P_1 and P_2 are the polarizations of the two beams. If parity is conserved, the theoretical cross sections obey the relations $\sigma^{++} = \sigma^{--}$ and $\sigma^{+-} = \sigma^{-+}$, leading to the more conventional definition:

$$A_{LL} = \frac{1}{P_1 P_2} \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \tag{2}$$

4.2 Parity Violating Asymmetries (PVA's)

Three[20] parity violating asymmetries can be measured with longitudinally polarized beams. In the first case, only one beam is polarized, and the cross section difference is measured for the two helicity states of the polarized beam. This is A_L, the single spin Parity Violating Asymmetry:

$$A_L = \frac{1}{P_1} \frac{\sigma^{-} - \sigma^{+}}{\sigma^{-} + \sigma^{+}} \quad . \tag{3}$$

A second case involves two polarized beams with the same helicities, which are both flipped e.g. from left-handed (−) to right-handed (+). This is the symmetric two-spin parity-violating asymmetry[13] (A_{LL}^{PV})

$$A_{LL}^{PV} = \frac{1}{P_1 P_2} \frac{\sigma^{--} - \sigma^{++}}{\sigma^{--} + \sigma^{++}} \tag{4}$$

which can be twice as big as A_L for special cases[13, 20]. There is also the anti-symmetric two-spin parity-violating asymmetry[20] where the beams have opposite helicities.

4.3 Statistical Errors on Asymmetries

Assuming equal integrated luminosity for each spin configuration, with N total number of events summed over the relevant spin configurations, e.g. $N = N^{++} + N^{--} + N^{+-} + N^{-+}$ or $N = N^{+} + N^{-}$, the error on the measured asymmetry A is approximately:

$$\delta A_{LL} = \frac{1}{P_1 P_2}\sqrt{\frac{1-A^2}{N}} \quad \text{and} \quad \delta A_L = \frac{1}{P}\sqrt{\frac{1-A^2}{N}} \quad . \tag{5}$$

For the purposes of this article, it is assumed that the statistical error in the number of events is the dominant error, with much smaller systematic errors. The challenge will be to achieve both these results in the acutal experiments.

5 Goals and Capabilities of the RHIC/Spin Program

The philosophy of the RHIC/Spin program is to use the existing major detectors[18], which are designed for Relativistic Heavy Ion Physics, to make a survey of a wide variety of spin effects in polarized $p-p$ collisions for many specific channels over a large range of kinematic variables (m, p_T). Conventional longitudinal spin effects, single and double transverse spin asymmetries and a general parity violation search will be made in all channels. Although spin physics is notable for its surprises, there are several channels for which precise and clear-cut predictions exist so that rates and sensitivities can be given. The desired measurements for polarized proton physics focus on the traditional hard processes, direct photons, jets (directly or via leading particles—π for light quarks, leptons for c or b quarks), high-mass lepton pair production (Drell-Yan), high-mass vector mesons via leptonic or semileptonic decay including J/Ψ, Υ, $W^{\pm}$, Z^0.

In general, the heavy ion detectors are designed with ultra-high granularity to cope with the expected charged particle multiplicity of $dn/dy \sim 1000$ in Au+Au central collisions. Although the detectors tend to be optimized at low values of transverse momentum where soft multiparticle production plays a major role in the thermalized physics of nuclear collisions, the high granularity and high resolution make them better in many ways for measuring hard scattering in their limited apertures than the 'conventional 4π' collider detectors. For instance, STAR, which emphasizes hadron physics, can reconstruct jets and di-jets over the full azimuth and nearly ± 1 unit of pseudorapidity; while PHENIX, a very highly segmented, high resolution detector with a smaller aperture, concentrates on measurements of leptons (both $e^{\pm}$ and $\mu^{\pm}$) and photons at the highest luminosities, with very selective triggers.

5.1 Luminosities for Rate Calculations and Sensitivity Estimates

The expected luminosities for polarized proton at RHIC are $\mathcal{L} = 2 \times 10^{32}$ cm^{-2} sec^{-1} at $\sqrt{s} = 500$ GeV, ~ 1 event/crossing, and $\mathcal{L} = 8 \times 10^{31}$ cm^{-2} sec^{-1} at $\sqrt{s} = 200$ GeV. It is assumed that the $\sqrt{s} = 500$ GeV run is dedicated for spin physics and, since the goal is to polarize the beams for all proton runs, the 200 GeV data are collected during comparison runs for the RHI program. The polarization of both beams is taken as $P_1 = P_2 = 70\%$. The physics sensitivity calculations at each $\sqrt{s}$ are based on runs of 4×10^6 seconds, or about 100 days with a duty factor of ~ 50%, which leads to the integrated luminosities $\int \mathcal{L}dt = 8 \times 10^{38}$ cm^{-2} at $\sqrt{s}$=500 GeV and $\int \mathcal{L}dt = 3.2 \times 10^{38}$ cm^{-2} at $\sqrt{s}$=200 GeV. Optimistically, these initial runs could be accomplished during the first two years of RHIC operation. It is worthwhile to point out that the 800 pb^{-1} integrated luminosity is ~ 20 times the total of the entire CERN collider program, ~ 6 times the present total of the Tevatron collider (Run I), and comparable to the integrated luminosity anticipated for the Tevatron 3-4 year 'Run II' which is planned to start in 1999.

