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PHENIX for the First Spin Collider RHIC

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Acceleration of polarized protons in Relativistic Heavy Ion Collider (RHIC) is to provide unique tools to study the spin structure of nucleon, covering the $\sqrt{s}$ region from 50 GeV to 500 GeV with proton polarization of 70 %. At 500 GeV the luminosity of $2 \times 10^{32}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ is expected. PHENIX, one of the two major detectors at RHIC, is going to investigate this new field of spin physics through the measurements of leptons and photons to probe possible spin carriers in the nucleon. Overview of the PHENIX spin program is presented and the expected physics outcomes are discussed.

§1. Introduction

The Relativistic Heavy Ion Collider (RHIC) will have a first collision in Y2000. RIKEN collaborating in this international project has brought a strong enhancement to the collider, namely to be the world first collider of polarized protons. Now the RHIC becomes the machine to explore "Creation of Quark Gluon Plasma" which has been a dream of physicists over 20 years, as well as to solve "Spin Puzzle of Nucleon" which relates to the fundamentals of the Quantum Chromo Dynamics.

The primary goal of the PHENIX spin program is to reconstruct the simple spin sum rule;

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

where $\Delta\Sigma$ is the proton spin carried by quarks, ΔG by gluons and L by angular momentum of quarks and gluons. Extensive studies done in SLAC and CERN in polarized lepton deep-inelastic scattering concluded that $\Delta\Sigma$ is in the range of 0.2 - 0.3, not unity as expected from a naive quark model [1]. Consequently, measurements of gluon polarization became vitally important to solve the "missing spin problem". $\Delta\Sigma$ includes contributions from quarks and anti-quarks inclusively,

$$\Delta\Sigma = (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s}).$$

Since the experimental observations did not agree with the Ellis-Jaffe sum rule [2], their assumption $\Delta s + \Delta\bar{s} = 0$ needed to be corrected and significant polarization of strange quarks as well as $\bar{u}$ and $\bar{d}$ quarks in the nucleon is strongly indicated. Thus measurements of sea quark polarization are also an interesting subject. Measurements of L is still open question theoretically and experimentally. If the amplitude of ΔG is not enough to account the rest of the proton spin, the question on L will become crucial as suggested by Sehgal in 1974. .

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The polarized proton collider enable us for the first time to measure directly those spin carriers unidentified in the former experiments using polarized lepton scattering. The range of $\sqrt{s}$ from 50 GeV to 500 GeV ensures variety of partonic interactions sensitive to the parton polarization and the reaction dynamics is calculable by perturbative QCD (pQCD). The luminosity is expected to reach $2\times 10^{32}/\mathrm{cm}^2/\mathrm{sec}$ at 500 GeV where gauge bosons will be produced copiously. The tasks charged to RHIC spin program are to measure ΔG, the first candidate of the missing spin carrier, and to decompose $\Delta\Sigma$ to flavors and to quarks and anti-quarks through the flavor sensitive channel, weak boson production.

The PHENIX detector consists of two arms for the electron and photon detection and other two for the muon detection. Those probes (leptons and photons) are essential to investigate the state of nuclear matter in heavy ion collisions, and also to detect the possible spin carriers (gluons and anti-quarks) to reconstruct the missing spin from individual constituents in the nucleon.

§2. PHENIX Detector

From a view point of spin physics, the PHENIX detector is characterized by e, μ, γ detections, with strong particle identification capability in a high rate circumstance. The whole view of the detector is schematically shown in Fig.1. High resolution μ detection in North and South Muon Arms cover a large acceptance in $1.2 < |y| < 2.3$. 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 by the 5 layers of iron-plate/streamer-tube sandwiches. Cathode readout chambers inside the magnets give 3-10% momentum resolution, ensuring the mass resolution of J/ψ and Υ to be 105 and 180 MeV/c^2 respectively.

