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Spin Physics at RHIC

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ABSTRACT

Acceleration of polarized protons at RHIC is now scheduled under the BNL-RIKEN collaboration by implementing an arrangement between the Science and Technology Agency of Japan and the Department of Energy of the United States of America. The project makes the acceleration of polarized protons possible up to 250 GeV with the luminosity of 2×10^{32} and the polarization of 70 %. Two set of spin rotators will be installed for the two major detectors, PHENIX and STAR. Overview of the project is reviewed from the view point of the detector systems and their spin-physics capabilities.

1. Introduction

RHIC-SPIN program opens the new era in high energy spin physics with use of the polarized proton collider, covering the $\sqrt{s}$ region from 50 GeV to 500 GeV. The energy region has never been studied with polarized hadron beams and the project provides many unique features to understand the spin structure of nucleon, complementary to the deep inelastic scattering experiments, as well as to test QCD itself. The program is in life and the construction is started as you can see in Fig. 1, to be completed before the first beam commissioning in 1999.

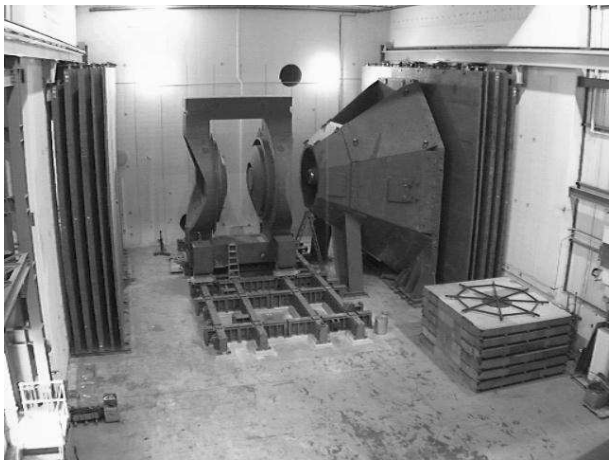


Figure 1: Today's PHENIX at RHIC

The two major detectors, PHENIX and STAR, are originally designed for heavy ion physics at RHIC. PHENIX has an emphasis on the detection of electrons, muons and γ's. STAR is characterized by the Time Projection Chamber covering a large acceptance with which a global view of an event is given. In order to obtain maximum outcomes for spin physics, necessary up-grades are being made for the baseline of both detectors. STAR has a large acceptance EM-calorimeter and PHENIX is equipped with double muon endcaps.

In this manuscript performances and capabilities of the two detectors for spin physics are reviewed. From a physics point of view, the two detectors will work complementary. Some highlights are given in this manuscript. Detail discussions on the spin physics in RHIC are covered in the talk by Y. Makdisi [1].

2. Physics Issues

Channel	Physics	$\sqrt{s}$ (GeV)	Spin-config.	Signal
$u\bar{d} \to W^+ \to l^+\nu$	Δu,$\Delta\bar{d}$	500	L/LL	high Pt single leptons
$d\bar{u} \to W^- \to l^-\nu$	Δd,$\Delta\bar{u}$	500	L/LL	*(Weak bosons)*
$q\bar{q} \to \gamma^*(Z^0) \to l^+l^-$	$\Delta\bar{q}$	500	LL	high mass lepton pairs
	h_1	200/500	NN	*(Drell-Yan/Z^0)*
$q + g \to \gamma + q$	ΔG	200/500	LL	high p_t single γ (+jet) *(gluon Compton)*
$x + x \to jet + jet$	ΔG etc	200/500	LL	di-jet reconstruction *(hard QCD scattering)*
$g + g \to q\bar{q}$ $\to l^+ + x + l'^- + x$	ΔG	200/500	LL	high Pt single lepton J/ψ,χ,Υ,$e\mu$ coincidence *(heavy flavor production)*

