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POLARIZED PROTONS AT RHIC

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ABSTRACT

The Physics case is presented for the use of polarized protons at RHIC for one or two months each year. This would provide a facility with polarizations of $\gtrsim$50%, high luminosity $\sim 2.0 \times 10^{32}$ cm^{-2} s^{-1}, the possibility of both longitudinal and transverse polarization at the interaction regions, and frequent polarization reversal for control of systematic errors. The annual integrated luminosity for such running ($\sim 10^6$ sec per year) would be $\int \mathcal{L}dt = 2 \times 10^{38}$ cm^{-2}—roughly 20 times the total luminosity integrated in $\sim$ 10 years of operation of the CERN Collider ($\sim$10 inverse picobarns, 10^{37} cm^{-2}). This facility would be unique in the ability to perform parity-violating measurements and polarization tests of QCD. Also, the existence of $p-p$ collisions in a new energy range would permit the study of "classical" reactions like the total cross section and elastic scattering, etc., and serve as a complement to measurements from $p-\bar{p}$ colliders.

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1. INTRODUCTION

The use of RHIC to study the interactions of longitudinally and transversely polarized protons, with a luminosity in excess of 10^{32} cm^{-2} s^{-1}, and c.m. energy in excess of 300 GeV, would open up a totally new field in elementary particle physics and fill a vital gap in the world's accelerators. This facility would be unique in the ability to perform parity-violating measurements and polarization tests of QCD. For many experiments, it would be preferable to run the machine at c.m. energy 300 GeV, rather than the nominal 600 GeV, to obtain the large values of Bjorken x, ($x > 0.4$), required to effectively transmit the polarization of the protons to the constituent quarks and gluons.

I divide 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.

2. PARITY VIOLATING EFFECTS

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:

$$A_L = \left(\sigma^+ - \sigma^-\right) / \left(\sigma^+ + \sigma^-\right) \tag{1}$$

This single spin asymmetry would be suitable for PVA measurements in the CERN collider, if a polarized proton source were available.

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_{PV}) can be defined as

$$A_{PV} = \left(\sigma^{--} - \sigma^{++}\right) / \left(\sigma^{--} + \sigma^{++}\right) \tag{2}$$

and is about twice as big as A_L, usually, and of opposite sign.

Parity violating effects due to interference between the strong and weak interactions are predicted to be large in the energy range accessible at RHIC. Two examples are: 1)the Total Cross Section for proton-proton interactions, which has a measured PVA (A_L) of $\sim 3 \times 10^{-7}$ at 1.5 GeV/c, 2.6×10^{-6} at 6 GeV/c laboratory momenta, and predictions of $> 10^{-4}$ at RHIC energies[1]; and 2)PVA in inclusive jet production, the leading strong interaction process at large transverse momentum, due to the interference of gluon and W exchange at the constituent level. At $\sqrt{s}$=300 GeV, A_{PV} was 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%, at p_T=95 GeV/c[2,3](see Fig. 4.1).

In addition to these relatively large interference effects in jet production, the energy and luminosity range of RHIC with polarized protons will open up a totally new regime of hadron physics, a situation in which parity violating effects are dominant. This concerns the direct production of the W and Z bosons of the weak interactions. Although W bosons are predicted to be produced by a parity-violating mechanism, this fact has not yet been demonstrated. The asymmetry A_{PV} is predicted[4,5] to be nearly 70% . RHIC could be the premier and unique laboratory for the study of the PVA in hadroproduction of $W \rightarrow e+\nu$, $\mu+\nu$. In addition to verifying the expected weak interaction PVA effect, this channel will provide the possibility of at least two other important and unique series of measurements:

1) By measuring the PVA for the reaction $W \rightarrow e + \nu$ as a function of $\sqrt{s}$, the spin dependent structure functions of the proton can be measured at values of $x \sim m_W/\sqrt{s}$. This brings to mind Val Telegdi's remark: "Yesterday's sensation is today's calibration (and tomorrow's background)."

