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SPIN PHYSICS AT RHIC
A NEW TWIST ON THE HEAVY ION EXPERIMENTS *

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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 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

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 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.

1. Introduction

More than 12 years ago, in May 1983, I gave a talk at BNL to the "Polarized Proton Beam Collaboration Meeting", organized by Alan Krisch, on "Measuring and using Polarized Protons at CBA" which was based principally on the work of Larry Trueman[1], Frank Paige[2], Gerry Bunce[3], Ron Longacre[4] and myself, with many other collaborators. This work was started[3] at Snowmass '82 and has continued (with a few notable interruptions) to the present day. In April 1989, pursuant to a recommendation of a BNL Physics Department Committee (of which I was a member) on "the Future of High Energy Physics at BNL", Sam Aronson, then deputy chairman, and Larry Trueman, then Associate Director, set up a task force (to start after the approval of RHIC) with Gerry Bunce and myself as co-leaders "including accelerator physicists...and theorists..." "to lay out the potential physics program...with polarized protons at RHIC." The approval of RHIC, in January 1990, led to the Polarized Collider Workshop[5] at Penn State in November 1990 at which 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 letter of intent was submitted in April 1991, and, in September 1992, the RHIC Spin Collaboration presented a proposal (R5) to the BNL HENP Program Advisory Committee for a program of Spin Physics using the RHIC Polarized Collider[6,7]. After

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several intermediate reviews of the physics and technical capability, final physics approval was given in October 1993. The proposal was in three parts. The first part, written by the original RHIC Spin Collaboration, was 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. This was followed by specific proposals by PHENIX and STAR for experiments to survey spin phenomena using the two major heavy ion detectors[8].

There are now three approved spin experiments, PHENIX/Spin, STAR/Spin, and (approved in 1995) PP2PP/Spin. These spin experiments are now all part of the responsibility of their full collaborations. There is also a Spin Accelerator Collaboration group in the RHIC collider division which is responsible for the design, construction, and installation of accelerator spin components, and the commissioning of the colliding polarized beams. Tom Roser is Spokesperson for the accelerator group. The original RHIC Spin Collaboration (RSC) still exists and retains the role to coordinate physics and accelerator issues that are common to the experiments.

Two major milestones occurred for PHENIX/Spin and RHIC/Spin this year. The 'Physics of Spin at RHIC' was reviewed for the BNL directorate in June 1995 by a panel of outside experts chaired by Charlie Prescott of SLAC. Their comments were very positive: "if sensitivities are reached, the results will be profound and form a cornerstone of the theory of hadronic structure." This led to the second major milestone, the signing of the BNL-RIKEN Agreement on Spin Physics, September 25, 1995 at BNL. 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 to implement the BNL-RIKEN RHIC/Spin program. Half the money will be used to build and install the Siberian snakes, spin rotators, polarimeters and other hardware needed to collide spin-polarized nucleons at RHIC. The other half goes to provide a second muon arm for PHENIX as outlined in the proposal[9] for an "Upgraded PHENIX Muon Spectrometer", approved in November 1994.

2. 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 in excess of 200 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 and further details in Tom Roser's presentation.) 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 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.

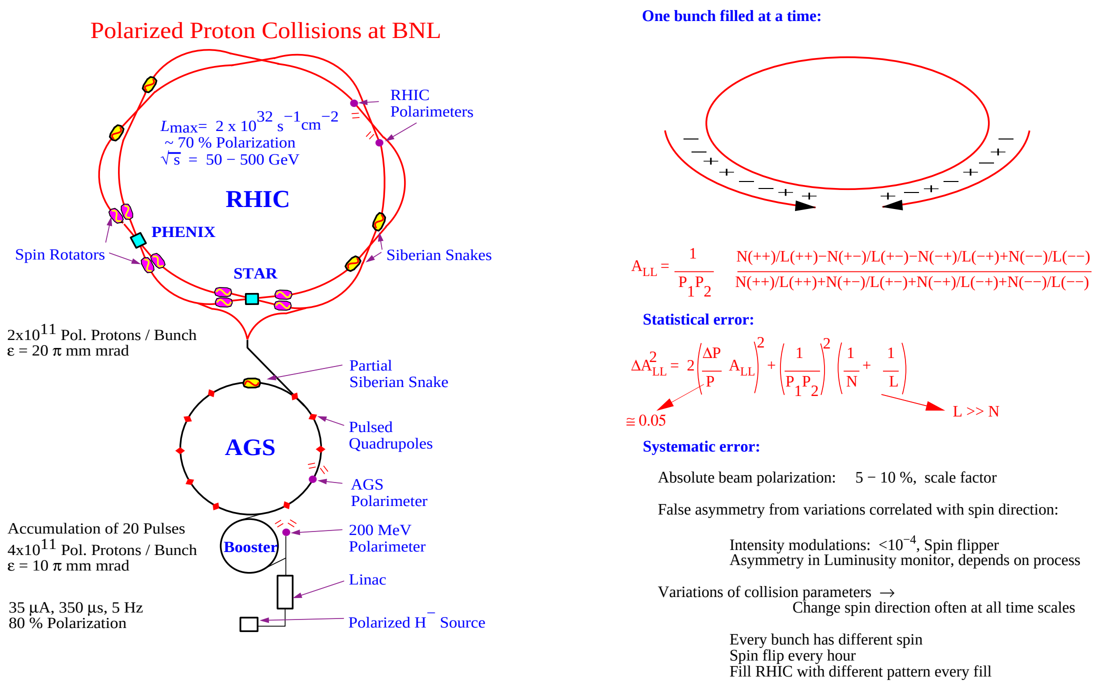

Fig. 1. a) Scheme for Polarized Proton Collisions at RHIC. b) Scheme for bunch polarization to minimize systematic errors

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.[a] 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 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

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

principle, and, for the cases of polarized d or ^{3}He, under active study.