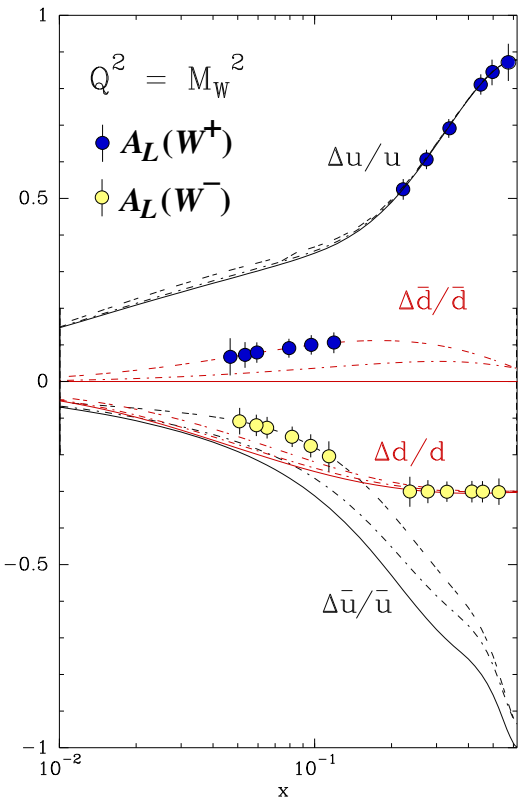
Table 1: Subprocesses sensitive to the polarized structure functions

Primary motivation in the RHIC spin program is to perform measurements to answer the EMC/SLAC spin crisis, and more generally to measure ΔG, $\Delta\bar{d}$ and $\Delta\bar{u}$, by direct accesses to parton interactions.

Table 1 summarizes clean and direct signals probing polarized parton structure functions. At the maximum energy, $\sqrt{s}$ = 500 GeV, weak boson W$^{\pm}$'s are produced for the first time with polarized protons, which provides a flavor sensitive probe to the polarization of sea quarks. Parity violating production of W^+ is sensitive to Δu and $\Delta\bar{d}$ via measured parity-violating single-spin asymmetry;

$$A_L^{PV}(W^+) = \frac{\Delta u_1 \bar{d}_2 - u_1 \Delta\bar{d}_2}{u_1\bar{d}_2 + u_1\Delta\bar{d}_2}. \quad (1)$$

Likewise W^- is sensitive to Δd and $\Delta\bar{u}$. With the PHENIX muon endcaps, measurements of the x_{bj} dependence of these structure functions can also be performed as demonstrated in Figure 2. Here experimental sensitivities of 1-year



courtesy of Jacques Soffer & Claude Bourrely

Figure 2: Sensitivities for the polarized parton distributions to be obtained through the $W^{\pm}$ production [2,3].

measurements are over-plotted on the theoretical predictions [2,3]. The experimental method to extract these wonderful sensitivities is discussed later.

Information of $\Delta\bar{q}$ is also accessible via the Drell Yan and Z production processes;

$$q + \bar{q} \rightarrow \gamma^*(Z^0). \tag{2}$$

The measurements of this channel are done with high-mass lepton-pair detections. Besides the helicity distribution of $\bar{q}$, other importance of this channel is emphasized by X. Ji and R. Jaffe [4] as the most effective way to study the h_1 structure function, which is a chiral-odd structure function and has never been measured before.

The gluon polarization, a key issue to solve "spin crisis", will be measured via direct photon production;

$$q + g \rightarrow \gamma + q. \tag{3}$$

The measurements will be done cleanly in PHENIX owing to the world-finest segmentation of the EM calorimeter which reduces π^0 background effectively. In STAR the coincidence measurements of the photon with an away-side jet will be made by taking advantage of its large acceptance, in order to pin down the x_{bj} dependence of the gluon polarization.

Additional information on ΔG can also be studied via di-jet detections by selecting a di-jet mass region sensitive to the $g + g \rightarrow jet + jet$ channel [5].

Heavy quarkonuim productions are known to be dominated by the gluon fusion process. At $\sqrt{s}$=200GeV high p_t leptons are mainly from the $gg \rightarrow c\bar{c}$ channel and at $\sqrt{s}$=500GeV from $gg \rightarrow b\bar{b}$. Gluon polarization can be studied through the asymmetry measurements of these channels [6,7].

Spin collider can provide many more new tools beside the determination of structure functions. Transverse asymmetry, A_N for example, is know to be vanished in the QCD leading order in the RHIC energy region. This implies that the higher twist effect can be studied effectively and crucial tests for QCD can be made.