2) By isolating parity violating production mechanisms, using the PVA subtraction, the rare decays of the W can be studied. The Z will be well studied at LEP and SLC; but there is no comparable facility for the study of W decays until LEPII runs. Thousands of $W \rightarrow e + \nu$ events will be produced in each month of running with polarized protons at RHIC. It will be possible to directly measure the leptonic branching ratio of the W, since the dominant hadronic decay, $W \rightarrow$jets, will be measurable[5]. Also, the background of electrons from light and heavy quark decays, which prevents electrons from W decay to be observed at transverse momenta below 20 GeV/c, can be substantially reduced (1/100) by the PVA subtraction (see Fig. 4.2), allowing the possibility of the study of rare decays, such as $W \rightarrow t + \bar{b}$, in this channel.

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 hard-hadron reactions. *THIS FIELD IS TOTALLY UNEXPLORED.* In the standard model, no parity violation is expected in hadron reactions. Of course, this is probably a consequence of the fact that nobody ever looked. Recently, some extensions of the standard model have included parity violation. For instance, one possible explanation of the several generations of quarks and leptons is that they are composites of more fundamental constituents, with a scale of compositenesss $\Lambda \gg 100$ GeV. The intriguing feature of composite models of quarks and leptons is that the interactions generally violate parity, since $\Lambda \gg m_W$. 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[6] contains an explicitly parity-violating left-left contact interaction between quarks, which results in a PVA in jet production[3,7] proportional to $(p_T/\Lambda)^2$. Without the PVA handle, the CDF detector at the Tevatron is limited to searching for substructure by deviations of jet production from QCD predictions at large values of p_T. The limit is presently[8] at $\Lambda \gtrsim 700$ GeV. Depending on the luminosity, RHIC can produce comparable or better limits. However, the advantage of the PVA signature is that it is a clear indication of new physics and, in addition, Λ can be determined by the dependence of the PVA on p_T—thus, the handedness and other details of any new coupling can be measured (see Fig. 4.3).

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.....

3. POLARIZATION TESTS OF QCD

QCD is a gauge theory in which helicity plays as fundamental role as "charge". The predicted polarization asymmetry,

$$A_{LL} = \left(\sigma^{++} - \sigma^{+-}\right) / \left(\sigma^{++} + \sigma^{+-}\right) \tag{3}$$

has been given in detail[9]. The (+) and (−) superscripts refer to the helicities of the colliding quarks and gluons. The effect is enormous at the constituent level. However at the particle level, the effect is greatly diluted because the proton polarization is not appreciably transmitted to the constituents, unless $x \gtrsim 0.5$. There is a recent detailed article on this subject[10]. 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, in experiment NA10, at CERN[10]. 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.*

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.

For the case of gluons, the structure function spin asymmetry can be measured directly using single photon production. This reaction is dominated by the subprocess:

$$g + q \to \gamma + q .$$

The asymmetry A_{LL} in this reaction is proportional to the product of the quark and gluon spin asymmetries, and is predicted to be surprisingly large, in the range $\pm$ 10 to 20 %. The charm quark structure function, and its polarization asymmetry, can also be measured in this reaction by tagging events with a lepton in the outgoing jet. Measurements of the spin dependent structure functions of the neutron can be made by colliding polarized protons, or polarized deuterons, against polarized deuterons. RHIC, of course, accomodates beams of different ion species.

To summarize, here is a subject with precise theoretical predictions and no experimental tests. It cries out for measurements—which can only be done using longitudinally polarized proton beams. RHIC is the place.

4. TRANSVERSE POLARIZATION EFFECTS

This subject is the opposite of the preceeding. Large effects have been observed—but there are no theoretical predictions. Examples include elastic scattering at the AGS[11] and a large single spin transverse asymmetry in pion production at large p_T [10]. 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 QCD predicts to be small. It is encouraging to note the renewed interest in these effects shown by the participants at this workshop.

