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Parity Violation Experiments at RHIC

M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973

Abstract

With longitudinally polarized protons at RHIC, even a 1 month dedicated run utilizing both approved major detectors could produce a significant search for new physics in hadron collisions via parity violation. Additionally, in the energy range of RHIC, large "conventional" parity violating effects are predicted due to the direct production of the weak bosons $W^{\pm}$ and Z^0. One can even envision measurements of the spin dependent sea-quark structure functions of nucleons using the single-spin parity violating asymmetry of $W^{\pm}$ and Z^0.

1 Introduction

Almost 10 years ago, in May 1983, I gave a talk to the "Polarized Proton Beam Collaboration Meeting" at BNL on "Measuring and using Polarized Protons at CBA." This 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. Just last week, the RHIC Spin Collaboration (RSC), a collaboration of accelerator physicists, theoretical physicists and experimental physicists with a common interest in spin, presented a proposal (R5) to the BNL HENP Program Advisory Committee for a program of Spin Physics using the RHIC Polarized Collider[5]. With an investment of ~ *10M$* for Siberian Snakes and spin rotators, RHIC will be able to produce polarized proton collisions over a large energy range, $\sqrt{s}$ = 50 to 500 GeV, with high luminosity (reaching $\mathcal{L} = 2 \cdot 10^{32}$ cm^{-2} s^{-1}), and with large polarization, ~ 70% , in each beam. Both longitudinally and transversely polarized protons can be provided at the interaction regions, and frequent polarization sign reversal will allow the systematic errors to be minimized.

2 Disclaimer

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[6]. Since these people are all in the audience, 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 ~ ppm (*~ 20 Hz cf 15.000000 MHz*).

3 MY Classification of Physics with Polarized Beams

I have previously[7] 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;
- 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.

I note that recently[5] there is new interest in "Transverse spin." However, in this presentation, I shall concentrate on Parity Violation.

4 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...

Parity Violation searches at RHIC satisfy all my

Criteria for The Maximum Discovery Potential:

- Look where the 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[8]. In the intervening quarter century, this channel was indeed the major source of discovery[9, 10, 11, 12]. I feel that parity violation searches offer the same discovery potential today!

5 Why RHIC?

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.

Two parity violating asymmetries (PVA's) 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:

$$A_L = (\sigma_- - \sigma_+)/(\sigma_- + \sigma_+) \tag{1}$$

The second case involves flipping the helicities of both beams so that they are either left handed ($-$) or right handed ($+$). The two-spin parity-violating asymmetry (A_{LL}^{PV}) is defined as

$$A_{LL}^{PV} = (\sigma_{--} - \sigma_{++})/(\sigma_{--} + \sigma_{++}) \tag{2}$$

and is about twice as big as A_L. Assuming equal integrated luminosity for both spin configurations, with N the total number of events, the error on the measured asymmetry is approximately

$$\delta A_{LL}^{PV} = \frac{1}{P^2}\frac{1}{\sqrt{N}} \quad \text{and} \quad \delta A_L = \frac{1}{P}\frac{1}{\sqrt{N}} \tag{3}$$

where P is the polarization of both beams, taken as $P = 0.7$. The statistical error for parity violation searches in leading π^0 or direct γ production, for example[5], is in the range $\delta A_{LL}^{PV} \sim 0.1\%$ to 1%, for a 1 month run (10^6 sec).

"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 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[2, 13]. 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.

6 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.