6 QCD and Hadron Collisions

The cross section for hard processes in $p-p$ collisions at c.m. energy $\sqrt{s}$ is taken to be a sum over the constituent reactions

$$a + b \rightarrow c + d \quad , \tag{6}$$

where the c.m. system for the constituent scattering is not generally the same as the $p-p$ c.m. system since the constituents have momentum fractions x_1 and x_2 of their respective protons. Thus, in the $p-p$ c.m. system, the constituent c.m. system has rapidity, $\hat{y} = \frac{1}{2}\ln\frac{x_1}{x_2}$, and invariant mass-squared, $\hat{s} = x_1 x_2 s$, where

$$x_1 = \sqrt{\frac{\hat{s}}{s}}e^{\hat{y}} \qquad x_2 = \sqrt{\frac{\hat{s}}{s}}e^{-\hat{y}} \quad . \tag{7}$$

If $a(x_1)$, $b(x_2)$, are the differential probabilities for constituents a and b to carry momentum fractions x_1 and x_2 of their respective protons, e.g. $u(x_1)$, then the overall $p-p$ reaction cross section in lowest order (LO) of α_s is

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{s d^3\sigma}{d\hat{s} d\hat{y} d\cos\theta^*} = \sum_{ab} a(x_1) b(x_2) \frac{\pi\alpha_s^2(Q^2)}{2\hat{s}} \Sigma^{ab}(\cos\theta^*) \quad , \tag{8}$$

where $\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess scattering angular distributions (see Fig. 2a), and $\alpha_s(Q^2) = \frac{12\pi}{25}\ln(Q^2/\Lambda^2)$, the strong coupling constant, are fundamental predictions of QCD[21, 22].

By contrast, the quantities $a(x_1)$ and $b(x_2)$, the "number" distributions of the constituents, are empirical—they need to be measured. However, in a triumph of the Standard Model, these distributions are related (for the electrically charged quarks) to the structure functions measured in Deeply Inelastic lepton-hadron Scattering (DIS), e.g.

$$F_2(x, Q^2) = x \sum_a e_a^2 \, a(x, Q^2) \tag{9}$$

where e_a is the electric charge on a constituent. The evolution of the structure functions with Q^2 is a higher-order QCD effect in hadron collisions, but is the leading order QCD effect in DIS.

It is important to realize that for fixed x_1, x_2, the hard scattering cross section is proportional to $1/s$

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s} \sum_{ab} a(x_1) b(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1 x_2} \Sigma^{ab}(\cos\theta^*) \tag{10}$$