RHIC spin is also suited to explore new physics. If a quark has a substructure as suggested by the new data of the high p_t jet production in CDF [8], parity violating asymmetry will provide much more sensitive tests for the sub-quark structure. It should be noted that beyond the standard model, with any new mass scale $\Lambda \geq M_W$, most of theoretical models predict violation of parity, and that there are very few measurements of parity violation in hadronic reactions and almost none at high energy.

3. The detectors; PHENIX and STAR

Both detectors are originally planned for relativistic heavy ion physics, they are also optimized for high energy proton-proton collisions with some modifications and additions.

PHENIX detector is dedicated to e, μ, γ detections, with strong particle identification capability in a high rate circumstance. The whole view of the detector is given in Fig. 3. High resolution μ detection in North and South Muon Arms

cover a large acceptance in $1.2 < |y| < 2.4$. The muon magnets have a special configuration of a lamp-shade-like return yoke with a piston inside, providing radial magnetic field along the beam. Identification of muon is made through the 6 layers of iron-plate/streamer-tube sandwiches. Cathode readout chambers inside the magnets give 3-10% momentum resolution.

The central arm covers the region of $\Delta\phi < 180°$, $-0.35 < y < 0.35$ with axial magnetic field of 1.0 Tm. Although the acceptance is rather limited, the area is covered by the fine-segment EM calorimeter. The segmentation of the calorimeter is 0.01-radian both in azimuthal and lateral directions. Such a fine segmentation is required for the particle identification in the heavy ion collisions, but also very useful in spin physics for clean detections of γ, e and π^0 with high p_t. The capability of π^0 detection reaches up to p_t of 25 GeV/c. Trackers in the central arm provides mass resolution of $\Delta M/M = 0.4\%$ at M=1GeV. The major detector components and their kinematical coverages are listed in Table 2.

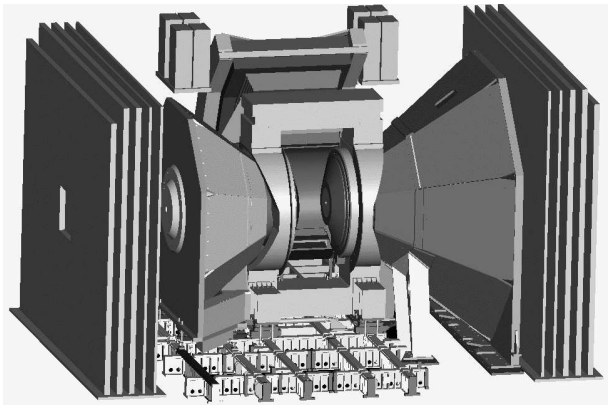


Figure 3: The PHENIX detector

Element	$\Delta\eta$	$\Delta\phi$	Purpose/Features
Magnet: central	± 0.5	360^o	Max. 1.0 Tm
Magnet: muon	$1.1 - 2.5$	360^o	0.72 Tm ($eta = 2$), 0.36Tm($\eta = 1.3$)
Silicon micro vertex	± 2.7	360^o	$d^2N/d\eta d\phi$, precise vertex
Beam-beam counter	± 0.35	360^o	Start timing and luminosity monitor
Drift chambers	± 0.35	$90^o + 90^o$	Tracking,$\Delta M/M = 0.4\%$ at M=1GeV
Pad chambers	± 0.35	$90^o + 90^o$	Pattern recognition, tracking
Time Expansion chambers	± 0.35	$90^o + 90^o$	Pattern recognition, tracking, dE/dx, future grade up for the TRD (e-ID)
Ring Image Cerenkov	± 0.35	$90^o + 90^o$	Electron ID
TOF	± 0.35	30^o	Hadron ID, $\sigma < 100ps$
Pb/Scinti cal.	± 0.35	$90^o + 45^o$	Electron/photon ID,e/π separation
Lead glass cal.	± 0.35	45^o	Electron/photon ID,e/π separation
Muon chambers	$1.1 - 2.4$	360^o	Muon tracking
Muon identifier	$1.1 - 2.4$	360^o	Steal absorber and chambers, μ/hadron separation

Table 2: Summary of the PHENIX detector

STAR stands for Solenoidal Tracker At Rhic. As shown in Fig. 4 a huge TPC with a drift space of ± 2 m is its heart, stored in a 1-Tesla solenoid magnet. For spin physics STAR modified its baseline design of the EM calorimeter, keeping

the segmentation size rather coarse (0.1 radian). Shower maximum detectors with effective segmentation of 0.01 radian are to be installed in the calorimeter to detect precise shower positions. With these detectors high p_t π^0's are not reconstructed, but are effectively eliminated through the shower size analysis, which extends the measurable p_t range of direct γ up to 20GeV.

