

# Measurement of Single Transverse-spin Asymmetry in Forward Production of Photons and Neutrons in pp Collisions at $\sqrt{s} = 200$ GeV

A. Bazilevsky\*, L. Bland<sup>†</sup>, A. Bogdanov\*\*, G. Bunce\*<sup>†</sup>, A. Deshpande\*,  
H. En'yo\*<sup>‡</sup>, B. Fox\*, Y. Fukao\*<sup>§</sup>, Y. Goto\*<sup>‡</sup>, J. Haggerty<sup>†</sup>, K. Imai<sup>§</sup>,  
W. Lenz<sup>†</sup>, D. von Lintig<sup>‡</sup>, M. Liu<sup>‡</sup>, Y. Makdisi<sup>†</sup>, R. Muto<sup>‡§</sup>, S. Nurushev<sup>||</sup>,  
E. Pascuzzi\*, M. L. Purschke<sup>†</sup>, N. Saito<sup>§\*</sup>, F. Sakuma<sup>‡§</sup>, S. Stoll<sup>†</sup>,  
K. Tanida<sup>‡</sup>, M. Togawa<sup>‡§</sup>, J. Tojo<sup>§†</sup>, Y. Watanabe\*<sup>‡</sup> and C. Woody<sup>†</sup>

\*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 119730-5000, USA

<sup>†</sup>Brookhaven National Laboratory, Upton, NY 11973-5000, USA

\*\*Moscow Engineering Physics Institute, State University Russia

<sup>‡</sup>RIKEN, Wako, Saitama 351-0198, Japan

<sup>§</sup>Kyoto University, Kyoto 606-8502, Japan

<sup>††</sup>Los Alamos National Laboratory, Los Alamos, NM 87545, USA

<sup>||</sup>Institute for High Energy Physics Protovino, Russia

**Abstract.** The Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL) was commissioned for polarized proton-proton collisions at the center of mass energy  $\sqrt{s} = 200$  GeV during the run in 2001-2002. We have measured the single transverse-spin asymmetry  $\mathcal{A}_N$  for production of photons, neutral pions, and neutrons at the very forward angle. The asymmetries for the photon and neutral pion sample were consistent with zero within the experimental uncertainties. In contrast, the neutron sample exhibited an unexpectedly large asymmetry. This large asymmetry will be used for the non-destructive polarimeter for polarized proton beams at the collision points in the RHIC interaction region.

## INTRODUCTION

There have been many interesting results of the single transverse-spin asymmetries,  $\mathcal{A}_N$  in the fixed-target energy region. One of the examples is the E704 results from Fermilab, which were obtained using the polarized proton and anti-proton beams of 200 GeV with the liquid hydrogen target [1]~[3]. Large asymmetries were observed especially in forward region;  $\pi^+$  and  $\pi^-$  showed mirror asymmetries as functions of  $x_F$  and  $\pi^0$  asymmetry was about a half of the  $\pi^+$  asymmetry in  $pp$  collision case. Since the asymmetry  $\mathcal{A}_N$  was expected to be small ( $\mathcal{O}(\alpha_s m_q / \sqrt{s})$ ) in high-energy hadron reaction, the results stimulated many theoretical works [4]~[8].

One of the motivation of our experiment is to see if such effects persist at higher energies, which was only achievable with the completion of the RHIC as the first polarized proton collider. In addition, we have been interested in neutral particle production in particular as a development of "Local Polarimeter", which measures the transverse

component of the beam polarization at the collision points at RHIC. Such equipment is extremely useful in understanding the spin dynamics in the RHIC accelerator system especially in obtaining the longitudinal beam polarizations by using spin rotators, which is a set of helical dipole magnets, located at RHIC. Since such polarimeter is non-destructive, it can co-exist with the experiments e.g. PHENIX and STAR. For the development of the "Local Polarimeter" at RHIC, STAR experiment has equipped with the Forward Pion Detector (FPD) to cover higher  $p_T$  but still forward region to search for any sizable  $\mathcal{A}_N$  in neutral pion production[9]. In the context of the "Local Polarimeter" development, our measurement and STAR FPD measurements are complimentary.