3. Asymmetry measurements—statistical and systematic errors

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 and further details in Tom Roser's presentation.) 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.

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

For a longitudinally polarized proton beam the polarization has two possible states, parallel to the momentum ('+' helicity) or opposite to the momentum ('−' helicity). For the case of two polarized beams, the typical observable is the two-spin longitudinal asymmetry. 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:

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

3.2. Parity Violating Asymmetries (PVA's)

Three[10] 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[2] (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[2,10]. There is also the anti-symmetric two-spin parity-violating asymmetry[10] where the beams have opposite helicities.

3.3. 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.

4. Goals and Capabilities of the RHIC/Spin Program

The philosophy of the RHIC/Spin program is to use the existing major detectors[8], 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.

4.1. The Major Detectors

The two major detectors for the RHIC heavy ion program are STAR and PHENIX. STAR, which emphasizes hadron physics, is a TPC covering the full azimuth over ± 1 unit of pseudorapidity, for the purpose of charged particle tracking in a magnetic field of 0.5 Tesla. The TPC is surrounded by a system of Time of Flight counters, for particle identification, and a moderate resolution ($15\%/\sqrt{E}$) electromagnetic calorimeter, for measuring π^0 production and charged-neutral energy correlations. The detector is completed by a Silicon Drift Vertex Tracker, for measurements of Hyperons, and possible TPC's external to the magnet, for tracking at small angles $2.0 \leq |\eta| \leq 4.5$.

PHENIX, a very high granularity, high resolution detector for leptons and photons emerging from the Quark Gluon Plasma (QGP), emphasizes the ability to run at the highest luminosities with very selective triggers to find these rare events. PHENIX has a highly instrumented electron, photon and charged hadron spectrometer, in the central region $|\eta| \leq 0.35$, with full azimuth di-muon measurement in two endcaps, $1.15 \leq |\eta| \leq 2.35$. The electron/photon central spectrometer emphasizes electron identification at the trigger level, with RICH, TRD and EM calorimetry. The EM calorimeter, with energy resolution $\sigma_E/E = 7\%/\sqrt{E(\mathrm{GeV})}$, also serves as an excellent photon and π^0 trigger because of its 5 by 5 cm segmentation at 5.1 m. The central spectrometer consists of two arms, each subtending 90° in azimuth (Φ) and ± 0.35 units in pseudorapidity (η). The total coverage is 1/2 of the azimuth—however, the two arms are not back-to-back: the gap between the edges of the two 90° arms is 67.5° on one side and hence 112.5° on the other. The charged particle momentum resolution is 1% at 5 GeV/c, and charged hadron identification is provided by TOF(100ps) for 1/3 of the azimuth of one arm. In addition, a silicon detector array is installed over a wide rapidity region.

4.2. 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 $\sim 50\%$, 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.

5. MY Classification of Physics with Polarized Beams

I have previously[5,11] divided the study of spin effects into 3 classes:

HIGHBROW —Parity Violation—both the weak interaction effects, which are predicted to be large in this c.m. energy range; and possible new effects in this unexplored realm;

MIDDLEBROW —Parity Conserving longitudinal polarization effects, which are fundamental tests of the gauge structure of QCD; Spin Structure Function measurements;

LOWBROW —Transverse Polarization effects, which are large experimentally, but are not able to be explained theoretically; Polarization effects which QCD predicts to be zero, but which may not be; and polarization of final state particles with unpolarized initial states.

6. The Spin Structure of the Nucleon

The structure of the nucleon, including its spin structure, are fundamental issues of the utmost significance. Viki Weisskopf once told me that I'd know QCD was solved when there were "proton harmonics" for the proton wave function just like the "Coulomb wave functions" for the hydrogen atom. However, at the present time, the information on the structure of the nucleon comes predominantly from Deeply Inelastic lepton-nucleon Scattering (DIS). The original naive assumption was that the helicity of the proton is carried mainly by the valence quarks, roughly in proportion to the fraction of momentum they carry. However, after extensive work at SLAC, CERN (SMC) and by our theoretical colleagues, it is clear that the spin structure of the nucleon is "richer" than originally assumed—the sea quarks and gluons are polarized and carry a considerable fraction of the proton spin. Thus the spin structure function of the sea quarks and gluons must be measured in order to gain a full understanding of the spin structure of the nucleon. This is where RHIC can make an important contribution for the polarized structure functions, just as unpolarized hadron collisions have contributed to the sea-quark and gluon unpolarized structure functions[12].

7. Quantum Chromo Dynamics (QCD) and Hadron Collisions

QCD is a gauge theory of the strong interactions in which helicity plays as fundamental role[12,13,14] as "charge". 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. Curiously, perturbative QCD has received surprising little detailed verification in the hadron physics domain[15]: "Two of the most remarkable features of QCD are its conceptual simplicity on the one hand, and its success in resisting clear-cut experimental verification on the other."

One of the great difficulties of QCD in hadron physics is that experiments can not generally be performed directly on the basic constituents. However, measurements of 'hard,' or high momentum transfer, processes in $p-p$ collisions[12] are consistent with the picture of massless point-like quark and gluon constuents inside the proton which scatter quasi-elastically according to the basic QCD subprocesses. Of course, if the proton contains quarks and gluons, I like to make them do tricks—scatter them, flip their spin, or rotate them from longitudinal to transverse...

