RHIC Spin-Physics Program

– for the DNP Town Meeting on
Nuclear Matter and Hadrons at High Energies –

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1 Overview

The RHIC SPIN program, having had a very successful commissioning this September, anticipates starting its study of the proton spin structure in 2001. We expect the base program, including direct and sensitive measurements of gluon, $\bar{u}$ and $\bar{d}$ polarization and transversity, to span five to seven years of RHIC running, which is shared with the heavy ion program.

The polarized proton collisions at RHIC will represent a qualitative advance in our studies of the proton and in spin physics. RHIC SPIN will be the first polarized proton collider. The energy will allow the collisions to be interpreted unambiguously as collisions of polarized quarks and gluons. The proton spin structure will be studied with perturbative QCD probes. This program is described in a review written for the Annual Reviews of Nuclear and Particle Science, published this winter and available at `http://arXiv.org/abs/hep-ph/0007218`. We do not repeat the review here, which discusses many of the planned measurements and sensitivities. In this document we will discuss the sensitivity of RHIC SPIN compared to other experimental programs, and present a time-table. We also sketch the complementary PP2PP experiment, which, along with the program in physics beyond the standard model at RHIC SPIN, will be presented at the Town Meeting at BNL in January.

Our presentations of sensitivity are based on a luminosity of 320 pb^{-1} for $\sqrt{s} = 200$ GeV and for 800 pb^{-1} for $\sqrt{s} = 500$ GeV. Both beams will be polarized at 70%. These luminosities are high, but are based on an already achieved polarized source intensity. Work is still needed on the polarization, which has reached 40% to 50% at RHIC injection energy. No depolarization is expected in RHIC due to Siberian Snakes. One Snake was operated in September, successfully manipulating and maintaining polarization. This was the first time that polarized protons were stored at high energy, the first use of a Siberian Snake at high energy in a storage ring, and the Snake worked as predicted.

2 Gluon Polarization

RHIC SPIN will use several channels to measure the gluon polarization: direct photon production, jet production, and open heavy quark production. These measurements will be made at both $\sqrt{s} = 200$ GeV and at $\sqrt{s} = 500$ GeV. Both large RHIC detectors, STAR and PHENIX will make very sensitive measurements; this is shown in Figure 1 for STAR, for one particular channel (direct photon plus jet production) and for one energy only. The open circles show the expected sensitivity for RHIC, and this is compared to HERMES (the single box point) and to COMPASS (four triangle points).

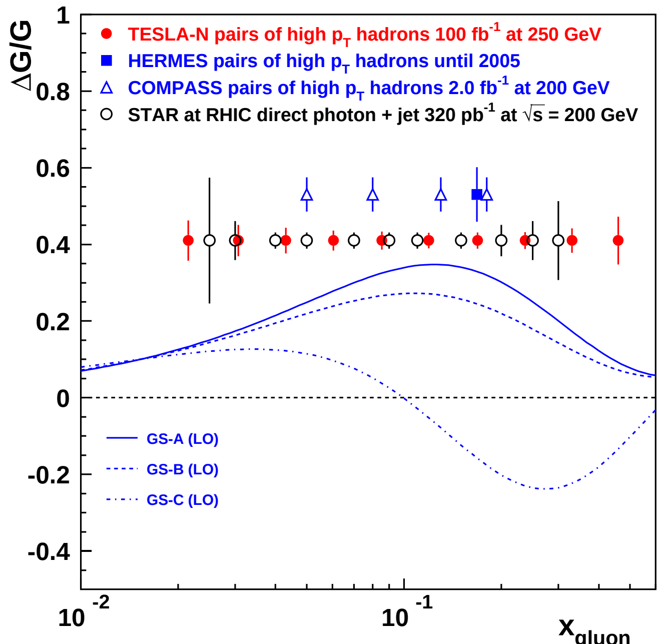

Figure 1: Models of gluon polarization in the proton with the projected statistical precision from current and future experiments [1].

The figure shows the strength of the RHIC SPIN measurement. Furthermore, the PHENIX measurements of direct photons will have similar errors with different systematic issues (more granularity in calorimetry, but no measurement of the away side jet), and both will have lower x measurements with similar sensitivity at $\sqrt{s} = 500$ GeV. Gluon polarization will also be measured by STAR using inclusive jet production, and by PHENIX using inclusive π^0 and charged π production as well as heavy quark production. These channels are all sensitive to the gluon polarization, and provide measurements with independent systematic and theoretical uncertainties.