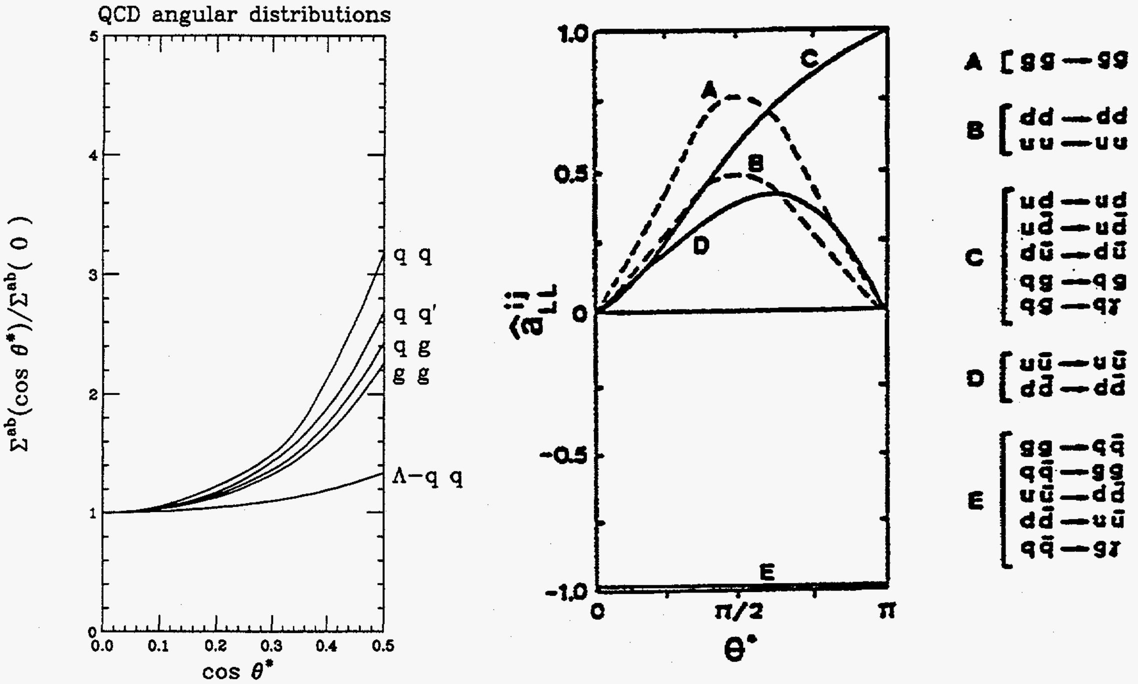

Figure 2: Characteristic QCD Subprocess angular distributions: (a) scattering; (b) spin asymmetry. θ^* is the scattering angle in the constituent c.m. system.

so that lower s leads to larger x for a given luminosity. Also, the structure functions fall precipitously with increasing x, which further leads to sharply falling cross-sections with increasing $\hat{s}$ for a given s. This explains why RHIC is better than higher energy colliders for attaining values of $x \sim 0.3$ where polarization effects are important.

6.1 Spin QCD

The two-spin longitudinal asymmetry for the constituent reaction (Eqs. 6, 8) is

$$A_{LL}(a+b \to c+d) = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \tag{11}$$

$$= \frac{\Delta a}{a}\frac{\Delta b}{b}\hat{a}_{LL}(a+b \to c+d) \quad , \tag{12}$$

where $\Delta a(x)$ is the helicity asymmetry of the constituent structure function $a(x)$

$$\Delta a(x) = a^+(x) - a^-(x) \tag{13}$$

and the '+' and '−' refer to constituents with the same or opposite helicity as the parent proton. The spin asymmetry of the subprocess[3, 4]

$$\hat{a}_{LL}(a+b \to c+d) \tag{14}$$

is a fundamental prediction of QCD (see Fig. 2b), **which has never been verified—to my knowledge.**

7 Spin Structure Functions and Tests of QCD

The predicted QCD constituent polarization asymmetries of Fig. 2b are enormous at the constituent level. However at the observational level, the effect is greatly diluted[15] because the proton polarization is not appreciably transmitted to the constituents, unless $x \geq 0.3$. At the outset of the RHIC/Spin program, we assume that QCD is valid and use Eqs. 11, 12 to determine the spin structure functions.

7.1 The Spin Structure Function of the Gluon—Direct Photon Production

A_{LL} in direct photon production should be a clean measurement of the spin dependent gluon structure function since the dominant subprocess in $p-p$ collisions is

$$g+q \rightarrow \gamma+q \quad , \tag{15}$$

with $q\bar{q} \rightarrow \gamma+g$ contributing on the order of 10%. This small contribution from the annihilation channel can be neglected in the first measurements of $\Delta G(x)$. Predictions[23] for A_{LL} (in NLO) are surprisingly large, in the range 5% to 20%.

This is one of the favorite QCD reactions in hadron physics[24], since there is direct and unbiased access to one of the interacting constituents, the photon. The only problem is the huge background of photons from π^0 and η decays which produce a *fake* direct γ signal. This background is effectively eliminated[16, 25] by π^0 reconstruction and gamma isolation cuts. By applying both of these rejection methods, the purity of direct photon candidates will be excellent. Spin effects from any residual η background can be measured and corrected.

The high segmentation of the PHENIX EM calorimeter, which is driven by the issues of occupancy and energy resolution in the high multiplicity, low p_T environment of Heavy Ion Collisions, allows the two gammas from π^0 decay to be resolved[16] for $p_T(\pi^0) \leq 30\text{GeV/c}$. In STAR, the calorimeter is less segmented and a 'shower-max' detector is used for γ/π^0 separation. However, the large solid angle allows the recoil jet to be detected so that the full constituent kinematic quantities x_1 and x_2 can be reconstructed. Similarly, di-jet production can be detected and used to measure the gluon spin structure function in the appropriate kinematic region.

To summarize, here is a subject with precise theoretical predictions and no experimental tests. It cries out for measurements—which can best, if not only, be done using longitudinally polarized proton beams.