7.1. Constituent Subprocesses

The scattering cross sections for the constituent subprocess

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

is given by the formula

$$\frac{d\sigma^{ab}}{d\cos\theta^*} = \frac{\pi\alpha_s^2(Q^2)}{2\hat{s}}\Sigma^{ab}(\cos\theta^*) \tag{7}$$

where $\sqrt{\hat{s}}$ is the constituent c.m. energy and θ^* is the scattering angle in the constituent c.m. system. The characteristic subprocess angular distributions, $\Sigma^{ab}(\cos\theta^*)$, for scattering of the various constituents (see Fig. 2a) are fundamental predictions of QCD[16,17]. A distinctive and fundamental feature of QCD is the prediction of the strong coupling constant, $\alpha_s(Q^2)$, and its evolution, with a characteristic scale Λ, as a function of the four-momentum transfer-squared Q^2 of the reaction

$$\alpha_s(Q^2) = \frac{12\pi}{33 - 2N_f}\ln(Q^2/\Lambda^2) \qquad , \tag{8}$$

where $N_f \sim 4$ is the number of active quark flavors. The scale Λ is not predicted; and the exact meaning of Q^2 tends to be treated more as a parameter than a dynamical quantity. Evidently, for the case of constituent scattering, the Mandelstam invariants $\hat{s}$, $\hat{t}$ and $\hat{u}$ have a clear definition in terms of the c.m. scattering angle:

$$\hat{t} = -\hat{s}\,\frac{(1-\cos\theta^*)}{2} \qquad \text{and} \qquad \hat{u} = -\hat{s}\,\frac{(1+\cos\theta^*)}{2} \quad . \tag{9}$$

The transverse momentum of a scattered constituent is:

$$p_T = p_T^* = \frac{\sqrt{\hat{s}}}{2}\,\sin\theta^* \quad . \tag{10}$$

A naive experimentalist would think of $Q^2 = -\hat{t}$ for a scattering subprocess and $Q^2 = -\hat{s}$ for a Compton or annihilation subprocess.

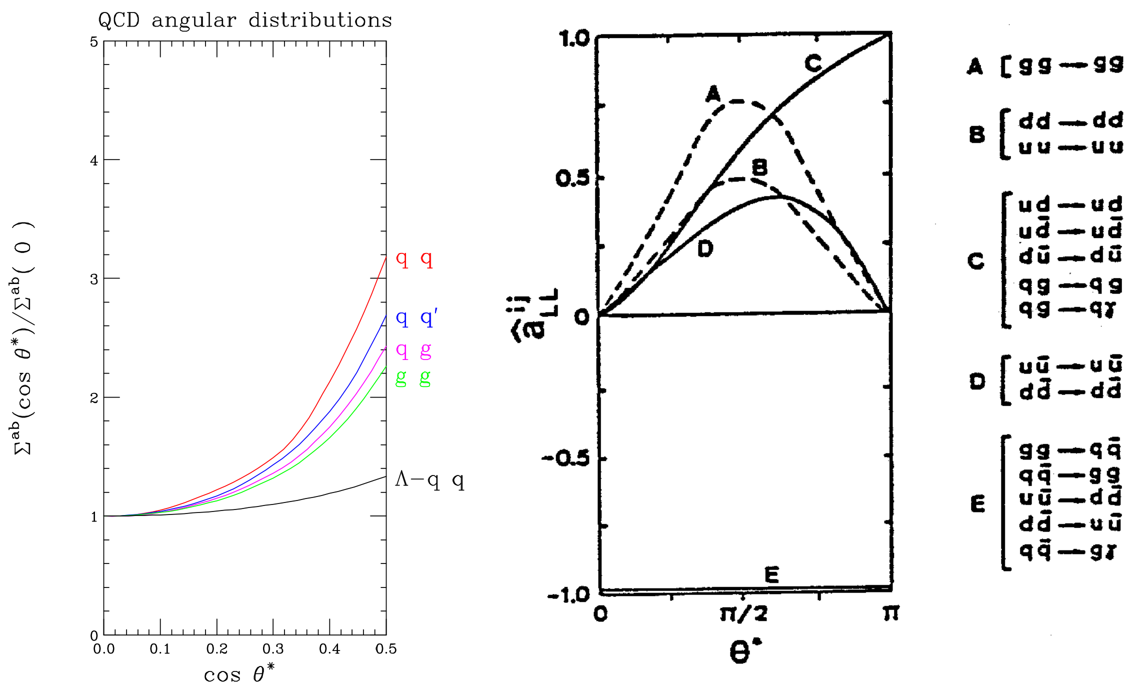

Fig. 2. Characteristic QCD Subprocess angular distributions: (a) scattering; (b) spin asymmetry

7.2. The cross section in $p-p$ 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. 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

$$x_1 = \sqrt{\frac{\hat{s}}{s}}e^{\hat{y}} \qquad x_2 = \sqrt{\frac{\hat{s}}{s}}e^{-\hat{y}} \quad . \tag{11}$$

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

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{s d^3\sigma}{d\hat{s} d\hat{y} d\cos\theta^*} = \sum_{ab} a(x_1) b(x_2) \frac{\pi\alpha_s^2(Q^2)}{2\hat{s}} \Sigma^{ab}(\cos\theta^*) \quad . \tag{12}$$

7.3. Structure Functions

The quantities $a(x_1)$ and $b(x_2)$ are the "number" distributions of the constituents, which are empirical (the theorists need us to measure them). However, in a triumph of the Standard Model, these distributions are related (for the electrically charged quarks) to the structure functions measured in DIS, e.g.

$$F_2(x, Q^2) = x \sum_a e_a^2 \, a(x, Q^2) \tag{13}$$

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 $1/s$

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s} \sum_{ab} a(x_1) b(x_2) \frac{\pi\alpha_s^2(Q^2)}{2 x_1 x_2} \Sigma^{ab}(\cos\theta^*) \tag{14}$$

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.