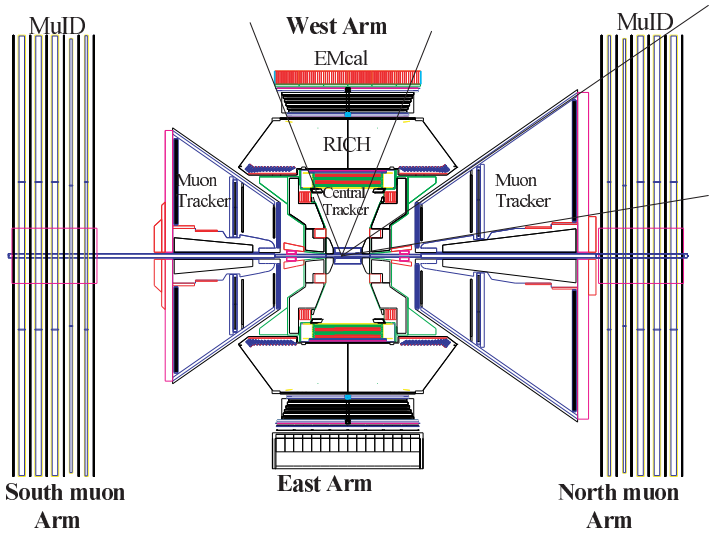

Fig. 1. The PHENIX detector, top view.

It should be noted that South Muon Arm is the major upgrade of PHENIX for the spin program and both Muon Arms together work as up/down counters for $\mu\nu$ decay of polarized $W^{\pm}$, as the counters used in the first discovery of parity vaiolation in β decay of polarized ^{60}Co by Wu et al. in 1957 .

Central Arms (West and East) cover 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 calorimeters. The segmentation of the calorimeter is 0.01-radian both in azimuthal and polar 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 20 MeV/c^2 for J/ψ and 160 MeV/c^2 for Υ. The major detector components and their kinematical coverage are listed in Table I.

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	–	360^o	Start timing and luminosity monitor
Drift chambers	± 0.35	$90^o + 90^o$	Tracking,$\Delta M/M = 0.4\%$ at M=1G eV
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 I. Summary of the PHENIX detector

For the measurements of electro-magnetic probes it is crucial to understand the calorimeter response for high energy particles. The test experiment was carried out at CERN in 1998 up to an electron energy of 80GeV. The energy resolution of the calorimeter is observed to be $d\sigma/E = 1.9\% + 8.2\%/\sqrt{E}$ with a linearity better than 2-3% (see Figures 2). The results showed that the PHENIX EM calorimeter originally designed for low energy particles can be reliably operated for high energy particles such from the gluon-Compton process and the W decays.

§3. PHENIX Spin Physics Highlights

In Table II we list important experimental probes in PHENIX to explore the internal spin carriers in protons. Helicity asymmetries of production A_{LL} of those

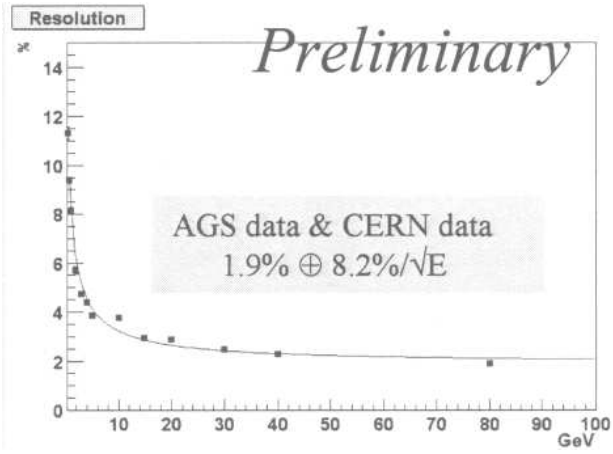

Fig. 2. Resolution of the EM calorimeter as a function of electron energy.

probes are used to extract the polarization of partons;

$$A_{LL} = \frac{1}{P_B^1 P_B^2} \frac{N^{+-}/L^{+-} - N^{++}/L^{++}}{N^{+-}/L^{+-} + N^{++}/L^{++}},$$

where P_B is beam polarization, Ns are the yields of the relevant channel and L is the luminosity of the collider. The signs "+" and "-" represents the helicity state of beam protons.

In the case of $gq \to \gamma q$, gluon Compton process, gluon polarization $\Delta G/G$ is directly measurable through the relation;

$$A_{LL} = \frac{\Delta G(x_1)}{G(x_1)} A_1^p(x_2) a_{LL}^{gq\to\gamma q},$$

where $a_{LL}^{gq\to\gamma q}$ is the partonic helicity asymmetry which is calculable by pQCD, and the quark asymmetry A_1^p is given by the lepton deep-inelastic scattering . In the case of $gg \to Q\bar{Q}$, heavy quark production, A_{LL} is given as,

