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# First measurement of transverse single spin asymmetry for very forward $\pi^0$ production in polarized $p+p$ collisions at $\sqrt{s}=510$ GeV

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Transverse single spin asymmetry, $A_N$, of very forward ($\eta > 6$) $\pi^0$ production plays an important role to understand the production mechanism from the view points of particularly diffractive and non-diffractive interactions. However, it has never been measured in detail because non-zero $A_N$ of $\pi^0$ has been usually interpreted by perturbative QCD framework. Since larger $A_N$ was observed by more isolated $\pi^0$ than less isolated ones recently, the diffraction is emerging as a possible origin of the non-zero $A_N$ of $\pi^0$. To disentangle this point, we installed a new electromagnetic calorimeter in the 0-degree area of STAR experiment and measured very forward $\pi^0$ over the transverse momentum ($p_T$) range of $0 < p_T < 1$ GeV/c in 510 GeV $p^{\uparrow}+p$ collisions. We report the first measurement of the $A_N$ in very forward $\pi^0$ production and its preliminary result as a function of $p_T$ recently released, which will provide more precise answer to the role of the diffractive interaction in near future by combined analysis with other STAR detectors.

*23rd International Spin Physics Symposium - SPIN2018 -*
*10-14 September, 2018*
*Ferrara, Italy*

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## 1. Introduction

When large transverse single spin asymmetries, $A_N$ of neutral and charged pions were observed for the first time [1, 2], it was a big surprise because leading-twist perturbative QCD (pQCD) had predicted the $A_N$ should be suppressed as $\alpha_s m_q/\sqrt{s}$, where $m_q$ is the quark mass. Afterward, in order to understand underlying mechanism of forward pion production, its $A_N$ has been explored inclusively by many experiments with various $\sqrt{s}$ (4.9 to 500 GeV) and surprisingly nearly $\sqrt{s}$-independent $A_N$ has been observed. Clear sign dependence was shown with the charged pions and smaller positive $A_N$ for $\pi^0$ [3] as the very first observation. Nowdays in pQCD framework, these results are being interpreted by transverse momentum dependent functions [4] and higher-twist effects between quark and gluon fields in the initial or final state [5, 6].

However, recently further study for $A_N$ of $\pi^0$ at STAR experiment showed an indication that there might be a finite contribution of diffractive interaction to its non-zero $A_N$ because larger $A_N$ was observed when no photon was detected near $\pi^0$ than one photon case [7]. Without identifying $\pi^0$, $A_N$ of photons also showed a tendency of decrease when the detected number of photons increased which was more hard scattering event topology [8]. Much smaller $A_N$ of forward jet production compared to that of forward hadron was observed by AnDY experiment [9]. This can be interpreted by an $A_N$ cancellation by $u$ and $d$ quarks asymmetries of opposite signs, expecting a possible contribution of the other process rather than pQCD picture.

Understanding of transverse single spin asymmetry, $A_N$ which is defined as left-right cross section asymmetry to the beam polarization provides qualitatively new information towards an understanding of the particle production mechanism. RHICf experiment has measured very forward particles produced in 510 GeV $p^{\uparrow}+p$ collisions at STAR to identify the origin of their non-zero $A_N$ from the view point of $p^{\uparrow}+p$ interaction. One advantage of the RHICf experiment should be the measurement of very forward $\pi^0$ ($6 < \eta$) itself which is expected to be produced by soft scattering but has never been studied in detail yet. The other noticeable advantage is the fine resolution of the detector. We expect less than 3% of energy resolution and less than 0.02 GeV/c of $p_T$ resolution for $\pi^0$. Therefore, We can precisely study the $A_N$ of $\pi^0$ and also contribution of diffractive scattering to it. In this report, we introduce our experiment and analysis scheme. The preliminary result of the $A_N$ for very forward $\pi^0$ production and future analysis prospect will be also presented.