7.4. Spin QCD

The two-spin longitudinal asymmetry for the constituent reaction (Eqs. 6,7) is

$$A_{LL}(a+b \to c+d) = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \tag{15}$$

$$= \frac{\Delta a}{a} \frac{\Delta b}{b} \hat{a}_{LL}(a+b \to c+d) \quad , \tag{16}$$

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

$$\Delta a(x) = a^+(x) - a^-(x) \tag{17}$$

and the '+' and '−' refer to constituents with the same or opposite helicity as the parent proton. The spin asymmetry of the subprocess[13,14]

$$\hat{a}_{LL}(a + b \to c + d) \tag{18}$$

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

7.5. How to Measure the Constituent Kinematics in Hadron Collisions

This description and theory is now an important component of 'The Standard Model'. The main issue confronting experimentalists at hadron machines is to convince themselves and their colleagues that precision measurements of 'confined constituents' can be made. Incredibly, at Snowmass in July 1982, many (if not most) people were skeptical! The International HEP conference in Paris[18], three weeks later, changed everything, with the first observation of jets in a large aperture calorimeter by UA2 at the CERN collider[19], and the first measurement of the constituent scattering angular distribution (using pairs of leading π^0) by CCOR at the CERN ISR[20].

The steeply falling structure functions and constituent cross sections lead to a Jacobean peaking at 90° in the $p - p$ c.m. system, so that the most likely origin for a jet observed with large transverse momentum, p_T, is from constituent scattering with the same c.m. system as the $p - p$ c.m. system ($\hat{y} = 0$), and with c.m. scattering angle $\theta^* = 90°$, so that

$$x_T = \frac{p_T}{\sqrt{s}/2} \simeq x_1 \simeq x_2 \quad . \tag{19}$$

Of course, if the other constituent is detected, then the full constituent kinematics can be reconstructed from the invariant mass-squared ($\hat{s}$) and net rapidity ($\hat{y}$) of the pair[20,12]. Jets are taken to represent constituents, and inclusive high p_T particles are taken to represent the leading fragments of jets[12]. Since for jet fragmentation (as in particle production), the $\langle p_t \rangle$ of a fragment relative to the jet axis is $\sim 300 - 500$ MeV/c, a particle with $p_T \geq 10$ GeV/c is quite close to the axis of its parent jet. The typical fragmentation probability[21] to pions is e^{-6z}, where z is the momentum fraction of the parent constituent carried by the pion fragment.

8. Polarization Tests of QCD and Polarized Structure Functions

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[5] because the proton polarization is not appreciably transmitted to the constituents, unless $x \geq 0.3$. Suffice it to say that the only existing measurement of a polarization effect expected to obey the predictions of QCD, involves the angular distribution of muon pairs produced at large mass and transverse momentum by a π^- beam[22,23]. The plane of the lepton pair shows a large azimuthal asymmetry with respect to the production plane—*which is not in accord with QCD predictions*[22,23].

8.1. The Spin Structure Function of the Gluon—Direct Photon Production

A school of thought, led by Jacques Soffer, has claimed for some time that QCD perturbation theory leads to strong polarization of gluons, at large Q^2, independently of any constraint that deep-inelastic lepton scattering data may provide for the distribution of the spin of the nucleon among its constituents. It is therefore important to measure the polarized structure function asymmetry, as directly as possible, in hard processes involving gluons, as well as quarks.

Direct photon production should be a clean measurement of the spin dependent gluon structure function since the dominant subprocess in pp collisions is

$$g + q \rightarrow \gamma + q \quad , \tag{20}$$

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 analysis of $\Delta G(x)$ from the measurement of the longitudinal spin asymmetry A_{LL} which is predicted[24] (in NLO) to be surprisingly large, in the range 10% to 20%.[b]

This is one of the favorite QCD reactions in hadron physics[25], 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[6,26] 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^0 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[6] for $p_T(\pi^0) \leq 25$GeV/c. For the worst case, where $\gamma_{real}/\pi^0 \sim 0.1$, $\gamma_{fake}/\gamma_{real}$ will be ~ 1 after the elimination of photons from reconstructed π^0's. The isolation cut will then bring $\gamma_{fake}/\gamma_{real}$ down to ~ 0.15, a factor of 6 improvement, and will also reduce any gammas from bremsstrahlung in jet fragmentation ($\sim$ 20% to 30% of the signal) to $\gamma_{brems}/\gamma_{real} \sim 0.05$.

Direct photon production is a single particle inclusive reaction, so the counting rates are trivial to calculate once the cross section is known. Furthermore, the

[b]Interestingly, in the PHENIX/Spin proposal, we noted that "in the case of transverse spin asymmetry, A_{NN}, the contribution from the Compton process vanishes and only the annihilation process contributes to the photon production asymmetry, which relates to the transversity of the quark polarization, the $h_1(x)$ structure function. An A_{NN} signal from $q\bar{q}$ annihilation is diluted by a factor of 10 by the Compton process." Further discussions on this subject took place at this meeting.

measured cross section in $p - \bar{p}$ collisions[27] can be used since the process is gluon dominated. However to be conservative in our rate estimates[6], we use the Lund Monte Carlo, PYTHIA, which gives predictions a factor of 2 lower than the measurements. (see Naohito Saito's presentation).

In STAR (see Aki Yokosawa's presentation), 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.