The RHIC SPIN measurements will be at high p_T and $\sqrt{s}$, and will be well into the region where the scattering is expected to be described by perturbative QCD. This can be seen by comparing the scale dependence of pQCD descriptions of unpolarized cross sections, as shown in Figure 2.

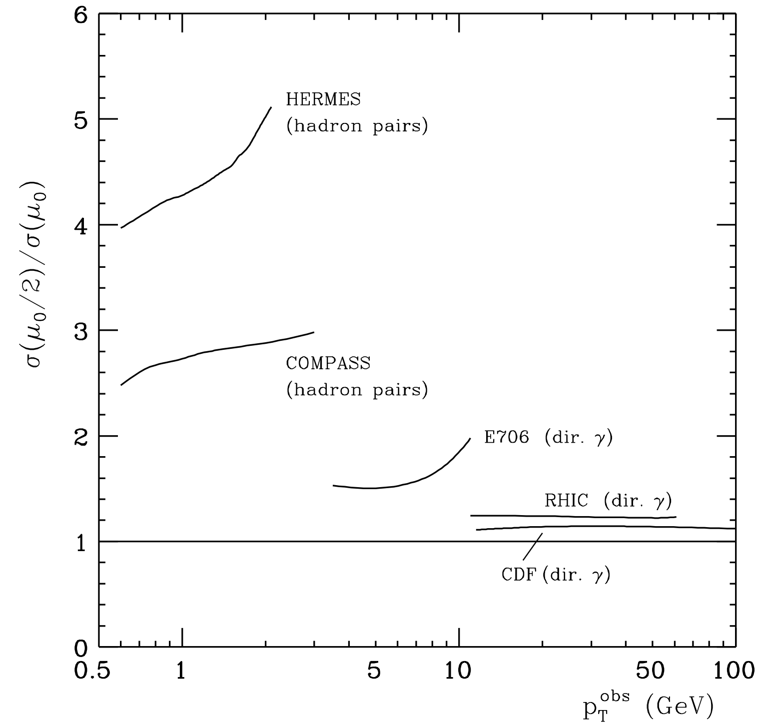

Figure 2: The theoretical scale dependence of the cross section, shown as a ratio of cross sections for two scales, $\sigma(\mu_0/2)/\sigma(\mu_0)$. Then HERMES, COMPASS and E706 are all fixed target experiments and show a very large scale dependence for pQCD description of the cross section. RHIC and CDF, collider experiments, show a small scale dependence implying stability in pQCD predictions. (CDF direct γ measurement are unpolarized; RHIC will be polarized measurement.) [2]

As can be seen here, the cross section at the HERMES energy varies by a factor of 4 for scale variation. For COMPASS energy, the variation is a factor of 2. For RHIC SPIN, the scale variation is 20%. We believe that, although one can argue that spin asymmetries will be likely to be less sensitive to scale than are cross sections, the RHIC SPIN results should be much more stable and reliable.

[2]The direct photon calculations (labeled as dir. γ) are next-to-leading order, and $p_T^{\rm obs} = p_T^\gamma$, $\mu_0 = p_T^\gamma$. In the case of the hadron pairs, only leading order is available. Here $p_T^{\rm obs}$ refers to the transverse momentum, p_T^{h+}, of the positively charged hadron, and we have integrated over $p_T^{h-} > 1.5$ GeV as in the HERMES experiment. The default scale was chosen to be $\mu_0 = p_T^{h+} + p_T^{h-}$ [2].

3 Quark and Anti-Quark Polarization

At RHIC, the parity-violating production of $u\bar{d} \to W^+$ and $d\bar{u} \to W^-$ will be used to directly measure the polarization of u, $\bar{d}$, d, and $\bar{u}$ quarks in a polarized proton. These measurements will be done by both Star and Phenix at $\sqrt{s} = 500$ GeV. The method and sensitivity are described in the review. These measurements can be compared to semi-inclusive DIS (SIDIS) of polarized lepton off the polarized nucleon.