8 Parity Violation in Hadron Collisions

The field of Parity Violation in hadron collisions has traditionally been the domain of *"ultra high precision"* physicists. The parity violating asymmetry in the total proton-proton cross section has been measured to be $\sim 3 \times 10^{-7}$ at 1.5 GeV/c, 2.6×10^{-6} at 6 GeV/c laboratory momenta, and predicted to be "large" $> 10^{-4}$ at RHIC energies[26].

8.1 "Large" effects at RHIC?

However, at RHIC there are other conventional parity violating effects which are predicted to be much larger. For instance, in inclusive jet production—the leading strong interaction process at RHIC—A_{LL}^{PV} due to the interference of gluon and W exchange at the constituent level is estimated[13, 27] to be $\sim 0.8\%$, at jet $p_T = m_W/2$; $\sim 0.5\%$, at $p_T = 50$ GeV/c; 1%, at p_T=70 GeV/c; and 2%, p_T=95 GeV/c at $\sqrt{s}$=300 GeV. Of course, a more spectacular effect at RHIC will be the opening up of a totally new regime of hadron physics, a situation in which parity violating effects are **dominant**. This concerns the direct production of the Weak Bosons $W^{\pm}$ and Z^0. The most spectacular channel is the leptonic decay $W^{\pm} \rightarrow e^{\pm}+X$, where the X means that the measurement is via the inclusive $e^{\pm}$ channel with no "missing energy" detection. This is a textbook example[28] of a process with virtually no background. The predicted PVA is really **HUGE** at production[11], on the order of **UNITY**. Both PHENIX and STAR have respectable counting rates (see Table 1) bringing towards reality something that I only dared to dream just a few years ago[29], *"By measuring the PVA for the reaction $W \rightarrow e + X$ as a function of $\sqrt{s}$, the spin dependent structure functions of the proton can be measured at values of $x \sim m_W/\sqrt{s}$."*

8.2 "Yesterday's sensation is today's calibration..."

An article by Bourrely and Soffer[20] has now presented the formalism for proton structure function measurements using the parity violating asymmetry of $W^{\pm}$ and Z^0 production. This really brings to mind Val Telegdi's statement, partially quoted above. In the standard model, the differential cross section for the reaction

$$pp \rightarrow W^{\pm} + \text{ anything} \tag{16}$$

is given in leading order[20] by the quark-antiquark fusion reactions $u\bar{d} \rightarrow W^+$ and $\bar{u}d \rightarrow W^-$. The parity violating single-spin asymmetry for W^+ production is given by[20]

$$A_L^{W^+}(y) = \frac{\Delta u(x_1, M_W^2)\bar{d}(x_2, M_W^2) - \Delta\bar{d}(x_1, M_W^2)u(x_2, M_W^2)}{u(x_1, M_W^2)\bar{d}(x_2, M_W^2) + \bar{d}(x_1, M_W^2)u(x_2, M_W^2)} \tag{17}$$

and with the reasonable assumption that $\Delta u\Delta\bar{d} \ll u\bar{d}$, the two-spin and single-spin PVA's are simply related by[20]

$$A_{LL}^{PV}(y) = A_L(y) + A_L(-y) \quad . \tag{18}$$

The sensitivity to unknown spin structure functions is generally much larger for the W^- than the W^+, which is easy to understand by simple arguments[20]. Near $y = 0$, the PVA's are given to a good approximation by

$$A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta u}{u} - \frac{\Delta\bar{d}}{\bar{d}}\right) \quad \text{and} \quad A_L^{W^-} = \frac{1}{2}\left(\frac{\Delta d}{d} - \frac{\Delta\bar{u}}{\bar{u}}\right) \quad , \tag{19}$$

and $\Delta u/u$ is large and well measured[30]. For large positive rapidity, $x_1 \gg x_2$, so that $A_L^{W^+} \simeq \Delta u/u$, $A_L^{W^-} \simeq \Delta d/d$; similarly at large negative rapidity, $x_1 \ll x_2$, $A_L^{W^+} \simeq -\Delta\bar{d}/\bar{d}$, $A_L^{W^-} \simeq -\Delta\bar{u}/\bar{u}$.