9. Transverse Polarization Effects and the New Physics of Transversity

This subject is the opposite of the preceding. Large effects have been observed—but there is no definitive theoretical framework. Examples include elastic scattering at the AGS[28] and a large single-spin transverse asymmetry in pion production at large x_F [29]. This is another subject that cries out for a systematic experimental program—to give the theorists some empirical insights into these large polarization effects, which LO-QCD predicts to be small. It is encouraging to note the renewed theoretical interest in transverse single-spin effects[30,31] and in the new physics of Transversity[32,7]—the possibility that the fraction of transverse polarization of a proton carried by its quarks could be different than the fraction of longitudinal polarization. For the latest word on Transversity, see Bob Jaffe's presentation.

10. 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[33]. Since these measurements represent heroic efforts, I feel that I must include the following disclaimer:

DISCLAIMER

- I have never measured an absolute cross section to better than a few percent.

- I have never published an asymmetry measurement.

BUT

- I routinely tune my SWradio to $\sim$ ppm ($\sim$ 20 Hz cf 15.000000 MHz).

11. Why Parity Violation?

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...

11.1. 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.

Everybody has their own stories, but these criteria were developed the hard way. In the late 1960's, I thought that the dilepton channel, particularly with an incident muon, satisfied all of these same criteria[34]. In the intervening quarter century, this channel was indeed the major source of discovery[35,36,37,38]. I feel that parity violation searches offer the same discovery potential today!

12. "Large" effects at RHIC?

"Conventional" parity violating effects are predicted to be "large" at RHIC. 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[2,39] 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.

13. Weak Boson Production

The "classical" parity violating processes are the production of the Intermediate Vector Boson $W^\pm$ of the weak interactions, and its leptonic decay $W^\pm \to e^\pm + \nu$. In the 1982 Snowmass Study[3], the suggestion was made to use the parity violating production process to extract the hadronic decay channel $W^\pm \to$ di-jets from the enormous hadronic background. The predicted PVA is really **HUGE** at production[1], on the order of **UNITY**. However this gets diluted by the leading QCD di-jet background to become a 0.5% effect at the W peak. Nevertheless, the conclusion was that the $W^\pm \to$ di-jet decay would give a clear signal from the parity violating asymmetry, with minimal background uncertainty.

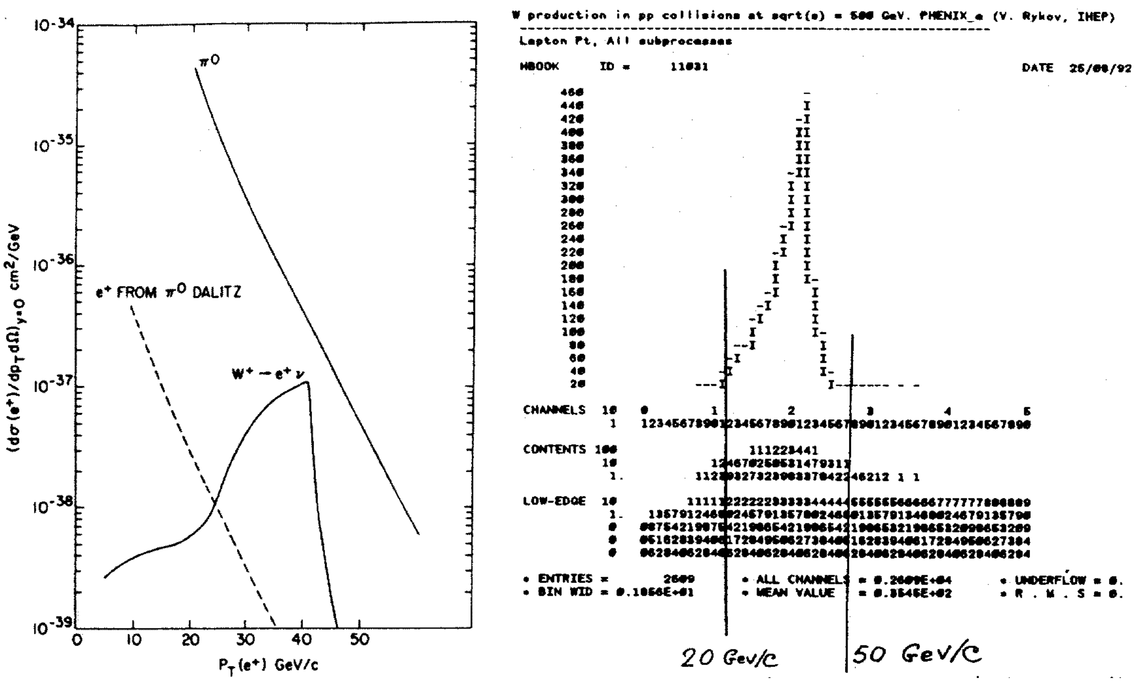

Fig. 3. a) Predicted p_T spectrum at $\sqrt{s}$=300 GeV from inclusive π^0, background e^+ from Dalitz decay of π^0, and e^+ from W^+ decay[11]. b) Simulation of the inclusive $e^\pm$ Jacobean peak in PHENIX from 20,000 $W^\pm \to e^\pm + X$ decays[41]. The 2609 entries in the histogram give the 13% acceptance in this channel.