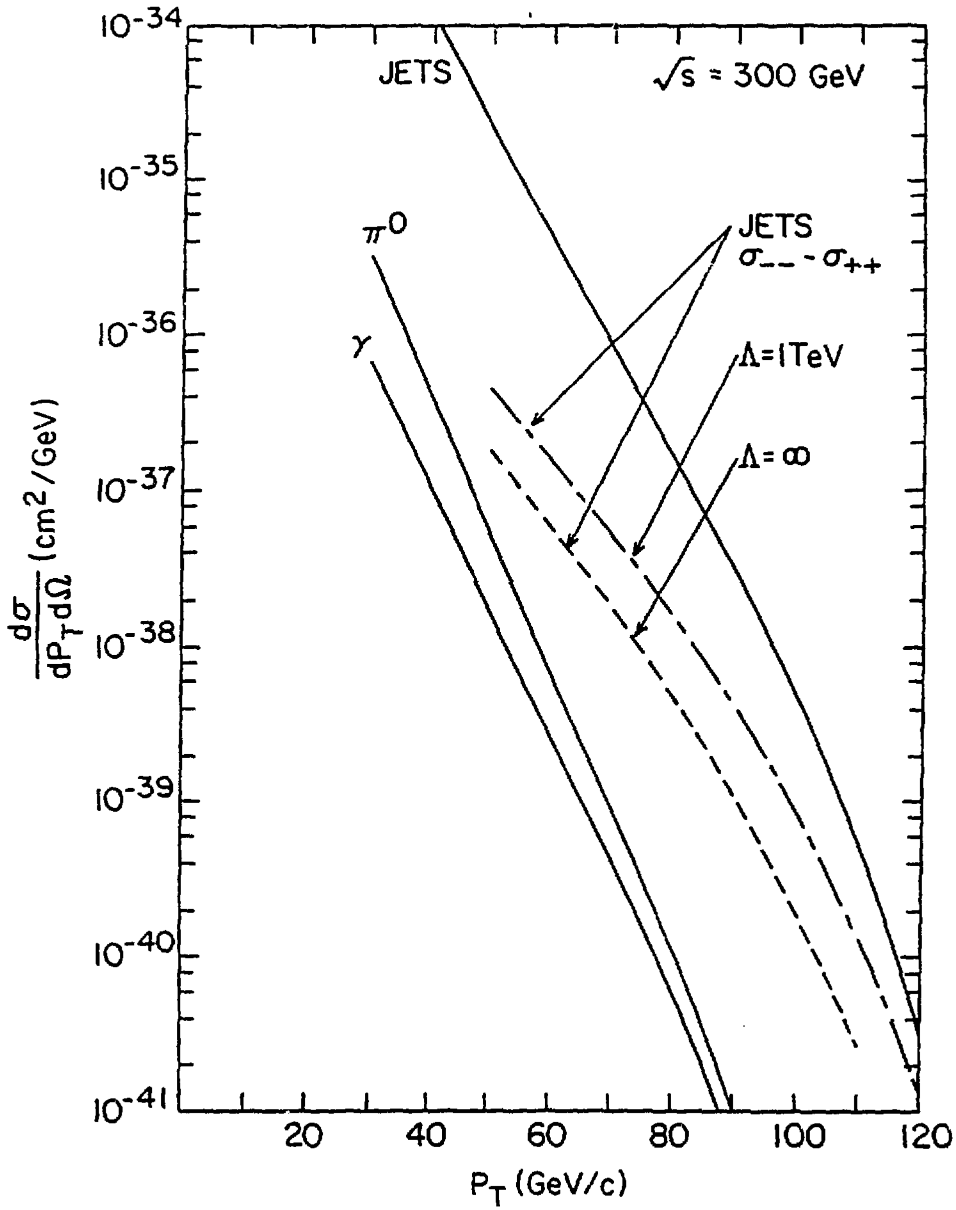

Figure 4.1: Predicted cross sections for representative hadronic inclusive processes at 90° c.m. for $p-p$ collisions at $\sqrt{s}$=300 GeV. The jet cross sections have been computed with ISAJET[3,7]. The π^0 and γ cross sections were estimated using a fit to ISR data[7]. Note that the parity-violating part of the Jet cross section (dashed curve with $\Lambda = \infty$) is much larger than the cross section for inclusive π^0 production. The Λ parameter in the figure refers to a model of quark substructure[6], taken with parameter $A = -1$.