Other attractive feature of the STAR detector is its large acceptance. Tracking of charged tracks in TPC together with neutral particle detection in the EM calorimeter is able to provide jet detections over the rapidity range of ± 2. STAR then is suited for the coincidence measurements like jet-jet, γ-jet, e^+-e^- etc..

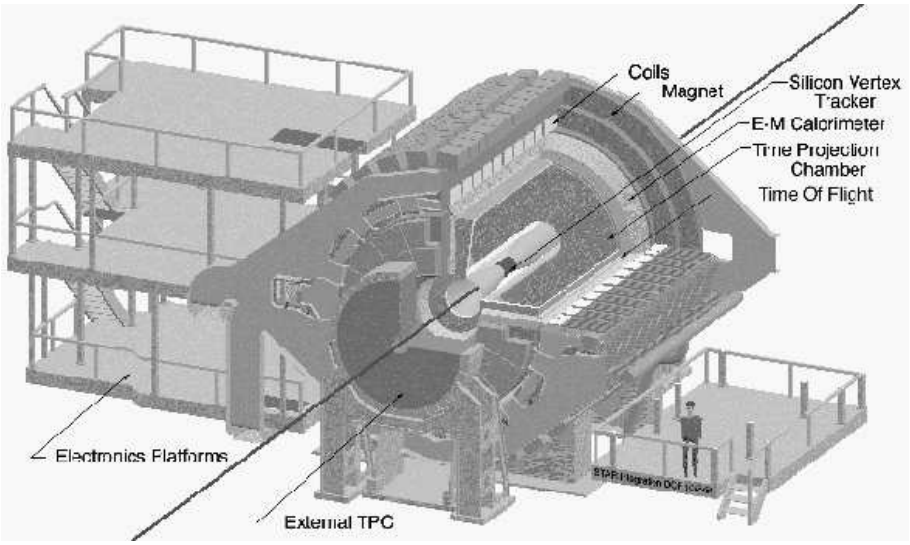


Figure 4: The STAR detector

Element	$\Delta\eta$	$\Delta\phi$	Purpose/Features
Solenoid	± 2	360^o	Max. 2.0 Tm
TPC	± 2	360^o	Particle ID ± 1
TPC endcap (MWPC)	$\pm 1-2$	360^o	trigger
Silicon tracker	± 1	360^o	Max. 1.0 Tm
Barrel EM cal.	± 1	360^o	e, γ id.
Endcap EM cal.	$1-2$	360^o	e, γ id.

Table 3: Summary of the STAR detector (elements relevant to spin physics)

4. Signals and Sensitivities

Here we describe how well we can perform the measurements. Sensitivities for the physics processes after one year-running will be shown. Recent expectations are $\sim$30 weeks for heavy ion runs and $\sim$10 weeks for polarized proton runs in each year. Runs at $\sqrt{s} = 200GeV$ are needed also for the heavy ion physics to compare AA and pp interactions. Dedicated beam time at 500 GeV will be allocated for the spin program. The integrated luminosities are (50 good days in each year) $\int \mathcal{L}dt = 8.0 \times 10^{38}\mathrm{cm}^{-2} = 800\mathrm{pb}^{-1}$ at 500 GeV, and $\int \mathcal{L}dt = 3.2 \times 10^{38}\mathrm{cm}^{-2} = 320\mathrm{pb}^{-1}$ at 200 GeV. At both energies the expected beam polarization is 70 %.