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[14] of a process with virtually no background. A prediction of the cleanliness of this channel dating from Snowmass[7, 3]is shown in Fig. 1a, with a recent simulation[15] of the Jacobean peak in the PHENIX detector[16] shown in Fig. 1b. In order to obtain a clean sample of $e^\pm$ from $W^\pm$ decays, one needs the following[14]:

- 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. Furthermore, even though PHENIX has a relatively small aperture, $|\eta| \leq 0.35$, $\Delta\phi = \pi$, the acceptance for the $W^{\pm} \to e^{\pm} + X$ channel is 13% , so that ~ 3000 W^+ and 1000 W^- per month will be collected, for a sensitivity $\delta A_L^{W^+} = 0.025$. This should allow the parity violating spin asymmetry for production of real W's to be observed for the first time. The counting rates in STAR, the Solenoidal Tracker at RHIC[17], with larger aperture, $|\eta| \leq 2$, $\Delta\phi = 2\pi$, will be an order of magnitude larger, bringing towards reality something that I only dared to dream just a few years ago[7], *"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 $x \sim m_W/\sqrt{s}$."*

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

A recent article by Bourrely and Soffer[18] has 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

$$pp \to W^{\pm} + \text{ anything} \tag{4}$$

is given in leading order[18] by the quark-antiquark fusion reactions $u\bar{d} \to W^+$ and $\bar{u}d \to W^-$,

$$\frac{d\sigma^{W+}}{dy} = G_F\pi\sqrt{2}\tau\frac{1}{3}[u(x_1, M_W^2)\bar{d}(x_2, M_W^2) + (u \to \bar{d})] \tag{5}$$

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. The computed W^+ production cross section[18] is given in Fig. 2a 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 $\hat{s} = M_W^2 = x_1x_2s$ at rapidity $y = \frac{1}{2}\ln\frac{x_1}{x_2}$. For serious structure function measurements, it is likely that "missing energy" detection would be desirable—to allow reconstruction of the momentum of the W.

The parity violating asymmetry for W production is given by[18]

$$A_L(y) = \frac{\Delta u(x_1, M_W^2)\bar{d}(x_2, M_W^2) - (u \to \bar{d})}{u(x_1, M_W^2)\bar{d}(x_2, M_W^2) + (u \to \bar{d})} \quad , \tag{6}$$

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[18]

$$A_{LL}^{PV}(y) = A_L(y) + A_L(-y) \quad . \tag{7}$$

The single-spin asymmetry A_L^W is shown in Fig. 2b[18], 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[18]: near y=0, the PVA's are given to a good approximation by

$$A_L^{W+} = \frac{1}{2}\left(\frac{\Delta u}{u} - \frac{\Delta\bar{d}}{\bar{d}}\right) \quad \text{and} \quad A_L^{W-} = \frac{1}{2}\left(\frac{\Delta d}{d} - \frac{\Delta\bar{u}}{\bar{u}}\right) \quad , \tag{8}$$

and $\Delta u/u$ is large.

This could be the birth of *Structure Function Physics* **using parity violation as a tool.**

8 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[19]. 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[19] contains an explicitly parity-violating left-left contact interaction between quarks, which results in a PVA proportional to $(p_T/\Lambda_c)^2$ in jet production[2, 4]. 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. However, the parity-violating signature would be **a clear indication of new physics.** Furthermore, Λ_c can be directly determined[7] by the dependence of the PVA on p_T—thus, the handedness and other details of any new coupling can be measured. The limit is presently[20] $\Lambda_c \geq 1.4$ TeV. 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 $\Lambda_c \sim 2$ 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 reference [7] for further details.