A much more spectacular channel is the leptonic decay $W^\pm \to e^\pm + X$, where the X means that the measurement is via the inclusive $e^\pm$ channel with no "missing energy" detection. This is a textbook example[40] of a process with virtually no background. A prediction of the cleanliness of this channel dating from Snowmass[11,3]is shown in Fig. 3a, with a more recent simulation[41] of the Jacobean peak in the PHENIX central spectrometer shown in Fig. 3b. In order to obtain a clean sample of $e^\pm$ from $W^\pm$ decays, one needs the following[40]:

- 10^{-3} charged hadron rejection for $p_T \geq 10$ GeV/c,
- Precision EM Calorimetry out to 50 GeV,
- Momentum Resolution sufficient to resolve the charge of $e^\pm$ out to 50 GeV/c,
- A good trigger, as $W^\pm$ is only $\sim 10^{-8}$ of the total cross section.

This will be no problem for PHENIX. The EM calorimeter will provide a factor of more than 500 rejection for charged pions above 10 GeV; and an isolation cut should provide an additional factor of $\sim 5-7$ rejection against hadrons (and Dalitz pairs) from jets[6]. In fact, the main background for W^- may be the e^- from Z^0 decay. Furthermore, even though PHENIX has a relatively small aperture, $|\eta| \leq 0.35$, $\Delta\phi = \pi$, the acceptance[41] for the $W^\pm \to e^\pm + X$ channel is 13%, so that ~ 120 $W^+ \to e^+ + X$ and 40 $W^- \to e^- + X$ **per day** will be collected. The momentum resolution of 10% at 50 GeV/c gives excellent charge separation. This should allow the parity violating spin asymmetry for production of real W's to be observed for the first time. Even more interesting effects occur in the two muon arms which are at forward and backward angles (see Naohito Saito's presentation).

The counting rates in STAR, with larger aperture, will be nearly an order of magnitude larger, bringing towards reality something that I only dared to dream just a few years ago[11], *"By measuring the PVA for the reaction $W \to e + X$ as a function of $\sqrt{s}$, the spin dependent structure functions of the proton can be measured at values of $x \sim m_W/\sqrt{s}$."*

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

An article by Bourrely and Soffer[10] 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

$$pp \to W^\pm + \text{ anything} \tag{21}$$

is given in leading order[10] by the quark-antiquark fusion reactions $u\bar{d} \to W^+$ and $\bar{u}d \to W^-$,

$$\frac{d\sigma^{W^+}}{dy} = G_F \pi \sqrt{2} \tau \frac{1}{3}[u(x_1, M_W^2)\bar{d}(x_2, M_W^2) + \bar{d}(x_1, M_W^2)u(x_2, M_W^2)] \tag{22}$$

$$\frac{d\sigma^{W^-}}{dy} = G_F \pi \sqrt{2} \tau \frac{1}{3}[d(x_1, M_W^2)\bar{u}(x_2, M_W^2) + \bar{u}(x_1, M_W^2)d(x_2, M_W^2)] \tag{23}$$

where G_F is the Fermi constant and $u(x)$ and $\bar{d}(x)$ are the structure functions of u and $\bar{d}$ quarks in the proton at momentum fraction x, and $Q^2 = M_W^2$. The computed W^+ production cross section[10] is given in Fig. 4a and shows a surprisingly large variation due to the still large uncertainty of the anti-quark structure functions. The kinematics are given simply by the production of a constituent state with $\hat{s} = M_W^2 = x_1 x_2 s$ at rapidity $y = \frac{1}{2} \ln \frac{x_1}{x_2}$. For the ultimate in structure function measurements, it is likely that "missing energy" detection would be desirable—to allow reconstruction of the momentum of the W.

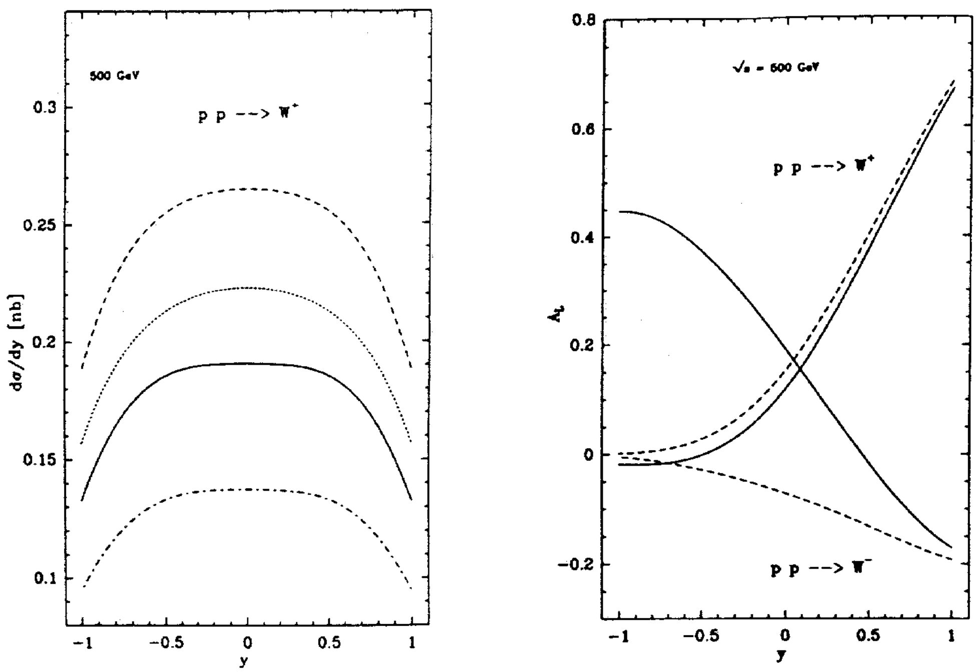

Fig. 4. a) $d\sigma/dy$ versus y for W^+ production at $\sqrt{s} = 500$ GeV for different choices of the anti-quark distributions[10]. b) The single-spin parity violating asymmetry A_L versus y for W^+ and W^- production. The solid lines correspond to a reasonable choice for the sea-quark polarization[10] and the dashed lines correspond to $\Delta\bar{u} = \Delta\bar{d} = 0$.