Measurements in Central Arms	
Prompt photon	High p_T π^0
$J/\phi \to e^+e^-$	$W^\pm \to e^\pm\nu$
$c\bar{c}/b\bar{b} \to e^\pm$	
Measurements in Muon Arms	
$c\bar{c}/b\bar{b} \to \mu^\pm$ (high p_T)	$J/\phi \to \mu^+\mu^-$
$W^\pm \to \mu^\pm\nu$	$Z/\gamma^* \to \mu^+\mu^-$
Measurements in both Arms	
$c\bar{c}/b\bar{b} \to \mu^\pm e^\mp$ (unlike sign pairs)	

Table II. Probes for spin physics in PHENIX

$$A_{LL} = \frac{\Delta G(x_1)}{G(x_1)} \frac{\Delta G(x_2)}{G(x_2)} a_{LL}^{gg\to Q\bar{Q}}$$

where $a_{LL}^{gg\to Q\bar{Q}}$ again is the partonic helicity asymmetry. Partonic asymmetry a_{LL} is usually in the range of 0.5 to 1.

It is important to remark that the effect of the background appears as;

$$A_{LL}^{data} = \frac{A_{LL}^{signal}}{1+\epsilon} + \frac{\epsilon A_{LL}^{background}}{1+\epsilon},$$

where ϵ is the ratio of background to the real signal. Thus in the asymmetry measurements, it is important to choose a channel with a large partonic asymmetry and with a low background rate. It is also desirable to measure the background asymmetry within the same apparatus. Below we describe the highlights of our simulation studies to show the PHENIX spin-physics capability. Integrated luminosity par year will be 800 pb^{-1} at $\sqrt{s}$ = 500 GeV and 320 pb^{-1} at 200 GeV, which correspond to 50 days of data accumulation in a year with the design luminosity. For the simulation we have used PYTHIA5.7 and JETSET7.4 using the set of the structure functions GRV94LO.

3.1. *Prompt Photons and high p_T π^0s*

Measurements of prompt photon production are characterized by its clean and direct access to the gluon polarization via the gluon Compton process $g + q \rightarrow \gamma + q$, and are the primary goal of the RHIC spin program. The detail description can be found in Bazilievsky's contribution in this symposium [3]. We show here the expected sensitivity of this channel in Fig.3 (left). The three models on ΔG proposed by Gehrmann and Stirling [4] will be clearly distinguished by the data of 320 pb^{-1}.

Key issue to reduce the background photons is reconstruction and elimination of π^0, for which the PHENIX EM-calorimeter is a powerful tool. The asymmetry measurement of π^0 production is an inevitable requirement to extract A_{LL}^{signal} in the prompt photon measurements. On the other hand π^0 itself can give an access to the gluon polarization. The asymmetry of high p_T π^0 production is given by an admixture of any combination of partonic interaction (qq, qg and gg). Thus the asymmetry to be observed is influenced by the limited knowledge on the polarized structure functions besides unknown gluon polarization. The amplitude of ΔG will however appear in the π^0 measurements as shown in Fig.3 (right). Although direct reconstruction of partonic kinematics is not possible for this channel, major contributions to the production originates in gg and gq scatterings. And we consider high p_T π^0 to be a good candidate for the first year surprise, with 5-10 times more yield than the prompt photons.

3.2. *Heavy quark production and high p_T leptons*

High p_T leptons are known to be a good tag for heavy quark production. In the RHIC energy the major channel is $gg \rightarrow Q\bar{Q}$, thus the gluon polarization is accessible with high p_T leptons. The studies on the high p_T muons in PHENIX revealed that the background level is equivalent to or less than the signal yield above $p_T = 4GeV/c$ where we expect muons of 6×10^4 charm decays and 2×10^5 bottom decays to be observed in a year. Uncertainty on the background level is due to the limited knowledge of bottom cross section of p+p interactions at $\sqrt{s}$ = 200 GeV. The major background sources are decays of pions and kaons between a collision point and the first muon absorber (the yoke of the central magnet) and hadrons punching thorough the muon-identifier. The available 5 layers of muon identifier are useful to estimate the yield of punch through background, and the collision point determination will give us a handle on the decay background. The work is in progress to find out how we can handle those background, and also to see how high p_T electrons are useful. It