Flavor sensitive measurements of Δq,$\Delta\bar{q}$; W productions and decays. In the central region (PHENIX central arm and STAR barrel) produced $W^{\pm}$'s are identified as a Jacobian peak in the p_t spectrum of electrons and positrons. In the PHENIX muon arms the p_t spectrum of decay muons from W's are expected as shown in Fig. 5. Here other sources for high p_t muons are also plotted. One can see that in the p_t region above 20GeV/c $W^{\pm}$'s are the dominant muon source and the major background is Z decays. Detail calculation showed that the background from Z decays amounts to $\sim$ 4% for W^+ and $\sim$ 20% for W^-.

As already shown in Fig. 2, these $W^{\pm}$ productions and decays will provide excellent tools, especially in the PHENIX muon arms, for the determination of polarized parton distributions. Figure 6 shows the decay kinematics of W^- detected in the muon arms in PHENIX, studied with Monte Carlo simulations.

Here x_1 is x_{bj} of a parton coming into North Arm, and x_2 into South Arm. The upper figure shows a clear correlation of $\sqrt{x_1 x_2} = M_W/\sqrt{s}$, which means that p_t of W^- is almost negligible. A gift from nature is striking so that the muon energy detected in North Arm has a clear correlation to x_1 which in most cases are d-quarks (lower left figure) and to x_2 which are $\bar{u}$-quarks (lower right figure) in South Arm.

This fact is due partly to the asymmetric decay of W^- and partly to the production kinematics. With use of the correlations, one can determine the x dependence of the polarized parton distributions as demonstrated in Fig. 2. In

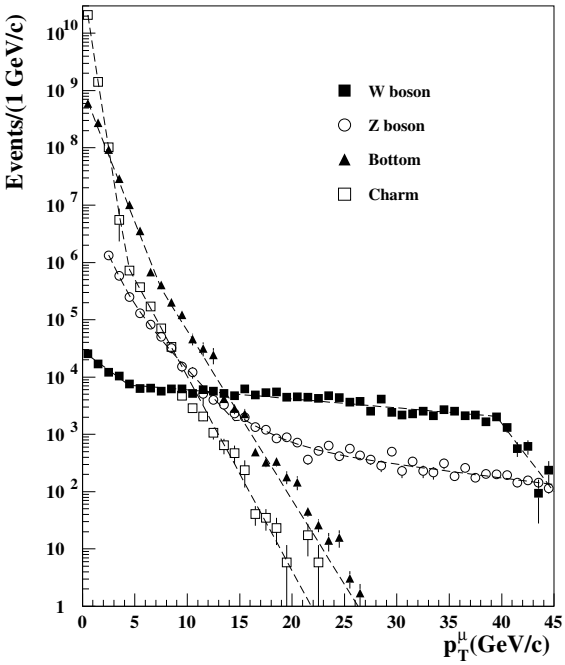


Figure 5: Various sources of high pt μ production at $\sqrt{s}$=500 GeV.

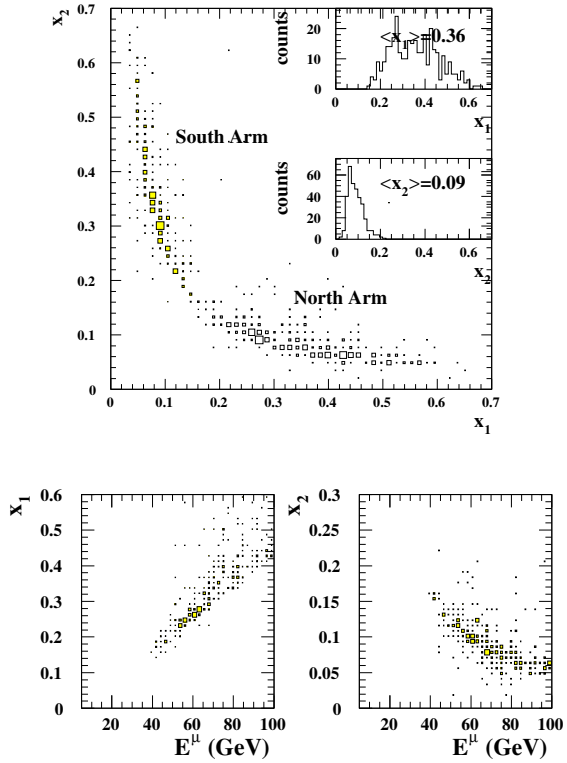


Figure 6: Kinematical correlation of d and $\bar{u}$ quarks in W^- production (see text).

the case of W^+ such a flavor selection is more mixed up, but still the extraction of flavor is possible by selecting the energy region of detected muons.