## EXPERIMENTAL SETUP

In this experiment, two detector systems were located 1800 cm upstream and downstream the collision point called IP12 (see Figure 1). Those were located right after the dipole magnets, which separate incoming and outgoing beams, and placed between two beam pipes. One of the detector systems is Electromagnetic Calorimeter based system (EM-Cal Polarimeter) facing the Blue Beam with the emphasis on photon and  $\pi^0$  detection, and the other is Hadron Calorimeter based system (H-Cal Polarimeter) facing the Yellow Beam for neutron detection. The geometry of 11 cm-horizontal gap of two beam pipes and rf filter inside the dipole magnet limit the angular coverage within  $\sim 3$  mrad. Charged particles are swept away by the dipole magnet in front of these detector systems and only neutral particles are expected to be detected by these systems.

In order to separate the beam-gas interaction, which is the beam interaction with the residual gas in the beam pipe, or collision events outside appropriate vertex distribution, two sets of hodoscopes are located at  $z = \pm 200$  cm covering pseudorapidity range of  $2.3 < |\eta| < 4.0$ . Since root-mean-square of vertex distribution is measured to be  $54 \pm 6.3$  cm, and the time resolution of hodoscopes is equivalent to 23 cm, beam collisions within the hodoscopes are well separated from the beam gas events or the events outside the hodoscope. In the high energy region, where we are interested in, contamination from the beam-gas/off-vertex events into the vertex cut is estimated to be  $\leq 1.1\%$

The beam polarization has been monitored by RHIC CNI Polarimeter [10] throughout the beam time and  $17 \pm 0.3 \pm 2.8\%$  for the Yellow Beam and  $11 \pm 0.3 \pm 2.5\%$  for the Blue Beam where the first and the second errors represent statistical and systematic ones, respectively.

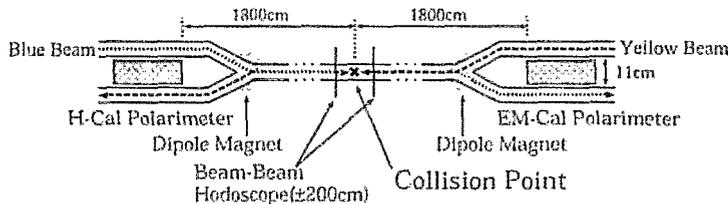


FIGURE 1. Top view of the experimental setup (not to scale) where the beams are indicated as dotted (Blue Beam) and dashed (Yellow Beam) lines with the arrows showing the circulation direction.

## EM Calorimeter based system

EM Calorimeter consists of sixty Lead-Tungstate ( $\text{PbWO}_4$ ) crystals, which have dimensions of  $2.0 \times 2.0 \times 20.0 \text{ cm}^3$ , with read-out by photo-tube. The crystals are arranged in an array of five by twelve so that total volume of the EM Calorimeter is 10 cm wide, 24 cm high, and 20 cm deep, which corresponds to 22 radiation length and  $\sim 1$  interaction length. This calorimeter was calibrated using electron beams at SLAC and an energy resolution of  $\Delta E/E = 10\%/\sqrt{E}$  and position resolution of 0.1 cm were achieved for electron beam. For hadronic showers, position resolution is estimated to be 0.5 cm using GEANT[11].

In front of the EM Calorimeter, pre-shower counter was located. This counter comprises five  $\text{PbWO}_4$  towers and these towers have same dimension as that of EM Calorimeter. Three scintillation counters were located for particle identification. One was located right after the dipole magnet and in front of the pre-shower counter to make sure neutral particles and called Charge Veto Counter (CVC). And two followed the EM Calorimeter with 1.1 inch-thick iron block in between for neutral hadron identification and referred to as Neutron Counter 1 and 2 (NC1 and NC2, respectively).

The logic of particle identification for photon and neutron is as follows: photons are identified by  $\overline{\text{CVC}} \otimes \overline{\text{NC}}$  and neutrons are identified as  $\overline{\text{CVC}} \otimes \text{NC}$ . We adopted this logic basing on the simulation and the real data by controlling the photon purity using the two photon invariant mass spectrum, in which we can identify  $\pi^0 \rightarrow 2\gamma$  easily. Our simulation studies show the purity of photon and neutron identification to be 98% and 89%, respectively with the systematic uncertainty of 16%.