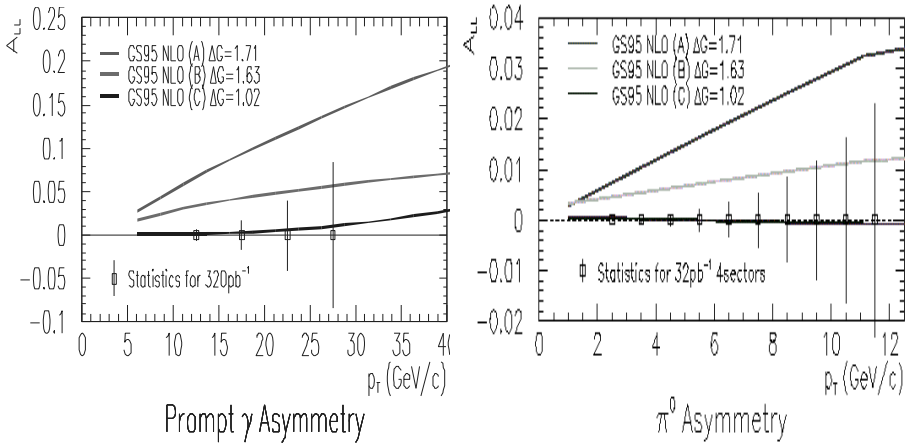

Fig. 3. Left: the sensitivity of the prompt photon measurements to A_{LL}, expected from 10 weeks (320 pb^{-1}) of data taking. The curves are obtained vased on the three different ΔG assumptions proposed by Gehrmann and Stirling [4]. Right: the sensitivity of the π^0 measurements to A_{LL} from one week (32 pb^{-1}). The curves are obtained as same as in the left figure.

should be noted that these channels are high rate to provide the precise asymmetry measurements even in the first year with lower luminosity.

The best signal from $Q\bar{Q}$ was found out to be the coincidence of an unlike-sign pair of electron and muon. As shown in Fig.4 the coincidence requirement suppress the decay background and enhance the leptons from $Q\bar{Q}$. One-year yield is expected to be 120k $b\bar{b}$, 100k $c\bar{c}$, with about 1/10 of background. Like-sign pairs are to give the best estimates of the yield and the asymmetry of background remained.

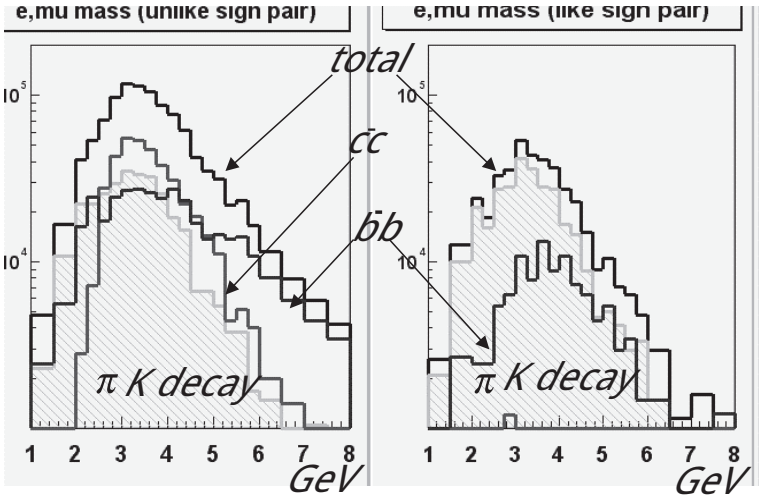

Fig. 4. Expected mass distributions of unlike-sign e-μ pairs (left) and like sign pairs (right). The hatched areas are the background from pion and kaon decays. Most of like-sign pairs are from such combinatorial background.

3.3. *Gauge bosons*

At $\sqrt{s}$ = 500 GeV, $W^{\pm}$ and Z are produced for the first time with polarized protons. In Central Arms produced $W^{\pm}$'s are identified as a Jacobian peak in the p_T spectrum of electrons and positrons. In Muon Arms the p_T spectrum of muons are dominated with $W \to \mu$ decays at the p_T region above 20 GeV/c.

These $W^{\pm}$s will provide excellent tools, especially in the PHENIX Muon Arms, for the determination of polarized parton distributions. Through our studies with Monte Carlo simulations on the decay kinematics of $W^{\pm}$ we found that the muon energy detected in Muon Arms has a clear correlation to x_{bj} of a incoming quark. This fact is due partly to the asymmetric decay of $W^{\pm}$ and partly to the production kinematics. With use of the correlations, one can determine the x dependence of the polarized parton distributions. Sensitivity expected from the Muon Arm data of 800 pb^{-1} is demonstrated in Fig.5. Those are obtained by the single spin asymmetry A_L.