## 2. RHICf experiment

To measure the very forward particles precisely, mainly neutron, single photon and $\pi^0$, an electromagnetic calorimeter (RHICf detector) that had been originally developed for the LHCf experiment [10] was moved from CERN to BNL and installed in 0-degree area which was 18 m away from the beam interaction point at STAR experiment . Fig. 1 shows the front and side view of the RHICf detector. RHICf detector has two towers with same structure, smaller one with 20 mm and larger one with 40 mm dimension. Each tower consists of 17 layers of tungsten absorbers, 16 layers of GSO plates for energy measurement, and 4 layers of GSO-bar hodoscope for position measurement. All 4 layers are covered by 1 mm thickness of thin GSO bars with both X and Y directions. For more detailed configuration of the detector, see [16] and [17].

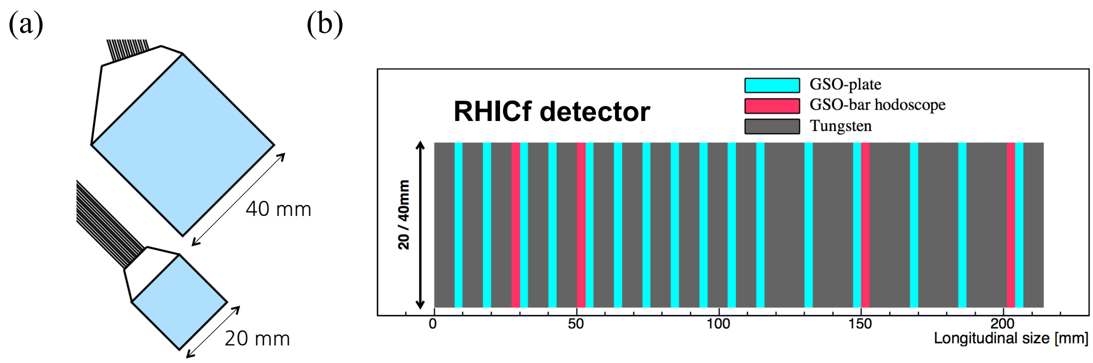


**Figure 1:** Schematic drawing of front (a) and side (b) view of RHICf detector. Two towers share same structure.

When $\pi^0$ is produced, two decayed photons can hit each tower or one same tower. The one will be called by Type-I $\pi^0$ and the other will be called by Type-II $\pi^0$ hereafter. Three kinds of trigger systems were used for the measurement of very forward neutral particles. First, a shower trigger was operated when the energy deposits of three successive layers of small or large towers were larger than 45 MeV. Single neutron and photon were mainly measured by this trigger. However, because single photons with lower energy is dominantly measured by shower trigger, a high electromagnetic trigger was used to enhance the yield of the higher energy photon and Type-II $\pi^0$. High energy electromagnetic trigger was issued when fourth GSO layer of small or large tower records larger than 500 MeV. Lastly, Type-I $\pi^0$ trigger was operated when the energy deposits of forward three successive layers up to 7th of both small and large towers were larger than 45 MeV.

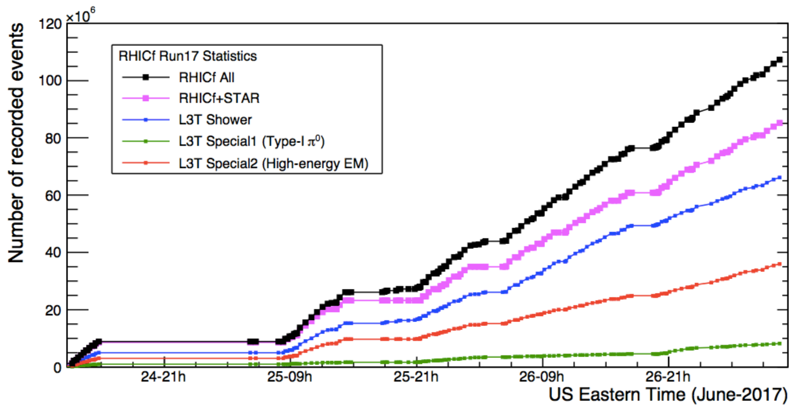


**Figure 2:** Accumulated number of events taken by each trigger during RHICf operation.

Number of accumulated events taken by each trigger were described in Fig. 2. About 110 M events were taken during 27.8 hours. To shorten possible multiple collision and avoid the additional uncertainty by beam emittance, we took data under a condition with a large $\beta^*$ of 8 m and low instantaneous luminosity about $1.0 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. We also took data with a horizontal beam polarization which was normal to usual vertical polarization to cover the wide $p_T$ range of the particles up to 1.0 from 0 GeV/c by moving the detector vertically. For the future combined analysis, data of other STAR detectors were also taken by RHICf trigger system.