## Hadron Calorimeter based system

Hadron Calorimeter has sandwich-like structure of 0.5 cm-thick tungsten plates and layer of optical fibers[12]. Its dimensions are 10 cm in width, 10 cm in height and 23 cm in length, which corresponds to  $\sim 2$  interaction lengths. Its energy response for neutron is calibrated using cosmic ray test and simulation and its resolution is estimated to be  $\sim 50\%$ .

The hadron calorimeter is followed by post-shower counter comprising five  $\text{PbWO}_4$  crystals to measure horizontal position of particle hits. The post-shower detector is identical to the pre-shower detector in the EM-Cal Polarimeter. By using the center-of-gravity of the energy deposits in the post-shower, position resolution is estimated to be 3 to 4 cm from GEANT study.

Photon samples are eliminated by introducing a two-inch lead block followed a plastic scintillation counter (Photon Veto Counter, or PVC). With this PVC, the sample becomes practically purely long-lived neutral hadron. Remaining question is the contaminations from  $K_L^0$ s. In the ISR energies, its contribution in the similar kinematical region is estimated to be 3-4% from observing charged kaon samples [13]. In our experiment, a lack of experimental data on the kaon production in this extremely forward region represents a major uncertainty in neutron identification.

## ASYMMETRY RESULTS

Energy, and position of the produced photon,  $\pi^0$ , and neutron were measured with the experimental apparatus described above. We have defined "Left" and "Right" and calculated the single transverse-spin asymmetry  $A_N$  with the Square Root Formula<sup>1</sup>. For the Blue Beam polarization, we can calculate the asymmetry for positive- $x_F$  using the EM-Cal Polarimeter and the one for negative- $x_F$  using the H-Cal Polarimeter. Similarly the asymmetries for positive and negative  $x_F$  can be obtained for the Yellow Beam polarization. The asymmetries for photon,  $\pi^0$ , neutron in the EM-Cal Polarimeter, and neutron in the H-Cal Polarimeter are plotted as functions of energy, except neutron samples in the EM-Cal, where observed energy is used instead. These plots show only statistical error for error bar, while there is additional systematic error. Two vertical scales of raw asymmetries uncorrected for beam polarization for each Blue and Yellow Beam are shown on the right side of the plots.

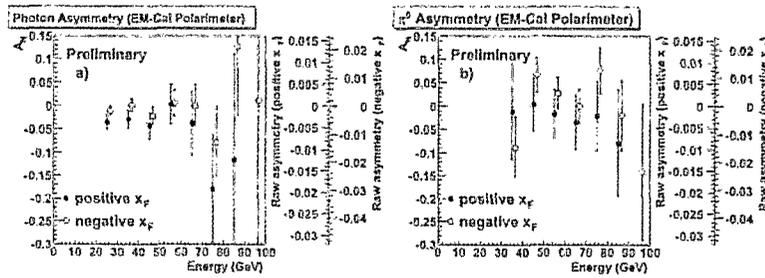


FIGURE 2. a) Photon and b)  $\pi^0$  asymmetry measured by EM-Cal Polarimeter

Figure 2.a) shows inclusive photon asymmetry as a function of energy. Closed and open circles are for positive and negative  $x_F$ , respectively. The analyzing power is small and consistent with zero within systematic errors in both positive and negative  $x_F$ . Figure 2.b) shows  $\pi^0$  asymmetry, and it is consistent with zero within statistical errors.