Measurements of ΔG; Direct photon production. Dominant contribution to the high p_t direct photons are $g + q \rightarrow \gamma + q$ (gluon Compton process)and $q + \bar{q} \rightarrow \gamma + g$ (annihilation process), with actual contributions of 90% and 10% respectively. As far as the polarization of anti-quarks is small (anyway measured in the RHIC-spin program), the gluon Compton channel is an ideal tool to extract the polarized gluon distribution.

In direct γ detection major background arises from meson decays. Figure 7 shows purity of the signal of interest (PHENIX simulation at $\sqrt{s} = 200GeV$). Signal to noise ratio is acceptable in the region above 10GeV/c p_t. Key issues to reduce the background are reconstruction/elimination of π^0 and a isolation requirement for the candidate γ's.

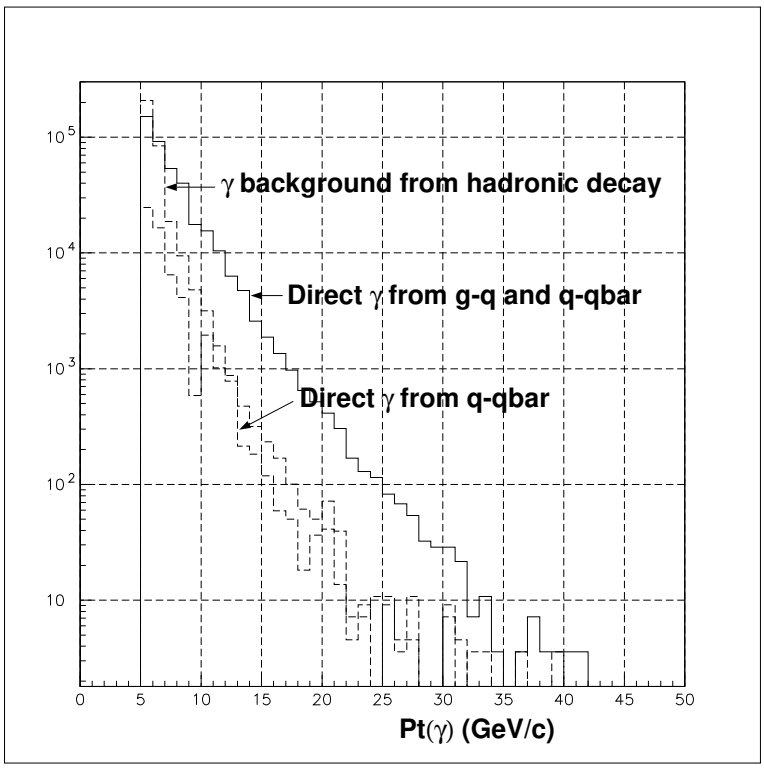


Figure 7 : P_t distribution of direct γ signal and major backgrounds

Table 4 summarizes expected 1-year-run statistics of the direct photon signals in PHENIX. If gluons carry a significant amount of proton spin, the effect is clearly visible through these measurements.

	$\sqrt{s} = 200GeV$		$\sqrt{s} = 500GeV$	
	Yield	ΔA_{LL}	Yield	ΔA_{LL}
Total	136000	0.0054	1260000	0.0018
$10 < p_{t\gamma} < 15GeV$	118000	0.0058	860000	0.002
$15 < p_{t\gamma} < 20GeV$	13800	0.017	270000	0.004
$20 < p_{t\gamma} < 25GeV$	2900	0.037	63000	0.008

Table 4: Yield of direct γ in PHENIX estimated with PYTHIA.

When glues are polarized, the x dependence must be studied. In principle gluon x_{bj} can be selected with p_T of photon. However the sensitivity is very much improved with an away-side jet detection. Table 5 shows the STAR sensitivity of this type of coincidence measurements. Distribution of ΔG will be determined as a function of x.