The parity violating asymmetry for W^+ production is given by[10]

$$A_L^{W^+}(y) = \frac{\Delta u(x_1, M_W^2)\bar{d}(x_2, M_W^2) - \Delta\bar{d}(x_1, M_W^2)u(x_2, M_W^2)}{u(x_1, M_W^2)\bar{d}(x_2, M_W^2) + \bar{d}(x_1, M_W^2)u(x_2, M_W^2)} \tag{24}$$

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[10]

$$A_{LL}^{PV}(y) = A_L(y) + A_L(-y) \quad . \tag{25}$$

The single-spin asymmetry $A_L^{W^\pm}$ is shown in Fig. 4b[10], and is huge as previously advertised. This figure illustrates the amusing feature of the single-spin asymmetry—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.*" The sensitivity to the spin structure function is much larger for the W^- than the W^+, which is easy to understand by a simple argument[10]: near $y = 0$, the PVA's are given to a good approximation by

$$A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta u}{u} - \frac{\Delta \bar{d}}{\bar{d}}\right) \quad \text{and} \quad A_L^{W^-} = \frac{1}{2}\left(\frac{\Delta d}{d} - \frac{\Delta \bar{u}}{\bar{u}}\right) \quad , \tag{26}$$

and $\Delta u/u$ is large. 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, $x_1 \ll x_2$, $A_L^{W^+} \simeq -\Delta\bar{d}/\bar{d}$, $A_L^{W^-} \simeq -\Delta\bar{u}/\bar{u}$.

This could be the birth of *Structure Function Physics* **using parity violation as a tool**. The expected sensitivities for spin-structure measurements in PHENIX with the latest Bourrely and Soffer polarized structure functions[42] are shown in Fig. 5. Table 1 gives an overall PHENIX/STAR comparison.

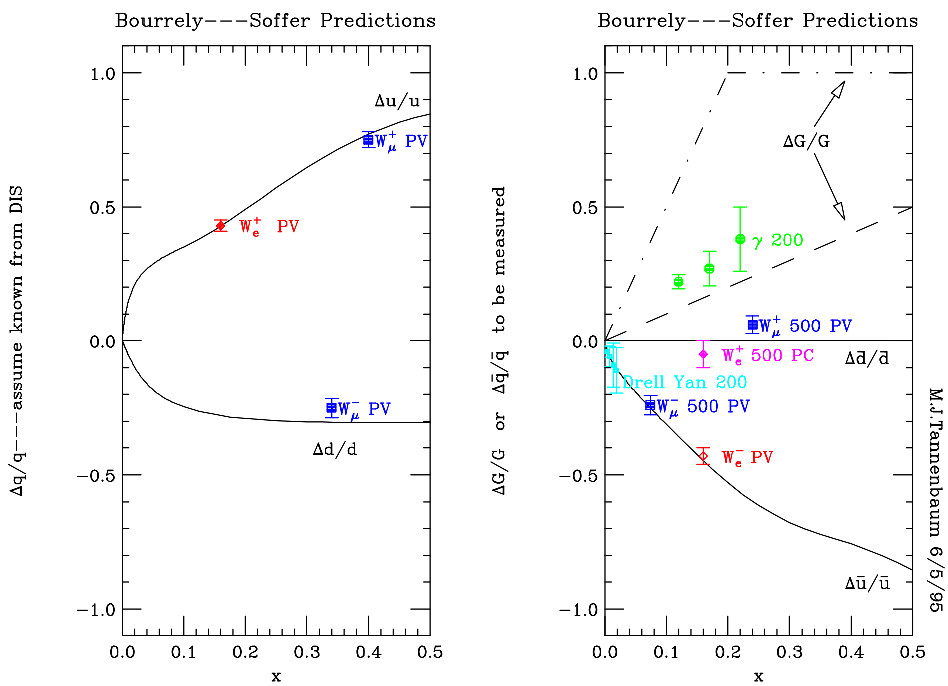

Fig. 5. Expected sensitivities for spin-structure function measurements in PHENIX shown with Bourrely-Soffer distributions[42] for 800 pb^{-1} at $\sqrt{s} = 500$ GeV and 320 pb^{-1} at $\sqrt{s} = 200$ GeV

15. New Physics—Surprises

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[43]. 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[43] contains an explicitly parity-violating left-left contact interaction between quarks, which results in a PVA in jet production[2,4], as well as a slight increase in the jet cross section at large p_T (See Fig. 6a).[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[44] is a case in point (see Fig. 6b). If the "% Difference from NLO QCD" were "% Parity Violation", the parity-violating signature would be **a clear indication of new physics**[11,45]. The limit is presently[44] $\Lambda_c \cong 1.4 - 1.6$ TeV.