The expected sensitivities for spin-structure measurements in PHENIX with the latest Bourrely and Soffer polarized structure functions[31] are shown in Fig. 3. Table 1 gives an overall PHENIX/STAR comparison. The structure functions assumed in Fig. 3[20] give huge single-spin asymmetries, $A_L^{W^\pm}$, as previously advertised. An amusing feature of the single-spin asymmetry is that the variables x_1 and x_2 can be distinguished in the otherwise symmetric $p-p$ collision. Also, single-spin asymmetries could be used in $p+A$ collisions to measure the evolution of the spin-dependent sea quark structure functions in nuclei—a combination of the two most famous "*EMC effects.*" This could be the birth of *Structure Function Physics* **using parity violation as a tool.**

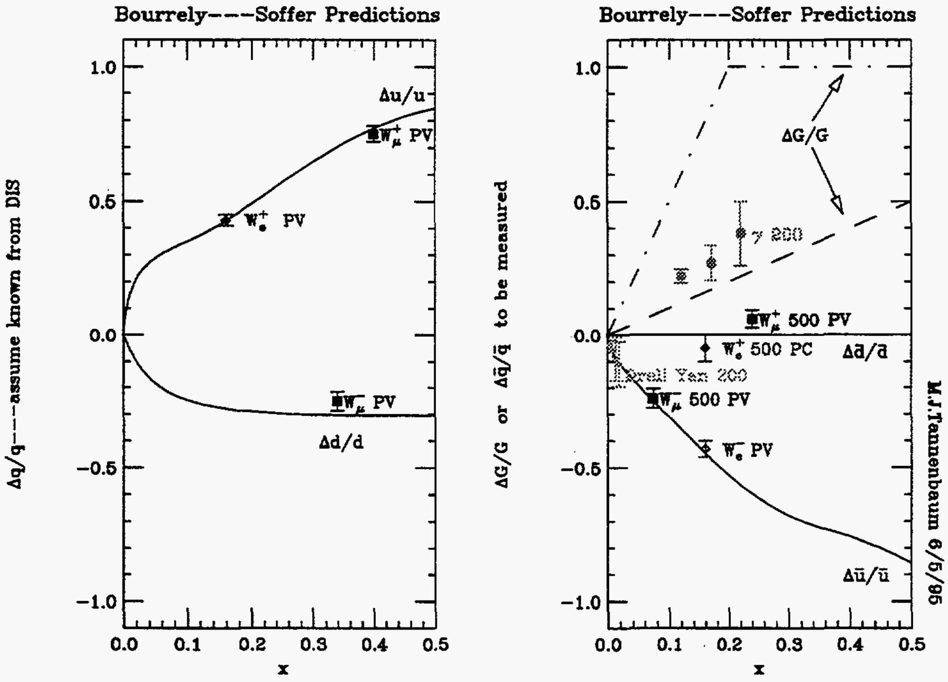

Figure 3: Expected sensitivities for spin-structure function measurements in PHENIX shown with Bourrely-Soffer distributions[31] for 800 pb^{-1} at $\sqrt{s} = 500$ GeV and 320 pb^{-1} at $\sqrt{s} = 200$ GeV

8.3 New Physics—Surprises

In my opinion, the most exciting feature of the study of parity violation in hadron interactions is the possibility of surprises. There are essentially no measurements of, or searches for, parity violation in hadron reactions at high energies ($\sqrt{s} \geq 10$ GeV). *THIS FIELD IS TOTALLY UNEXPLORED.* In the standard model, no parity violation is expected in strong interactions. Of course, this is probably a consequence of the fact that nobody ever looked. But, to quote Maurice Goldhaber (who was quoting astronomers), "The absence of evidence is not the evidence of absence." Thus, there are limitless possibilities beyond the standard model for parity violating effects in hadronic interactions since the subject has hardly been studied. Perhaps the B quark production mechanism is 30% parity violating...

Table 1: RHIC Spin Collaboration:PHENIX/STAR Comparison

	PHENIX	**STAR**
$W^\pm \to l^\pm + X$ Parity Violation, $\Delta\bar{q}$	$e^\pm$: 15K W^+, 3K W^- $\mu^\pm$: 9K W^+, 10K W^-	$e^\pm$: 72K W^+, 21K W^-
$Z^0 \to l^+l^-$ Transversity $h_1(x)$, $\bar{u}(x)$	e^+e^-: 120 Z^0 $\mu^+\mu^-$: 700 Z^0	e^+e^-: 4200 Z^0
Direct γ (ΔG)	Highly Segmented EMCAL Resolve π^0 $p_T \leq 25$ GeV/c	Shower Max Detector γ, $p_T < 20$ GeV/c
γ+Jet (ΔG)	Away-Jet 15% efficiency via leading particle.	γ+ Jet $\Delta G(x)$, $x < 0.2$
JETS (ΔG, PV) Di-Jets	π^0's as Leading Particles π^0 pairs	Full Jets $\vert\eta\vert \leq 0.5$ $\geq 10^6$ Di-jets
Drell-Yan ($\Delta\bar{q}$, $\Delta_T\bar{q}$)	$\mu^+\mu^-$: 30K pairs mass 9 to 12 GeV	e^+e^-: 37K pairs mass 9 to 12 GeV
$J/\psi \to l^+ + l^-$ (ΔG?) $\Upsilon \to \mu^+\mu^-$	200K e^+e^-; $\geq$ 1M $\mu^+\mu^-$ 25K events	Sizable rates for e^+e^- trigger only at high p_T

8.4 My Criteria for the Maximum Discovery Potential

Parity Violation searches at RHIC satisfy all

My Criteria for The Maximum Discovery Potential:

- Look where most theorists predict that nothing will be found.
- Look in a channel where the known rates from conventional processes are small, since low background implies high sensitivity for something new.
- Be the first to explore a new domain—something that has never been measured by anybody else.