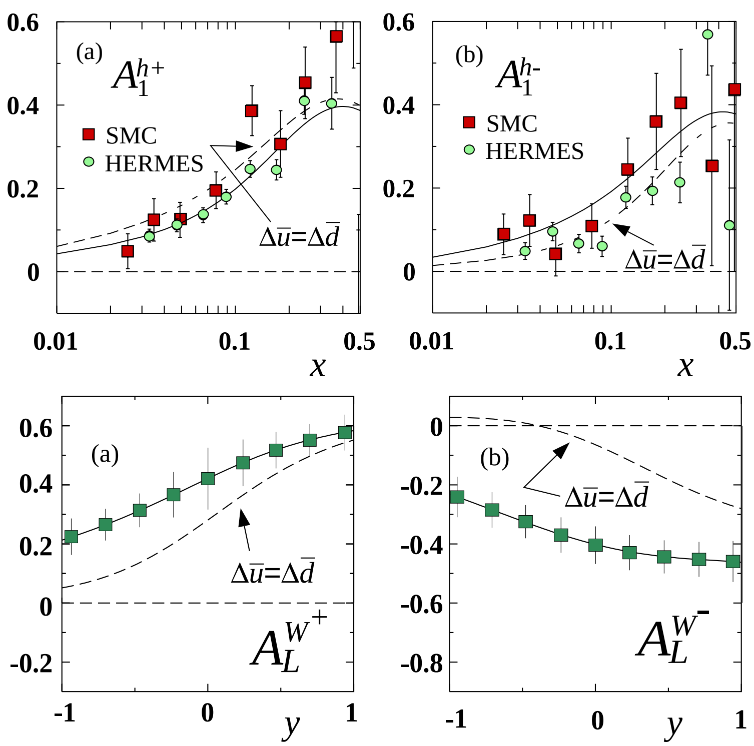

Figure 3: **Top row**: Model predictions of spin asymmetry in semi-inclusive DIS, $A_1^{h^+}$ and $A_1^{h^-}$ [3]: one with $\Delta\bar{u} = \Delta\bar{d}$ (dashed line) and the other with the chiral-quark soliton model (solid line). Hermes has 10 times more statistics now and the precision will be improved. **Bottom row**: Model predictions of single longitudinal-spin asymmetry, $\mathcal{A}_L$ for $W^\pm$ production in polarized pp collisions at $\sqrt{s} = 500$ GeV [4]: one model assumes $\Delta\bar{u} = \Delta\bar{d}$ (dashed line) and the other uses the chiral-quark soliton model (solid line).

For Rhic Spin measurements the scale is at the W mass, while for Hermes the scale is much lower. This will provide a precise test of QCD evolution and universality. The SIDIS involves the assumption that leading hadron in jets carry information on flavor of the quark jet, and these fragmentation functions are a source of uncertainty in this method.