9 Acknowledgement

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DISCLAIMER

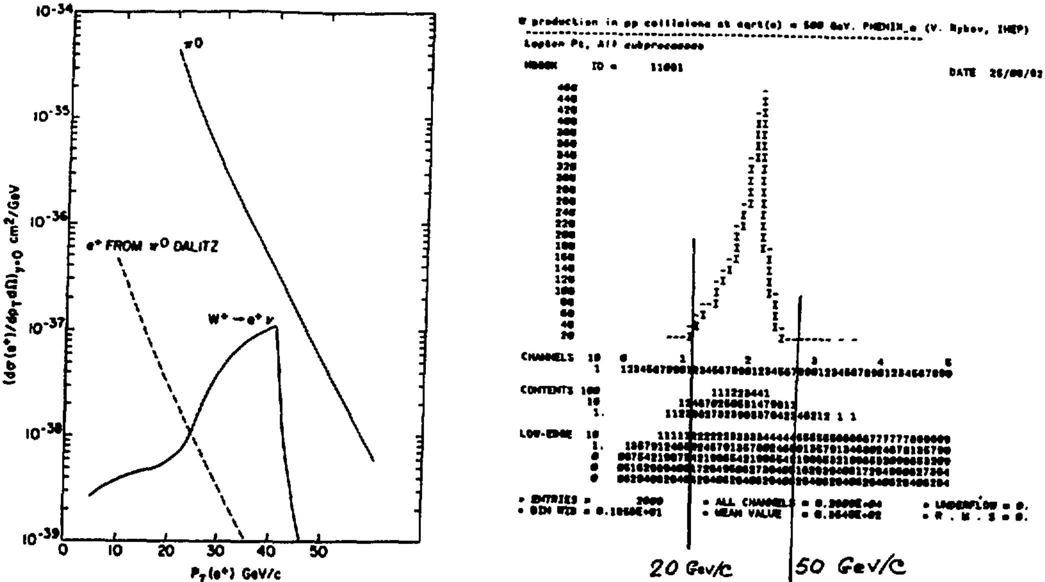

Figure 1: a) Predicted p_T spectrum at $\sqrt{s}$=300 GeV from inclusive π^0, background e^+ from Dalitz decay of π^0, and e^+ from W^+ decay [7]. b) Simulation of the inclusive $e^\pm$ Jacobean peak in PHENIX from 20,000 $W^\pm \to e^\pm + X$ decays [15]. The 2609 entries in the histogram give the 13% acceptance in this channel.

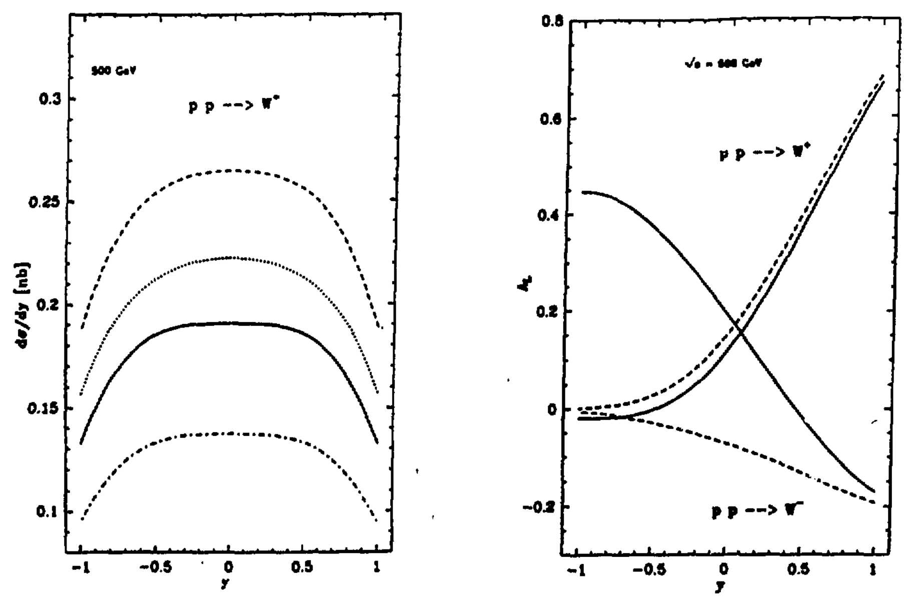

Figure 2: a) $d\sigma/dy$ versus y for W^+ production at $\sqrt{s}$ = 500 GeV for different choices of the anti-quark distributions [18]. b) The single-spin parity violating asymmetry A_L versus y for W^+ and W^- production. The solid lines correspond to a reasonable choice for the sea-quark polarization [18] and the dashed lines correspond to $\Delta\bar{u} = \Delta\bar{d}$ =0.