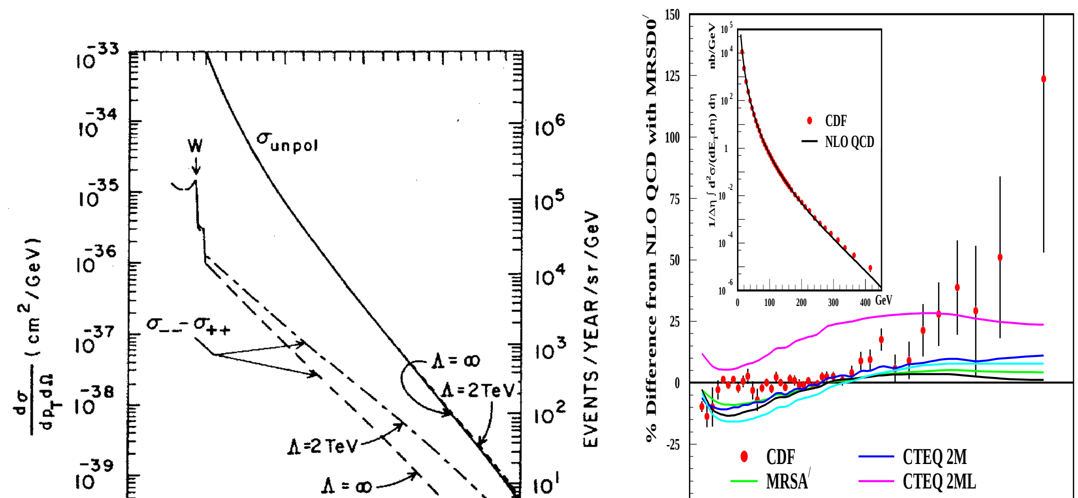

Fig. 6. a) Prediction[2,4] from 1983 for the effect of Quark Substructure on inclusive jet cross section with and without Parity Violation capability. b) Latest CDF[44] Inclusive jet cross section and ratio to NLO QCD.

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

[c]There is a factor of 4 dilution of the substructure effect in the spin-averaged cross section[2] in this model.

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! Furthermore, Λ_c can be directly determined[11] by the dependence of the PVA on p_T—thus, the handedness and other details of any new coupling can be measured. This is easy to understand in the limit of large Bjorken x, where the identical quark (uu) subprocess dominates. Since the the cross-section is dominated by one QCD subprocess and the substructure scattering is 100% Parity Violating, the PVA can be well estimated from the subprocess distributions:

$$A_{LL}^{PV} \simeq 2\,\frac{\Delta q(x)}{q(x)}\,\frac{\Sigma^{qq}_{\Lambda_c}(\cos\theta^*)}{\Sigma^{qq}_{QCD}(\cos\theta^*)} \quad \text{so} \quad A_{LL}^{PV}(90^\circ) \cong -2\,\frac{\Delta u(x)}{u(x)}\,\frac{12}{11}\,\frac{A\hat{s}}{\alpha_s\Lambda_c^2}\ . \qquad (27)$$

The effect, which depends on $x \simeq x_T$ and $\cos\theta^*$, with a factor of $-A\hat{s}/\alpha_s\Lambda_c^2$ ($A=\pm1$), is maximum at 90°, $\cos\theta^*=0$, where $\hat{s}=-2\hat{t}=4p_T^2$. My simple parameterization[11] of the original calculation[2,4] (see Fig. 7) did not explicitly mention $\Delta u/u$, since the "conservative SU(6)" spin-structure functions used at the time had constant $\Delta u/u$ for $x \geq 0.2$. The latest calculation[46] of this effect 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 Violating Asymmetries in strong interaction processes.

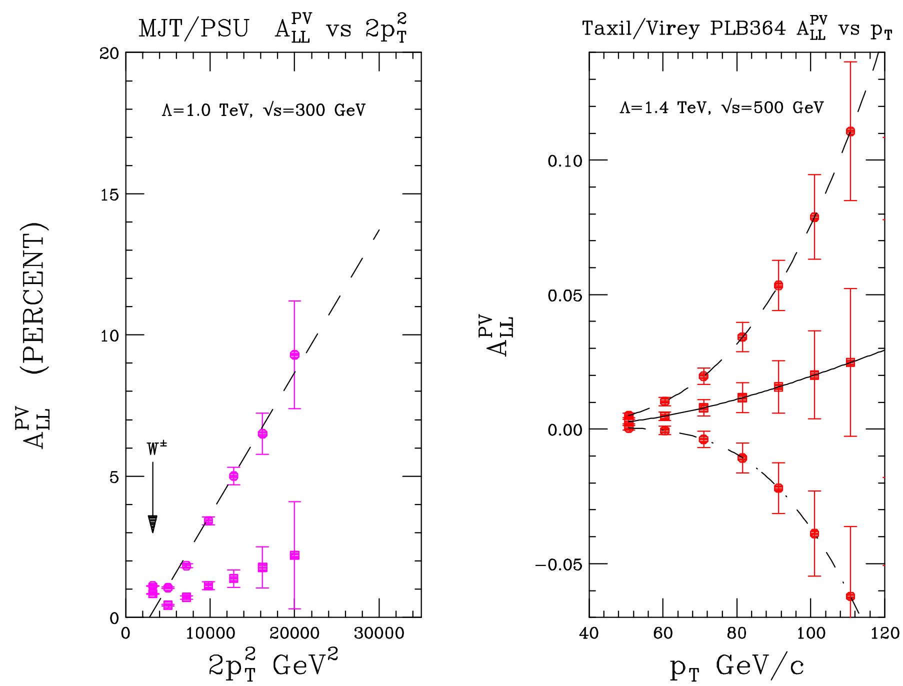

Fig. 7. a) Predicted[2,11] single jet A_{LL}^{PV} for quark substructure $A=-1$ (circles) versus $2p_T^2 \sim -\hat{t}$. The squares are the standard model PVA from $W^\pm$ production (arrow) and W-gluon interference. b) Latest calculation for RHIC[46] versus p_T for substructure with $A=\pm1$ (circles) and W-gluon interference (squares). The errors on (b) indicate sensitivity estimates for RHIC.

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 $\lvert\eta\rvert \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

16. Acknowledgement

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