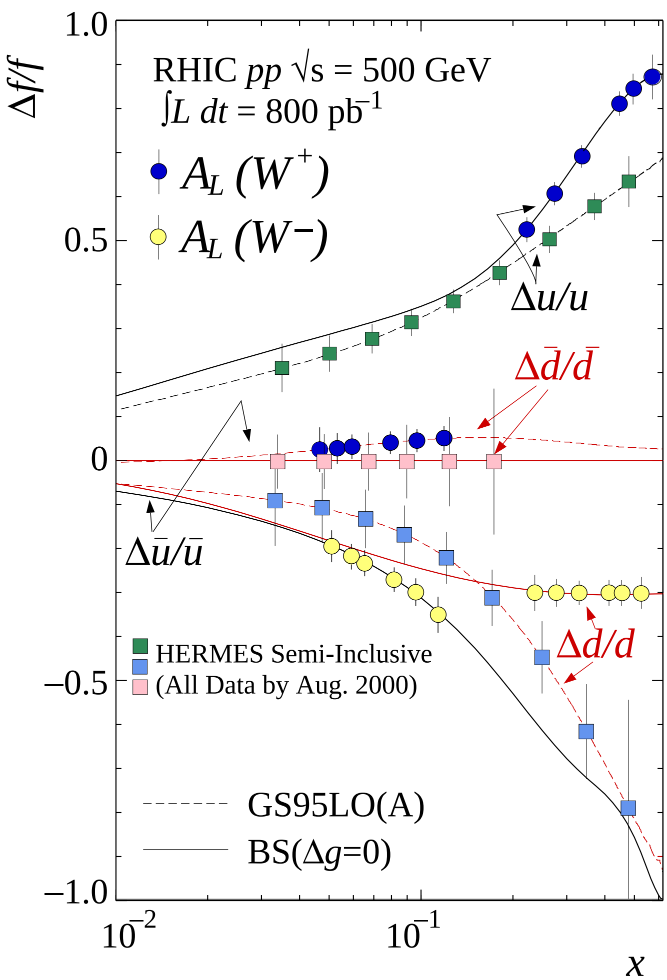

Figure 4: Polarization of u, d, $\bar{u}$, and $\bar{d}$ as functions of x modeled by Bourreley-Soffer, and Gehrmann-Stirling. Error bars associated with closed circles represent projected statistical precision from W measurements at RHIC (PHENIX only). Projected errors from all HERMES data (as of November 2000) are represented by the error bars with squares. HERMES cannot separate the flavor dependence of u and d anti-quark polarizations without additional model assumptions, currently $\Delta\bar{u}/u = \Delta\bar{d}/d$.

4 Transversity

High energy, deeply inelastic lepton-nucleon and hadron-hadron scattering cross sections can be described with the help of three independent nucleon helicity amplitudes. Measurements of the nucleon structure functions $F_1(x, Q^2)$ -the helicity average- and $g_1(x, Q^2)$ -the helicity difference-, have explored the helicity conserving part of the cross sections with great experimental accuracy.

In contrast, no information is presently available on the helicity flip amplitude. The absence of experimental measurements is a consequence of the chiral-odd nature of the helicity flip amplitude and the related "transversity quark distributions", $\delta q(x, Q^2)$, which prevents the appearance of helicity flip contributions at leading twist in inclusive DIS experiments.

The current excitement in transversity distributions results from recent HERMES [5] and SMC results [6] in semi inclusive deep inelastic scattering, which suggest that Collins's function $H_1^{\perp}$ *and* the transversity distribution function δq are different from 0 and measurable. Although precise statements on the shape and magnitude of the functions cannot be made from this data, clearly the prospects are exciting to have a tool at hand which, for the first time, provides access to the complete helicity structure of nucleons in hard scattering processes. At DESY two years of the extended HERMES experimental program have been assigned to transversity measurements [7]. A future measurement at RHIC does not only offer the high rate environment of hadron hadron collisions but also avoids theoretical uncertainties connected with the soft scales at HERMES.

In a partonic picture of the nucleon, transversity distributions are interpreted as describing the probability of probing a quark with spin parallel vs antiparallel in a transversely polarized nucleon target. Among the interesting characteristics of transversity distributions are:

- The helicity flip gluon distribution is zero at leading order and thus there is no mixing between quark and gluon degrees of freedom in the Q^2 evolution.
- Recently Jaffe and Weiss have brought up the relation between chiral symmetry breaking and transversity in the nucleon[11].

The fact that gluons do not contribute to helicity flip amplitudes has the interesting consequence that the first moment of transversity quark distributions, $Q_T = \int dx(\delta u(x) + \delta d(x) + \delta s(x))$ the tensor charge, is a pure quark observable. This is very different from the situation for longitudinal quark spin distributions, which mix under renormalization and evolution with gluon spin distributions. It is not possible to define a separate quark spin independent from ambiguities (scheme dependence) associated with gluon spin. Also both valence and sea ($q\bar{q}$ pairs) quarks contribute to longitudinal spin. As a result we still don't know how the nucleon spin is shared among valence and sea quark spins, gluon spin, and orbital angular momentum. In contrast, transversity is a pure non-singlet quark observable. It does not mix with glue or with $q\bar{q}$ pairs. It may well be that the nucleon's transversity is much more *quark-model-like* than its spin. In this context it is interesting to note that first QCD lattice results for the tensor charge predict a value of about $Q_T \approx 0.6$ [13], close to quark model expectation.