I feel that parity violation searches offer, at the present time, the same discovery potential as di-lepton searches in the 1970's.

8.5 A timely illustration—Quark Substructure (?)

It is difficult to predict surprises. However, as an example of something that might happen, a recent extension of the standard model has included a new parity violating interaction due to quark substructure[32]. One possible explanation of the several generations of quarks and leptons is that they are composites of more fundamental constituents, with a scale of compositeness $\Lambda_c \gg 100$ GeV. The intriguing feature of composite models of quarks and leptons is that the interactions generally violate parity, since $\Lambda_c \gg M_W$. The parity-violating asymmetry then provides direct and much more quantative tests for substructure than other methods. The sensitivity to quark substructure is, of course, model dependent. One model of quark substructure[32] contains an explicitly parity-violating left-left contact interaction between quarks, which results in a PVA in jet production[13, 14], as well as a slight increase in the jet cross section at large p_T (See Fig. 4a).[c] Without the PVA handle, detectors at the Tevatron are limited to searching for substructure by deviations of jet production from QCD predictions at large values of p_T. It is difficult to prove that a small deviation is really due to something new. The latest CDF measurement[33] is a case in point (see Fig. 4b). If the "% Difference from NLO QCD" were "% Parity Violation", the parity-violating signature would be **a clear indication of new physics**[29, 34]. The limit is presently[33] $\Lambda_c \cong 1.4 - 1.6$ TeV.

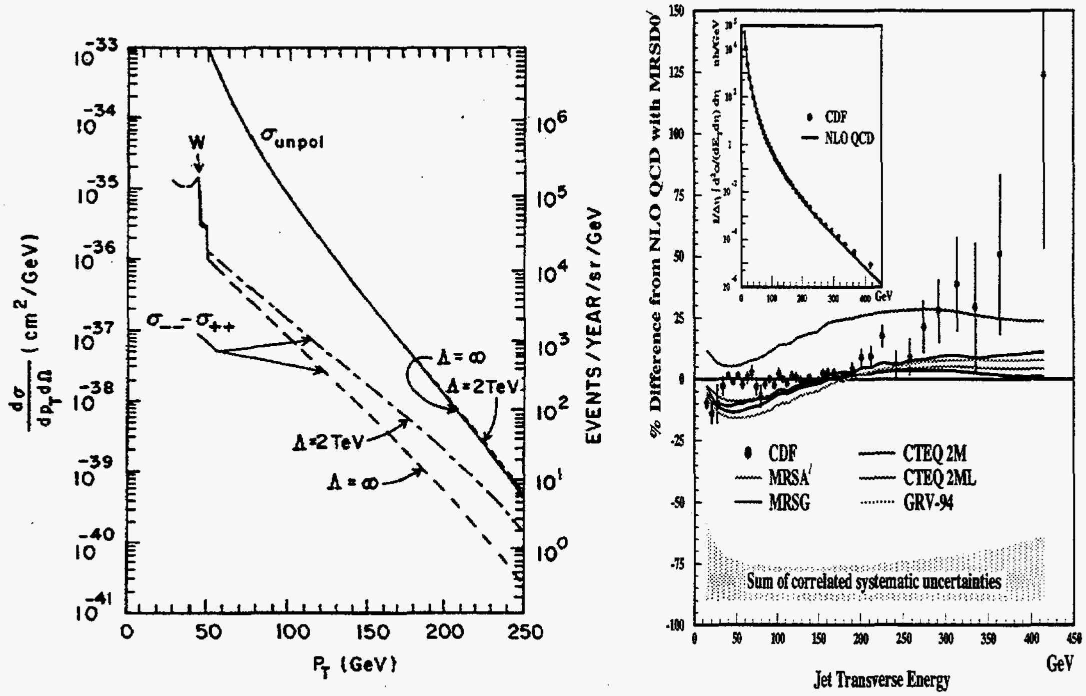

Figure 4: a) Prediction[13, 14] from 1983 for the effect of Quark Substructure on inclusive jet cross section with and without Parity Violation capability. b) Latest CDF[33] Inclusive jet cross section and ratio to NLO QCD.