	$max(x_1, x_2)$			
$min(x_1, x_2)$	≥ 0.2	0.2-0.3	0.3-0.4	> 0.4
0.00-0.05		0.012	0.009	0.007
0.05-0.10	0.006	0.006	0.010	0.012
0.10-0.15	0.007	0.010	0.020	0.030
0.15-0.20	0.0210	0.019	0.038	0.060

Table 5: Statistical errors for the A_{LL} measurements of the $\gamma + jet$ channel in STAR ($\sqrt{s} = 200GeV$)

Physics capability of RHIC spin program. Table 6 summarizes the spin-physics capability of RHIC. The subprocesses which can probe unknown polarized parton distributions are listed together with expected statistics in one RHIC-year for PHENIX and STAR (50 good days with full luminosity). Typical backgrounds for a specific channel are also listed.

About Z^0, di-jet and quarkonium production channels, there haven't been much explained in this manuscript. Please cite the RSC proposals or related articles [2,9,10] for detail discussions.

Channel	PHENIX	STAR	Typical B.G.
$ud \to W^+ \to e^+\nu$	15k	72k	$5\%(Z^0)$
$ud \to W^+ \to \mu^+\nu$	6k x_{bj} sensitive		$8\%(Z^0)$
$d\bar{u} \to W^- \to e^-\nu$	2.5k	21k	$5\%(Z^0)$
$d\bar{u} \to W^- \to \mu^-\nu$	5k x_{bj} sensitive		10-20%
$q\bar{q} \to Z^0 \to l^+l^-$	e^+e^-: 120 $\mu^+\mu^-$: 700	4200	$\sim 0\%$ $\sim 0\%$
$q\bar{q} \to \gamma^* \to l^+l^-$	$\mu^+\mu^-$: 30k $9 < M < 12GeV$	e^+e^-: 37k $9 < M < 12GeV$	$\sim 0\%$
$q + g \to \gamma + q$	120k EMcal:$\Delta\eta = 0.01$ $p_t < 25GeV$ resolve π^0	300k Shower max $p_t < 20GeV$	10-20%
γ+jet	15% away jet efficiency	100k $G(x), x < 0.2$	$\sim 0\%$
$x + x \to jet + jet$	π^0 as leading particle	single:10^9 pair: 10^7 $p_t > 10GeV$	$\sim 0\%$ $\sim 0\%$
$g + g \to b\bar{b}/c\bar{c}$	200k $J/\psi \to e^+e^-$ 1M $J/\psi \to \mu^+\mu^-$ 25k $\Upsilon \to \mu^+\mu^-$ 6M $b \to \mu\nu$ @500GeV 6M $c \to \mu\nu$ @200GeV	e^+e^- sizable trigger high Pt	

Table 6: RHIC spin physics at a glance, RHIC-year-yield of the signals and typical backgrounds are shown for both detectors.

5. Conclusion

Relativistic Heavy Ion Collider at BNL is now also a polarized proton collider of $\sqrt{s} = 500\ GeV$ with highest luminosity of $\mathcal{L} = 2.0 \times 10^{32}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

Physics measurements are to be done with use of the detectors, PHENIX and STAR, under construction for the heavy ion program. Both detector are also well-optimized for the spin program and additional scopes on the detectors needed for spin physics are in place or nearly so. The two works complementary toward the final goal of the spin physics.

The physics is excellent, especially for the study of the polarized parton structure functions (ΔG, $\Delta\bar{q}$) which are directly probed in the specific subprocesses.

One year running ($\sim$ 10 weeks with proton, $\sim$ 30 weeks with heavy ion) provides fruitful spin-physics outcome with good precision, which will be followed by 10 years of measurements, containing an outstanding potential for the discovery of new physics.

The first machine commissioning will be in 1999, and the Year 2000 will already be productive for high energy spin physics.

The author would like to thank all the members of RSC, RHIC Spin Collaboration. RSC is a new type of collaboration of spin specialists of accelerator, spin enthusiasts from PHENIX and STAR, and theorists, who, as a whole, leaded the project into life. This manuscript contains materials provided by STAR and PHENIX collaborations. The author owes to N. Saito (PHENIX) and T. Hallman (STAR) for the preparation of the materials.

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