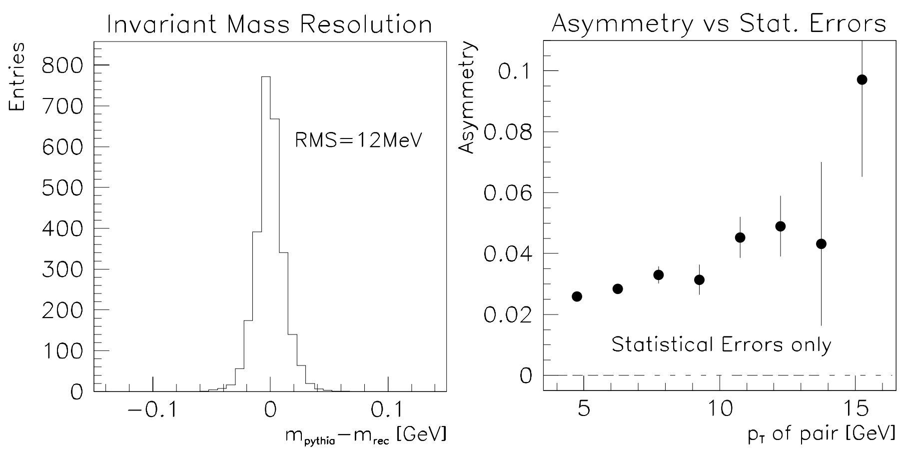

Figure 5: *Left Plot*: The invariant mass resolution for pion pairs in the ρ-mass region. *Right Plot*: Projected transverse single spin asymmetries compared to statistical errors, $\int L dt = 32\,\mathrm{pb}^{-1}$.

At RHIC the proposal of Collins et al. [8] and Jaffe et al. [9] to utilize two meson interference fragmentation is a promising channel for transversity measurements [10]. The process is pion pair production in pp scattering with one proton transversely polarized. Sensitivity to transversity distributions arises from a dependence of the cross section on $\vec{p}_{\pi^+} \times \vec{p}_{\pi^-} \cdot \vec{s}_\perp$, where $\vec{p}_{\pi^+}$, $\vec{p}_{\pi^-}$ and $\vec{s}_\perp$ are the pion momenta and the target spin vector. Experimentally we identify pairs of oppositely charged mesons coming from the invariant mass region of S/P-wave interference (e.g. the ρ/σ region). Rates are high at RHIC and the invariant mass resolution of the PHENIX and STAR detectors are more than sufficient for this purpose, see left plot in Fig. (5). Projected sensitivities, based on Tang's and Jaffe's model calculations [9], are shown in the right plot of Fig. (5). The experimental single spin asymmetry $A_T \sim \sum_q \delta q \cdot H_q^{\pi^+,\pi^-}$ is proportional to the product of transversity distributions and the interference fragmentation functions $H_q^{\pi^+,\pi^-}$. The extraction of quark transversity distributions from measured single spin asymmetries requires knowledge of the currently unknown functions $H_q^{\pi^+,\pi^-}$. However, this fragmentation functions can be measured in $e^+e^- \longrightarrow Jet + Jet$ and efforts are underway to analyze LEP data [12].

5 PP2PP Experiment at RHIC

The PP2PP experiment will measure total and differential elastic pp polarized and unpolarized cross sections throughout the RHIC energy range. The detector description and details can be found in [14]. It will cover a t range $10^{-4} < |t| < 1.3\,(\mathrm{GeV}/c)^2$. Employing transversely polarized beams, both the single-spin asymmetry A_N and the double-spin asymmetry A_{NN} will be measured with an expected accuracy of a few times 10^{-3}.

Historically, when high-energy hadronic beams first became available, near-forward elastic scattering was at the center of attention, because the optical theorem encodes the sum of all cross sections in the forward amplitude. With the advent of quantum chromodynamics (QCD) attention turned to high energy primarily as a source of rare events with large momentum transfer: short-distance processes. Short-distance processes are only part of the picture, however, even for high-energy hadronic collisions. There is now once again a large audience, well-versed in QCD and eager for data that shed light on the Regge region. For the RHIC nuclear program, near-forward hadronic sections may have a special relevance, through a dual description in terms of soft partons [15].

Roughly, we can divide unpolarized near-forward elastic scattering into four fairly well- defined regions, toward increasing $-t$: the Coulomb interference, pomeron-exchange, "dip", and (tentatively) perturbative ranges. In the very forward Coulomb Nuclear Interference (CNI) region, the electromagnetic and hadronic amplitudes are of comparable magnitude, resulting in a small but significant asymmetry A_N in pp scattering near the point of maximum interference [16]. An up to date status of calculation can be found in [17]. Projected errors from our measurements are compared with the prediction of A_N appropriate to the parameters of PP2PP in Figure 6.