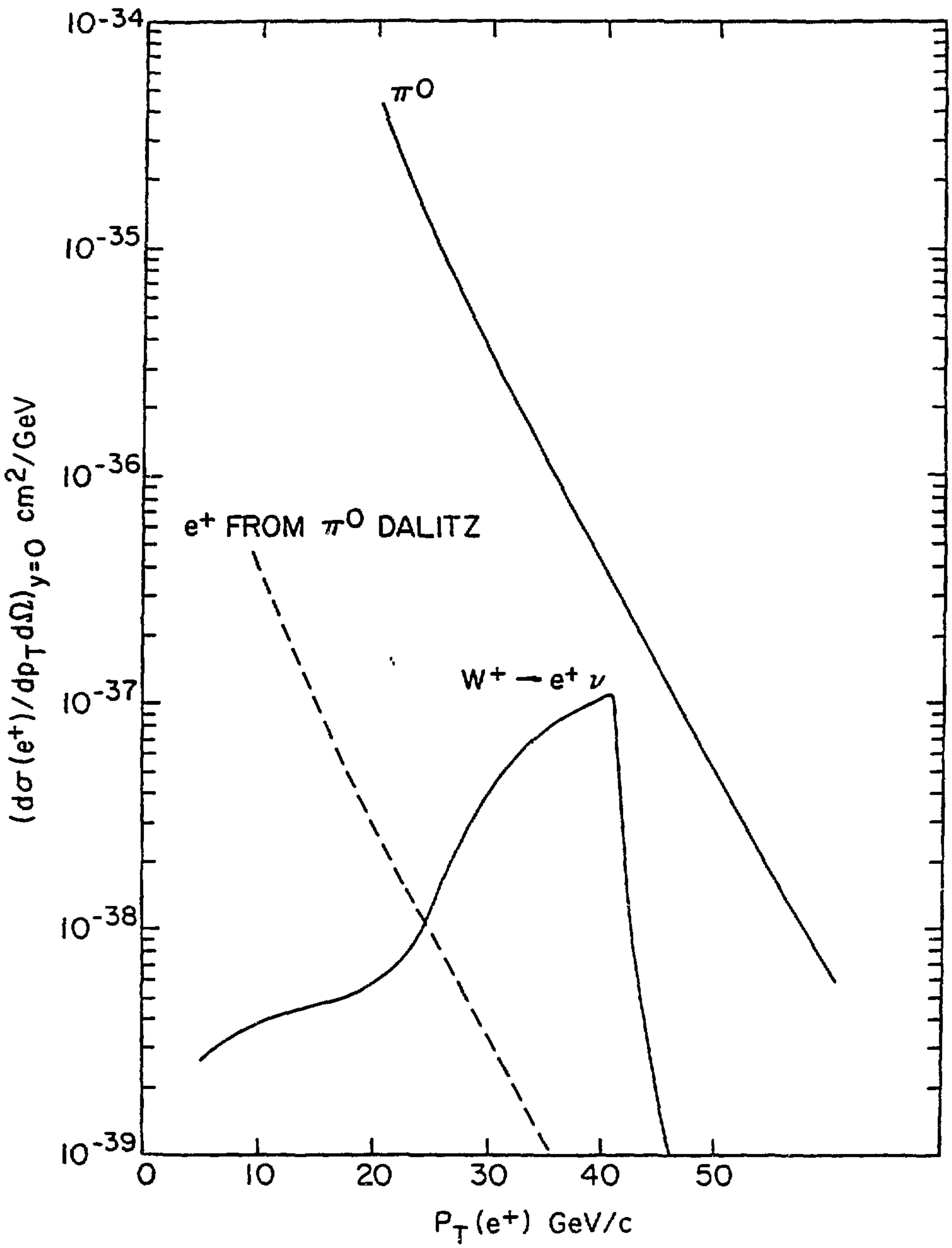

Figure 4.2: Predicted p_T spectrum at $\sqrt{s}$=300 GeV from inclusive π^0, background e^+ from Dalitz decay of π^0, and e^+ from W^+ decay.