In the case of W^-, measured A_L follows,

$$A_L^{W^-} = \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)\, d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{d}(x_1)\bar{u}(x_2)}.$$

Thus at large x_2 where $\bar{u}$ is small, $A_L^{W^-}$ simply becomes $\Delta\bar{u}/\bar{u}$, and at large x_1 $A_L^{W^-}$ is $\Delta d/d$. Likewise from W^+, $\Delta\bar{d}/\bar{d}$ and $\Delta u/u$ can be extracted. The major background in the W signal is Z decays which amount to $\sim 18\%$ for W^+ and $\sim 22\%$ for W^-. Systematic errors can be minimized to a few % level with the yield and the asymmetry measurements of Z production

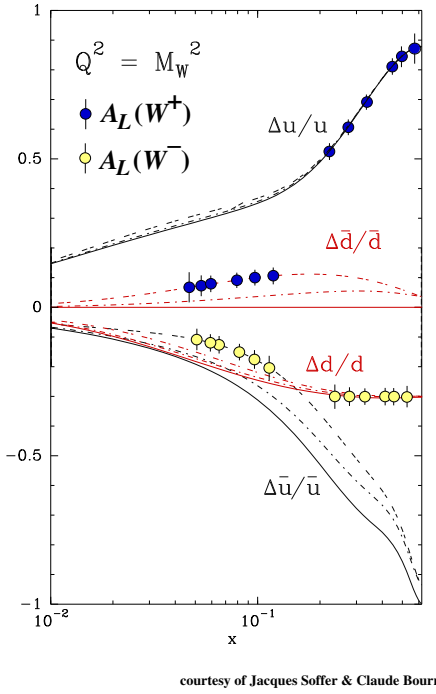

Fig. 5. Sensitivity of PHENIX measurements on quark and anti-quark polarization plotted with model predictions [5].

Recent results of the Drell-Yan muon pairs by FNAL E866 showed a clear signal of asymmetric flavor structure of nucleon, namely $\bar{d} \neq \bar{u}$ [6]. It is surprising, but at the same time it is clear that there is no reason to believe the flavor symmetry of sea quarks in the nucleon. The weak boson measurements at PHENIX will provide a unique tool to study the flavor structure of nucleon. Figure 6 shows the predicted production ratio of W^+ to W^- as a function of rapidity of Ws for various models of structure function, some assume the symmetric sea and some does not. The mid rapidity region is covered by the PHENIX Central Arms and the large rapidity regions are covered by PHENIX Muon Arms to give a clear distinction on the flavor structure in the sea.

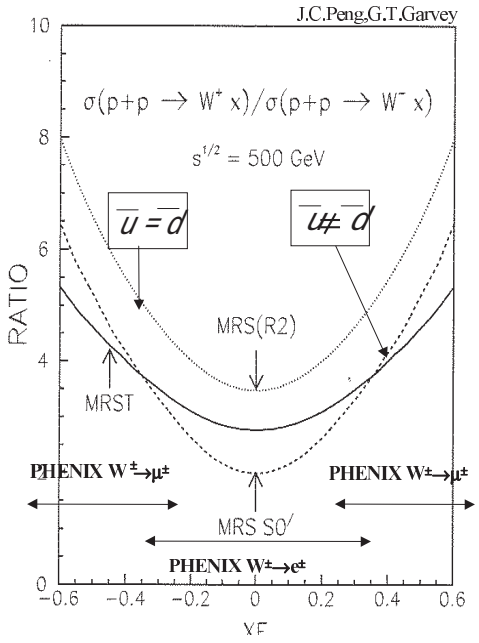

Fig. 6. Prediction of W^+/W^- production ratio. Asymmetric sea is taken in for the MRST and MRS(R2) structure functions.[7)]

§4. Conclusion

The PHENIX will observe the first collision of Au on Au in Spring 2000, which will be soon followed by the commissioning of polarized-proton acceleration. The detector is suited to the spin program by its high rate capability and its powerful particle identification on leptons and photons probing QCD processes perturbatively. In Year 2001 we will be able to see surprises in the data of high p_T π^0 and high p_T lepton, if ΔG is sizable as we are expecting. In Year 2002 the statistics will be much improved at $\sqrt{s} = 200$ GeV, which ensures the determination of ΔG in the prompt photon and the e-μ coincidence data. "Spin Crisis" will hopefully be solved by then. And later Weak Bosons will be produced at $\sqrt{s} = 500$ GeV, the new flavor-sensitive tool to measure the anti-quark/quark polarization and the unpolarized structure function of anti-quark.

Beyond this point, nature will perhaps be more imaginative than we are.

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