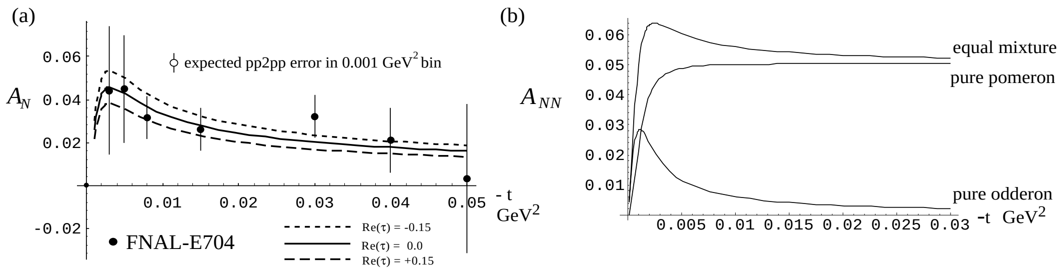

Figure 6: (a) A_N as a function of $|t|$ in the CNI region for three values of the ratio of spin-flip to non-flip coupling, τ. The data is from FermiLab E704 [18]. The expected error from PP2PP is also shown. (b)This illustrates the CNI enhancement of the odderon contribution to A_{NN}. The three curves correspond to pure odderon equal to .05 times the non-flip, pure Pomeron equal to .05 times the non-flip and an equal mixture of the odderon and Pomeron.

At somewhat larger $-t$, the sensitivity of asymmetries to exchanged quantum numbers [19] gives the PP2PP experiment a unique capability to test QCD-inspired predictions. Of special interest is C-odd, three-gluon exchange (the "odderon") and its interference with the pomeron, observable in both A_N and A_{NN} [20]. PP2PP can also study the unknown spin-dependence of diffractive processes, currently of very wide interest. One of the lessons of Regge theory, which is surely relevant at RHIC energies, is the importance of spin to a full description of near-forward dynamics.

Passing through the dip region, a steep exponential fall in momentum transfer, characteristic of pomeron exchange, matches on to an appoximate t^{-8} dependence at larger $-t$ in unpolarized cross sections. This qualitative "profile" is fairly stable with energy, even as the details of its shape change. The observation of a stable "profile" in polarized elastic scattering over the PP2PP range would surely initiate of a new class of theoretical investigations.

Polarization-dependence at high energy is still little explored, but what is known is sometimes spectacular when plotted in t. The dramatic spin dependence of proton-proton elastic scattering in the Argonne and BNL experiments of twenty years ago remains an outstanding puzzle. Its energy-dependence could be a key missing piece. The PP2PP experiment, sensitive to spin dependence and quantum number exchange, affords an unrivalled opportunity to venture into virgin territory, with significant implications for our perturbative and nonperturbative descriptions of the strong interactions.

6 Polarized Proton Physics with Luminosity and Energy Upgrades

The existing RHICollider may permit certain luminosity and energy upgrades for the proton program. It may be possible to achieve a 25-fold increase in luminosity and a maximum center of mass energy of $\sqrt{s} = 650\,\text{GeV}$. The existing RHIC SPIN program would benefit from this upgrade through significantly higher rates in the rare event channels such as prompt photon production, Drell-Yan lepton pair production and W-boson production. For example, a high luminosity gluon polarization measurement in the direct photon channel will significantly extend the measurement's reach towards high p_T and thus avoid the theoretical uncertainties at lower p_T.

In addition to the benefit to the existing spin program a combined luminosity and energy upgrade results in sensitivities for the search for contact interactions and leptophobic gauge bosons. This will be discussed in the next section.

6.1 Contact Interactions and Leptophobic Gauge Bosons

If new physics is present around the TeV scale, *spin* dependent processes at RHIC might be an excellent tool to test for physics beyond the Standard Model (SM). The process to consider is jet production where there are still some windows for discovery. The new interactions under considerations are:

- The existence of some new quark-quark contact interactions parametrized by the effective Lagrangian :

  $$\mathcal{L}_{qq} = \epsilon g^2/(8\Lambda^2)\bar{\Psi}\gamma_\mu(1-\eta\gamma_5)\Psi\,.\,\bar{\Psi}\gamma^\mu(1-\eta\gamma_5)\Psi \ , \qquad (1)$$

  Λ is the energy scale, Ψ a quark doublet, $\epsilon = \pm 1$ and η characterizes the chiral structure.

- The existence of new gauge bosons that couple mainly to quarks (*i.e.* "leptophobic").

The relevant observable to test such new physics ideas is the one-spin parity violating asymmetry $A_L = (d\sigma^- - d\sigma^+)/(d\sigma^- + d\sigma^+)$, where $d\sigma^h \equiv d\sigma^h/dE_T d\eta$ is the differential inclusive one-jet cross section, E_T and η are the transverse energy and the pseudo-rapidity of the jet, and h is the helicity of the polarized protons. This asymmetry does not vanish due to non-zero QCD-EW interference effects. The left plot in Fig. (7) gives A_L versus E_T for the SM along with the expectations for different new physics models.