Although this limit is well above the RHIC c.m. energy, the PVA signature provides such a sensitive probe that the substructure could be measured at RHIC up to values of $\Lambda_c \sim 2 - 3$ TeV. The limit of the sensitivity is set by the standard model PVA in inclusive jet production due to the interference of gluon and W exchange in the constituent scattering! (See Fig. 5.) The latest calculation[35] of the substructure PVA for jet production at RHIC by Taxil and Virey (with sensitivity estimates for $\Delta\eta = 1$ jet acceptance, typical of STAR) nicely illustrates the potential for new physics discoveries at RHIC by the search for Parity

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[c] There is a factor of 4 dilution of the substructure effect in the spin-averaged cross section[13] in this model.

Violating Asymmetries in strong interaction processes.[d]

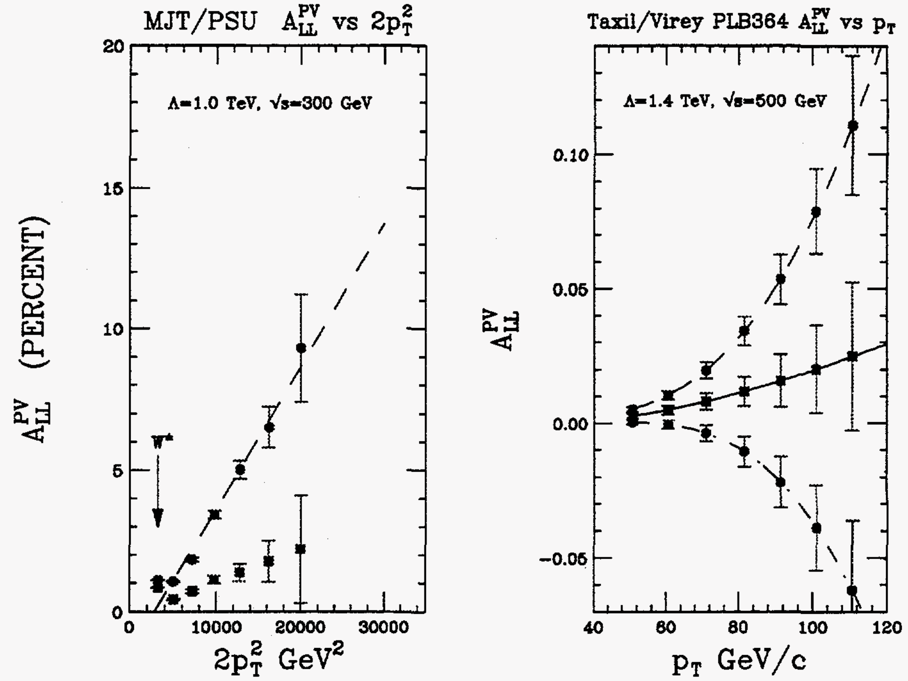

Figure 5: a) Predicted[13, 29] single jet A_{LL}^{PV} for quark substructure $A = -1$ (circles) versus $2p_T^2 \sim -\hat{t}$. The squares are the standard model PVA from $W^{\pm}$ production (arrow) and W-gluon interference. b) Latest calculation for RHIC[35] versus p_T for substructure with $A = \pm 1$ (circles) and W-gluon interference (squares). The errors on (b) indicate sensitivity estimates for RHIC.

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References

[1] M. W. McNaughton, *et al., Phys. Rev.* **C53**, 1092 (1996).

[2] See, for example, J. F. Owens, *Rev. Mod. Phys.* **59**, 465 (1987)

[3] J. Babcock, E. Monsay and D. Sivers, *Phys. Rev.* **D19**, 935 (1979).

[4] N. S. Craigie, K. Hidaka, M. Jacob and F. M. Renard, *Phys. Rep.* **C99**, 69 (1983).

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[d] Of course, if the effect is in the gluon structure function as some claim[36], we measure that too.

[5] G. E. Uhlenbeck and S. Goudsmit, *Naturwiss.* **13**, 953 (1925); *Nature* **117**, 264 (1926). See also, C. N. Yang in Reference [10].

[6] Thanks to Bob Crease for confirming this tidbit.

[7] M. Goldhaber, L. Grodzins and A. W. Sunyar, *Phys. Rev.* **109**, 1015 (1958).

[8] See, for example, E. D. Courant in *High Energy Physics with Polarized Beams and Polarized Targets, Proceedings of the 1980 International Symposium*, Eds. C. Joseph and J. Soffer (Birkhauser, Basel, 1981), pp 102-109.

[9] D. G. Crabb, *et al., IEEE Trans. Nucl. Sci.* **NS-26**, 3202 (1979). Also see, for example, L. G. Ratner in Reference [10], pp 412 - 418.