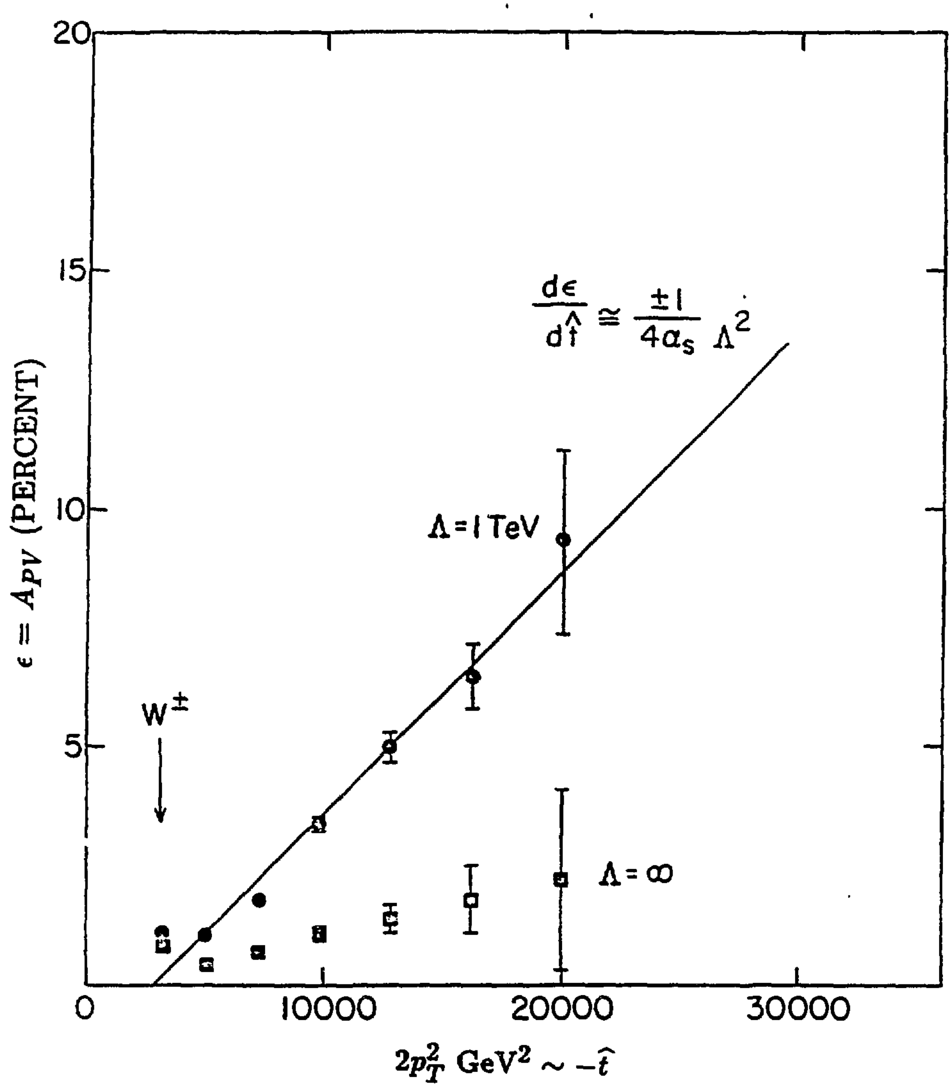

Figure 4.3: Predicted single jet PVA (A_{PV}) for quark substructure model[6] with parameters $\Lambda = 1$ TeV and $A = -1$. The A_{PV} is plotted in percent as a function of the quantity $2p_T^2$ which is a good estimator of $-\hat{t}$, the invariant-four-momentum-transfer-squared of the constituent scattering. The value of Λ can be derived from the observed linear slope, as illustrated. The error bars are calculated assuming an integrated luminosity of 2×10^{39} cm^{-2}, corresponding to 10 months running, and a "nominal" collider detector covering $\Delta\phi = 2\pi$, $\Delta y = \pm 2.5$. This figure indicates that the sensitivity of PVA measurements at RHIC can be much larger than the c.m. energy of the $p - p$ collisions, with sufficient integrated luminosity.

5. CONCLUSION

The use of polarized protons at RHIC, with polarizations of $\gtrsim 50\%$, high luminosity $\sim 2 \times 10^{32}$ cm^{-2} s^{-1}, the possibility of both longitudinal and transverse polarization at the interaction regions, and frequent polarization reversal for control of systematic errors, is both possible and desirable. It is time to prepare a detailed case for the implementation of a Polarized Proton Physics program at RHIC.

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