The parameters used to obtain these different curves are given on the figure, for more details on these models see [21].

With conventional energy and luminosity parameters for RHIC, *i.e.* $\sqrt{s} = 500\,GeV$ and $L = 800\,pb^{-1}$, we have obtained the following conclusions [22] :

1) RHIC is competitive with Tevatron in spite of the large energy difference,
2) A_L gives unique information on the chiral structure of the new interaction,
3) luminosity is a key parameter if systematic errors are not too large,
4) if new physics is discovered in polarized pp collisions, the use of polarized neutrons will be very useful to constrain the Higgs content of the model and hence to distinguish different models.

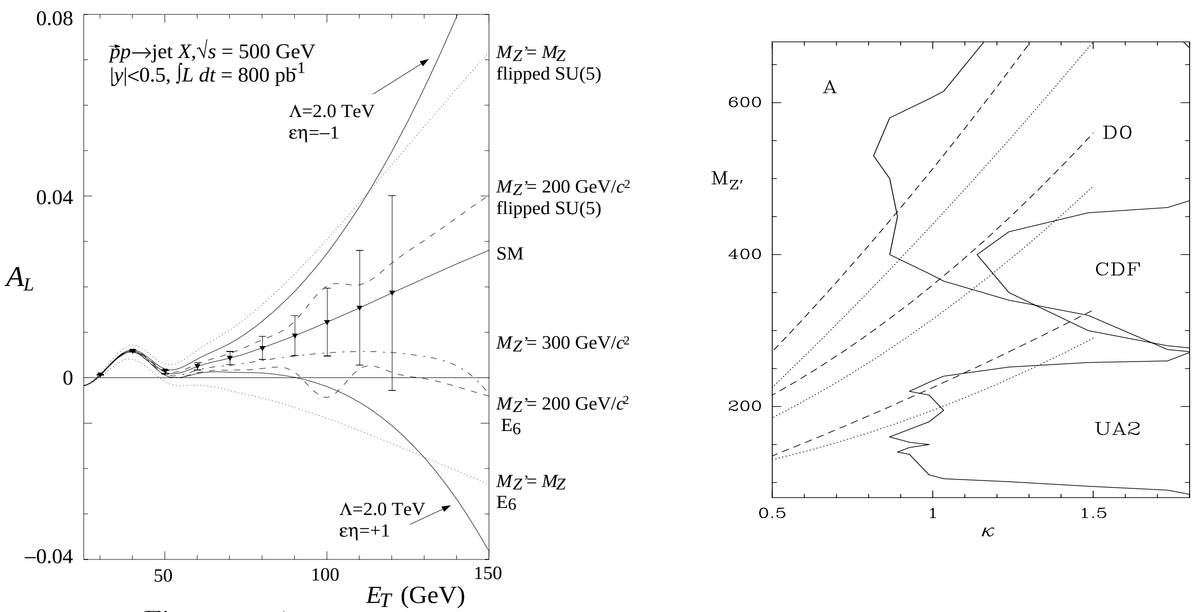

Figure 7: a) Spin asymmetry A_L, the labels of the different curves are given on the figure, see [21, 22] for more details. b) Constraints on leptophobic flipped SU(5) Z' models, see text for explanations.

With energy and luminosity upgrades, the sensitivity to new physics at RHIC will increase drastically :

• Concerning contact interactions, at the Tevatron, the present sensitivity (with $L = 110\,pb^{-1}$) is around $2 - 2.7\,TeV$. Expectations with future data are, $\Lambda \sim 4\,TeV$ with $L = 2\,fb^{-1}$ (Run II) and eventually $\Lambda \sim 5\,TeV$ with $L \sim 30\,fb^{-1}$ (Run III).

At RHIC, assuming a systematic error $\Delta A/A = 10\%$, a degree of polarization of $P = 0.7$ and a (pseudo-)rapidity interval $\Delta\eta = 1$, we obtain the following results for different values of L and $\sqrt{s}$:

$\sqrt{s}$ (GeV)	500	500	500	500	650	650	650
L (fb^{-1})	0.8	1	10	100	1	10	100
Λ (TeV)	3.18	3.33	5.45	7.50	3.80	6.25	8.75

Table 1 : Limits on Λ_{LL^-} at 95% CL with $\Delta A/A = 10\%$, $P = 0.7$, $\Delta\eta = 1$.