[10] *AIP Conf. Proc.* **95**, *High Energy Spin Physics-1982*, Ed. Gerry M. Bunce (American Institute of Physics, New York 1983).

[11] F. E. Paige, T. L. Trueman and T. N. Tudron, *Estimates of W production with polarized protons as a means of detecting its hadron jet decays*, *Phys. Rev.* **D19**, 935 (1979); R. F. Peierls, T. L. Trueman and L.-L. Wang, *Estimates of production cross sections and distributions for W bosons and hadronic jets in high-energy pp and $\bar{p}p$ collisions*, *Phys. Rev.* **D16**, 1397 (1977).

[12] G. Bunce, et al., *W, Z^0 Production at a PP collider*, Proceedings of the 1982 DPF Summer Study on Elementary Particle Physics and **Future Facilities**, June 28-July 16, 1982, Snowmass, CO, eds. R. Donaldson, R. Gustafson and F. Paige, pp 489-499.

[13] F. E. Paige and M. J. Tannenbaum, *QCD Tests with Polarized Beams at CBA*, BNL-33119, March 1983 (unpublished).

[14] R. Longacre and M. J. Tannenbaum, *QCD Tests and Large Momentum Transfer Reactions at CBA*, BNL-32888, March 1983 (unpublished). See also CBA Newsletter 4, March 1983, BNL; and R. Ruckl, *J. Phys.* **46** (1985) C2-55, T. L. Truemen, *ibid.* C2-721.

[15] *Proceedings of the Polarized Collider Workshop*, University Park, PA (1990), eds J. Collins, S. Heppelmann and R. W. Robinett, AIP conf. proc. No. 223, (AIP, New York, 1991).

[16] M. Beddo, *et al., Proposal on Spin Physics Using the RHIC Polarized Collider*, submitted August 19, 1992, BNL; Update submitted Sept 2, 1993.

[17] See, also, G. Bunce, *et al., Polarized protons at RHIC, Particle World,* **3**, 1 (1992).

[18] For further information see http://www.rhic.bnl.gov/

[19] PP2PP Collaboration, W. Guryn, *et al., Experiment to Measure Total and Elastic $p-p$ cross sections at RHIC*, Updated Version, September 1995, BNL.

[20] Claude Bourrely and Jacques Soffer, *Parton Distributions and Parity-Violating Asymmetries in $W^{\pm}$ and Z Production at RHIC*, *Phys. Lett.* **B314**, 132 (1993).

[21] R. Cutler and D. Sivers, *Phys. Rev.* **D16**, 679 (1977); **D17**, 196 (1978).

[22] B. L. Combridge, J. Kripfganz and J. Ranft, *Phys. Lett.* **70B**, 234 (1977).

[23] A. P. Contogouris, *et al., Phys. Rev.* **D48**, 4902 (1955).

[24] H. Fritzsch and P. Minkowski, *Phys. Lett.* **69B**, 316 (1977). Also, see, for example, *Proceedings of the International Workshop on QUARK GLUON PLASMA SIGNATURES*, Strasbourg, 1990, eds. V. Bernard, et al. (Editions Frontieres, Gif-sur-Yvette, France, 1991).

[25] M. E. Beddo, H. Spinka and D. G. Underwood, ANLHEP internal report, June 25, 1992.

[26] T. Goldman and D. Preston, *Prediction of a Large Parity-Violating Total Cross Section Asymmetry at High Energies*, *Phys. Lett.* **168B**, 415 (1986).

[27] G. Ranft and J. Ranft, *Phys. Lett.* **87B**, 122 (1979); F. E. Paige, in *Workshop on the Production of New Particles*, Madison WI, 1979, (BNL-27066).

[28] G. Altarelli and L. DiLella, *Proton-Antiproton Collider Physics*, (World Scientific, Singapore, 1989).

[29] M. J. Tannenbaum, *Polarized Protons at RHIC*, in reference 15.

[30] E143 Collaboration, K. Abe *et al., Phys. Rev. Lett.* **74**, 346 (1995).

[31] Claude Bourrely and Jacques Soffer, *Nucl. Phys.* **B445**, 341 (1995).

[32] E. J. Eichten, K. D. Lane and M. E. Peskin, *Phys. Rev. Lett.* **50**, 811 (1983).

[33] CDF Collaboration, F. Abe, *et al., Phys. Rev. Lett.* **68**, 1104 (1992); *ibid.* **77**, 438 (1996). See also New York Times, Feb 8, 1996.

[34] P. Taxil, *Beyond the Standard Model with Polarized Beams at Future Colliders*, in reference 15.

[35] P. Taxil, J. M. Virey, *Phys. Lett.* **B364**, 181 (1995).

[36] J. Huston, *et al., Phys. Rev. Lett.* **77**, 446 (1996).