## 3. Data analysis

Lateral position where the photon develops the electromagnetic shower is calculated by fitting the energy deposit distribution of GSO bars with a function motivated by Lorentzian as follows

$$f(x) = \frac{C}{2}\left[\frac{\sigma_S a}{((x-x_0)^2+\sigma_S)^{3/2}} + \frac{\sigma_W(1-a)}{((x-x_0)^2+\sigma_W)^{3/2}}\right] + C_0, \tag{3.1}$$

where $x_0$ corresponds with the incident position of photon. $\sigma_S$ and $\sigma_W$ describe comparatively sharp and wide energy distribution by electromagnetic shower respectively. $a$ is the weight between these two distributions, $C$ is a parameter for peak height, and $C_0$ is for noise level. Once the position of the photon is fixed, its energy is reconstructed considering position-dependent shower leakage effect and light collection efficiency of the GSO plate. These position-dependent corrections were studied by Geant4 simulation [11].

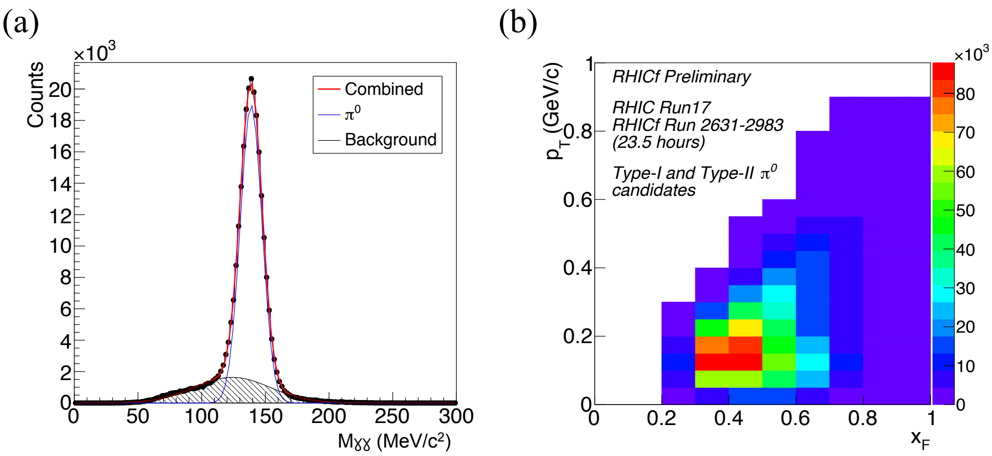


**Figure 3:** (a): Reconstructed invariant mass of two photon. Black filled area is the background region estimated by fitting. (b): Kinematics of final $\pi^0$ candidate.

Distribution of reconstructed invariant mass of two detected photons is shown in Fig. 3 (a). There is a clear peak around 135 MeV/c$^2$ with about 10 MeV/c$^2$ width surrounded by a wide background distribution. Most of background events are not wrong reconstruction but two detected photons from different $\pi^0$. Invariant mass distribution was fitted by superposition of Gaussian for actual $\pi^0$ peak and 6th-order polynomial for background considering its asymptotic tendency near 50 and 200 MeV/c$^2$. Invariant mass in the range of $\pm 3\sigma$ from $\pi^0$ peak was considered as the final $\pi^0$ candidate. Number of $\pi^0$ candidate events in $x_F$ and $p_T$ bins is described in Fig. 3 (b).