• Leptophobic gauge boson : In this case, the predictions are highly model dependent. We have chosen a particular model (model A of [21]) for illustration, however the features of the results are very general. Figure 1.b gives the constraints on this model in the plane $(M_{Z'}, \kappa)$, where $M_{Z'}$ is the Z' mass and $\kappa = g_{Z'}/g_Z$ is the ratio of coupling constants.

The areas labeled by D0, CDF and UA2 correspond to the forbidden regions obtained by these experiments from the analysis of the unpolarized jet cross sections. The other curves provide the bounds one can get at RHIC for different $\sqrt{s}$ and L, the areas below them being forbidden. The dotted curves correspond to $\sqrt{s} = 500\,GeV$ and the dashed curves to $\sqrt{s} = 650\,GeV$. From bottom to top they correspond to $L = 1$, 10, 100 fb^{-1}.

Undoubtedly, luminosity and energy increases are very powerful possibilities for new physics searches at RHIC. Several kind of models could be constrained in a domain not covered by present and future Tevatron data.

7 The RHIC SPIN Plan

The 6-year plan given in the table below assumes that 10 weeks per year are used for spin physics at RHIC. The luminosity is assumed to reach its design value in FY2002. Running efficiency is assumed to be 1/4 in FY2001, and 1/2 thereafter. The sensitivities presented here and in the review will be reached after the FY2006 run. The future (and actual plan) depends on our results.

The RHIC SPIN Plan

Year	$\sqrt{s}$	Weeks	$\int \mathcal{L}dt$
FY2001	200 GeV	5	7 pb^{-1}
Status	COLLIDER: 4 Snakes, P=50% STAR: 20% $\times 2\pi$ Barrel EMC PHENIX: Central Arms + South Muon Arm PP2PP: Engineering run		
Goals	Commissioning; First measurements of **gluon polarization with pions** Efficiency assumed: 1/4		
FY2002	200 GeV	8	160 pb^{-1}
Status	COLLIDER: All Spin Rotators, P=70% STAR: 50% $\times 2\pi$ Barrel EMC PHENIX: Central Arms + South Muon Arm PP2PP: Complete detector		
Goals	First run with spin rotators, full luminosity; sensitive measurements of **gluon polarization** with direct photons, jets, heavy flavors ; test run for **transversity** Efficiency assumed 1/2 PHENIX:7wks "LL" run; 1wk "TT" run STAR:7wks "LL" run; 1wk "TT" run PP2PP:8wks "TT" run		
	500 GeV	2	90 pb^{-1}
Goals	Commissioning, sensitive measurem of **parity violating W production, u-quark polarization**		
FY2003	200 GeV	8	160 pb^{-1}
Status	PHENIX: comeplte detector STAR: 100% $\times 2\pi$ Barrel EMC, 50% $\times 2\pi$ EndCap EMC PP2PP:		
Goals	**Gluon polarization**, first measurements with γ+jet		
	500 GeV	2	120 pb^{-1}
Goals	**Gluon Polarization, parity violating W production, first direct measurements of $\bar{u}$ and $\bar{d}$ polarizations**, search for **new physics** using parity violation		

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Year	$\sqrt{s}$	Weeks	$\int \mathcal{L} dt$
FY2004	500 GeV	8	480 pb^{-1}
Status			
	RHIC SPIN baseline complete. Possible upgrades		
Goals			
	Gluon polarization using γ(+jet), 2-jet, heavy flavor. $\bar{u}$ **and** $\bar{d}$ **using parity violating** W **production**, search for **new hysics** using parity violation.		
	200 GeV	2	48 pb^{-1}
Goals			
	γ(+jet), 2-jet, heavy flavor for **gluon polarization**.		
FY2005	500 GeV	5	300 pb^{-1}
Status			
	RHIC SPIN Possible upgrades.		
Goals			
	Continued statistics for **gluon polarization** and $\bar{u}$ **and** $\bar{d}$ **polarization** and search for **new physics**		
	200 GeV	5	120 pb^{-1}
Goals			
	Complete statistics for longitudinal polarization measurements, running for **transversity**		
FY2006	200 GeV	10	210 pb^{-1}
Status			
	RHIC SPIN Possible upgrades.		
Goals			
	Complete statistics for longitudinal polarization measurements, running for **transversity**		

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