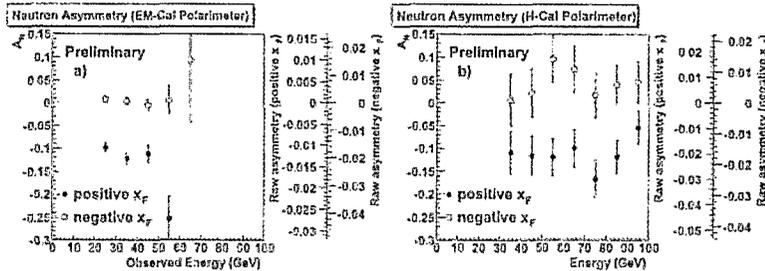


FIGURE 3. Neutron asymmetries measured by a) EM-Cal Polarimeter and b) H-Cal Polarimeter

<sup>1</sup> The formula is typically represented as  $A_N = \frac{1}{P_B} \frac{\sqrt{N_{L,R}} - \sqrt{N_{R,L}}}{\sqrt{N_{L,R}} + \sqrt{N_{R,L}}}$  where  $N_{iL}$  means number of particle detected in "Left" by the collision of upward polarized beam for example. Using this formula, we can eliminate luminosity and detector asymmetry and obtain physics asymmetry precisely.

Figure 3.a) and b) show neutron asymmetries which were measured using EM-Cal Polarimeter and H-Cal Polarimeter, respectively. Positive- $x_F$  asymmetries are significantly large in both EM-Cal and H-Cal Polarimeters, while negative- $x_F$  asymmetries are practically zero. Averaged values of  $\mathcal{A}_N$  for positive- $x_F$  measured in EM-Cal and H-Cal Polarimeter are  $-0.109 \pm 0.007$  and  $-0.110 \pm 0.015$ , respectively, which are consistent each other within statistical uncertainties.

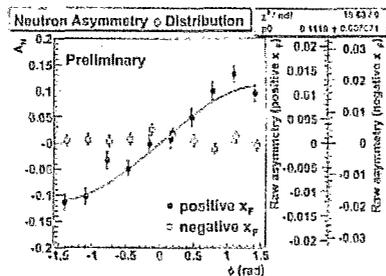


FIGURE 4. Neutron asymmetry versus  $\phi$  angle

Figure 4 shows another neutron asymmetry from the EM-Cal Polarimeter averaged over observed energy as a function of azimuthal angle ( $\phi$ ) of produced neutron with respect to the beam polarization. The asymmetries are fitted to a sine curve, which is expected for  $\mathcal{A}_N$ . The results is  $-0.112 \pm 0.007$  with a reduced  $\chi^2$  of 1.7 showing a reasonable agreement with the expected  $\sin(\phi)$  dependence.

## CONCLUSION

We have measured the single transverse-spin asymmetry  $\mathcal{A}_N$  for photon,  $\pi^0$ , and neutron production in polarized proton-proton collisions at  $\sqrt{s}=200$  GeV for the first time. The asymmetry for photon and  $\pi^0$  is consistent with zero within error, while significant asymmetry has been observed in forward production of neutron. This makes it possible to develop a non-destructive polarimeter and modified H-Cal Polarimeter is planned to be installed at PHENIX-experiment collision point for spin rotator commissioning.

## REFERENCES

1. Adams, D.L. et al., *Phys. Lett.* **B261**, 201-206 (1991)
2. Adams, D.L. et al., *Phys. Lett.* **B264**, 462-466 (1991)
3. Bravar, A. et al., *Phys. Rev. Lett.* **77**, 2626-2629 (1996)
4. Qiu, J., and Sterman, G., *Phys. Rev. Lett.* **67**, 2264-2267 (1991)
5. Collins, J.C., *Nucl. Phys.* **B396**, 161-182 (1993)
6. Efremov, A., Korotkian, V., and Teryaev, O., *Phys. Lett.* **B348**, 577-581 (1995)
7. Anselmino, M., Boglione, M., Murgia, F., *Phys. Lett.* **B362**, 164-172 (1995)
8. Artru, X., Czyzewski, J., Yabuki, H., *Z. Phys.* **C73**, 527-534 (1997)
9. Rakness, G., *These proceedings*
10. Jinnouchi, O., *These proceedings*
11. *GEANT Detector description and simulation tool* CERN Program Library Long Writup W5013, CERN Geneva (1993)
12. Adler, C. et al., *Nucl. Instrum. Meth.* **A470**, 488-499 (2001)
13. Flauger, W., and Mönnig, F., *Nucl. Phys.* **B109**, 347-356 (1976)