In RHICf experiment, $A_N$ is calculated by following formula due to detector geometry

$$A_N = \frac{1}{P}\frac{1}{D_\phi}\left(\frac{N^\uparrow - RN^\downarrow}{N^\uparrow + RN^\downarrow}\right) \tag{3.2}$$

where $P$ is polarization of the proton beam and $D_\phi$ is a dilution factor to correct the diluted $A_N$ by azimuthal angle distribution of $\pi^0$. $P$ was measured by p-Carbon polarimeter [18]. p-Carbon polarimeter measures the beam polarization using the asymmetry of the recoil carbon nuclei from proton-carbon elastic scattering. Raw asymmetry by $\pi^0$ with larger azimuthal angle to beam polarization usually brings out more diluted $A_N$. $N^{\uparrow(\downarrow)}$ represents the detected number of $\pi^0$ in specific kinematic range with polarized up (down) proton beam. $R$ corresponds with luminosity ratio between polarized up and down proton beams. $R$ was calculated by counting the number of events by scaler that charged particles leave signals bigger than specific threshold at both BBC [12] and VPD [13] detectors.

## 4. Results

$A_N$ of very forward $\pi^0$ was calculated as a function of $p_T$ for three different $x_F$ ranges as described in Fig. 4. Error with stick represents the statistical uncertainty and box represents the systematic one by uncertainties of polarization, dilution factor, beam center calculation, and background $A_N$ subtraction. Invariant mass range further than $5\sigma$ of $\pi^0$ peak was used for the calculation of background $A_N$. Surprisingly, non-zero $A_N$ was observed even in very forward $\pi^0$ production with comparable magnitude of the $A_N$ of forward $\pi^0$. It seems that $A_N$ of very forward $\pi^0$ in the largest measured $p_T$ is even higher than the one of the forward $\pi^0$. Fig. 4 shows increasing ten-

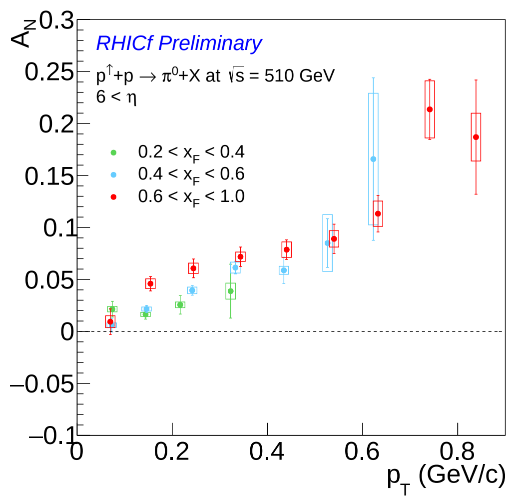


**Figure 4:** Preliminary result of the $A_N$ of very forward $\pi^0$ production. Three different colors of data points correspond with three different $x_F$ ranges.

dency as $p_T$ and $x_F$ increases. Diffractive interaction may have a comparable contribution with partonic one to the non-zero $A_N$ of $\pi^0$. Since the data of the STAR subdetectors were also recored by RHICf trigger system, more concrete study than inclusive measurement should be possible to understand our result. One practical way would be studying how the $A_N$ changes according to the $p^\uparrow + p$ interaction by specifying the event type definitions. Here, we started combined analysis



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with STAR using forward detectors and Roman pot [15]. More detailed correlation study by the combination of RHICf and STAR detectors may be able to make our current understanding to the production mechanism of (very) forward $\pi^0$ one step deeper.

## 5. Summary

In June, 2017, we installed an electromagnetic calorimeter in the 0-degree area which was 18 m away from the beam interaction point at STAR experiment and measured very forward particles, mainly single neutron, photon, and $\pi^0$ in 510 GeV $p+p^{\uparrow}$ collisions. Recently, our preliminary result showed non-zero $A_N$ even in very forward $\pi^0$ production. It indicates that diffractive process may contribute to the non-zero $A_N$ of $\pi^0$ and shows possible agreement with previous study for the forward $A_N$ of $\pi^0$ at STAR. However, our preliminary result is inclusive measurement, more detailed and strict study with other STAR detectors is expected to give more precise answers.

**Acknowledgements** We thanks the BNL staff, STAR and PHENIX Collaborations for their essential contributions to the successful operation of RHICf. This work was partially supported by the U.S.-Japan Science and Technology Cooperation Program in High Energy Physics and the National Research Foundation of Korea (No. 2016R1A2B2008505).

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