Transverse single-spin asymmetry for very forward $\pi^0$ production in $p^\uparrow + p$ collisions at $\sqrt{s} = 510$ GeV

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Transverse single spin asymmetry ($A_N$)

- In polarized $p + p$ collision, $A_N$ is defined as a left-right cross section asymmetry of a specific particle.

- Though the non-zero $A_N$ of $\pi^0$ has been intensively studied for longer than 30 years, the origin of it is still open question.
$A_N$ in forward $\pi^0$ production

- Observed non-zero $A_N$ of $\pi^0$ ever has been interpreted based on only perturbative picture theoretically.

- Non-zero $A_N$ comes from an asymmetry of the partonic-level fragmentation process or spin-dependent quark-gluon correlations in the proton.
New question to the $A_N$ of forward $\pi^0$

Larger $A_N$ was observed by more isolated $\pi^0$ than less isolated one.

Non-perturbative process may have a finite contribution to the $\pi^0 A_N$ as well as perturbative one.
No detailed measurement ever for the $p_T$ range below 1 GeV/c.

In June, 2017, RHICf experiment measured the $A_N$ of very forward $\pi^0$ ($6 < \eta$ and $p_T < 1$ GeV/c) where the non-perturbative process is expected to be dominant.
RHIC forward (RHICf) experiment

- 18 m away from IP.
- $0.2 < x_F < 1.0$.
- $0.0 < p_T < 1.0$ GeV/c.

Large tower
Small tower

40 mm
20 mm

With three Det. positions
0-degree position

RHICf detector

DX dipole magnet

ZDC

Intersection point

24 mm
RHICf detector & $\pi^0$ measurement

Small tower: 20/20 mm
Large tower: 40/40 mm
17 tungsten absorbers
(44 $X_0$, 1.6 $\lambda_{int}$)
16 GSO plates for energy measurement
4 GSO bar layers for position measurement

Type-I $\pi^0$ trigger

dE $> 45$ MeV AND
RHICf detector & $\pi^0$ measurement

Small tower: 20/20 mm
Large tower: 40/40 mm
17 tungsten absorbers (44 $X_0$, 1.6 $\lambda_{int}$)
16 GSO plates for energy measurement
4 GSO bar layers for position measurement

Type-II $\pi^0$

High EM trigger

$\pi^0$  $\gamma$  $\gamma$  $\gamma$

$dE > 500$ MeV  OR  $\cdots$
Operation summary

- Total 110 M events were accumulated for neutral particles (neutron, $\pi^0$, and single photon) during 4 fills (28 hours).

- 90°-rotated radial polarization.

- Higher $\beta^* = 8$ m and lower luminosity = $10^{31}$ cm$^{-2}$s$^{-1}$ than usual.
Position reconstruction of photon

- If a photon hit a tower,\( \gamma \) (x, y)
- Positions of decayed photons are measured by 1 mm dimension GSO bars.
Energy reconstruction of photon

- If a photon hit a tower, 

\[ \gamma(x, y) \]

Cor. 1

\[ \frac{dE(x,y)}{dE_{\text{center}}} \]

Simulation

Cor. 2

\[ \frac{dE_{\text{center}}}{\text{Sum}dE} \]

Cor. 1

\[ \frac{E_{\gamma}}{\text{Sum}dE} \]

Cor. 2

\[ dE(x, y) \]

Simulation

\[ dE_{\text{center}} \]

\[ \text{Sum}dE \]

\[ E_{\gamma} \]
**Invariant mass of two photons**

- Data is well matched with simulation showing clear $\pi^0$ peak around 135 MeV/c$^2$ with $\sim$8 MeV/c$^2$ peak width.

- Invariant mass was fitted by polynomial function for background and Gaussian one for $\pi^0$. 
**π^0** kinematics & $A_N$ calculation

- Very forward $\pi^0$ over the $x_F$ range of $0.2 < x_F < 1.0$ and $p_T$ range of $0.0 < p_T < 1.0$ GeV/c was measured.

- Systematic uncertainties by polarization, background $A_N$ subtraction, and beam center were included.

\[
A_N = \frac{1}{P \cdot D_\Phi} \left( \frac{N^\uparrow - RN^\downarrow}{N^\uparrow + RN^\downarrow} \right)
\]

- $P$: Polarization
- $D_\Phi$: Dilution factor
- $R$: Relative luminosity
Very forward $\pi^0 A_N$ as a function of $x_F$

- The higher $p_T$ range the $A_N$ is measured in, the more clearly it increases as a function of $x_F$.

- Note that $x_F$ resolutions of the RHICf detector are much finer than $x_F$ binning.
Comparison with previous measurements

There can be perturbative contribution even in lower $p_T$ area?

The origin of the $x_F$ scaling is non-perturbative process?

We need to explore what makes the non-zero $A_N$ in more direct way.
Non-zero $A_N$ was observed even in very forward $\pi^0$ showing clear increasing tendency as a function of $p_T$.

Note that $p_T$ resolutions of the RHICf detector are also much finer than the $p_T$ binning.
Comparison with previous measurements

What’s the real origin of the non-zero $A_N$ of $\pi^0$?

How competitively each perturbative and non-perturbative process contribute to the $\pi^0 A_N$ will be answered by combined analysis with STAR and follow-up experiments in near future.
The very forward neutron $A_N$ is also being analyzed.

The ongoing analysis shows the data is well matched with the previous measurements \(\rightarrow\) will be extended to the higher $p_T$. 

\(\sim 1.2\)
RHICf experiment measured the $A_N$ of very forward ($6 < \eta$) neutral particles (neutron, $\pi^0$, single $\gamma$).

Large non-zero $A_N$ was also observed in the kinematic range where the non-perturbative process is expected to be dominant.

More detailed analysis with STAR detectors and follow-up experiment will provide a hint for the origin of the $\pi^0 A_N$.

Result of the very forward neutron $A_N$ will be also released soon.
Backup
Contents..
New question to the $A_N$ of forward $\pi^0$

Smaller $A_N$ was observed with increasing multiplicity of photons (closer to hard scattering event topology).

RHICf experiment was successfully operated in June 2017.

Total 110 M events were accumulated for neutral particles (neutron, $\pi^0$, and single photon) during 28 hours.

Radial polarization.

Higher $\beta^*$: 8 m and lower luminosity: $10^{31}$ cm$^{-2}$s$^{-1}$ than usual.
Shower trigger: Energy deposits of three successive layers at large or small tower are larger than 45 MeV. (for neutron and single photon)

High EM trigger: Energy deposit of 4th layer at large or small tower is larger than 500 MeV. (for high energy photon and Type-II $\pi^0$)

Type-I $\pi^0$ trigger: Energy deposits of three forward (up to 7th) successive layers at large and small tower are larger than 45 MeV. (for Type-I $\pi^0$)
Beam center calculation (by neutron)

- Neutrons were used for beam center calculation.
- Square root formula shows good agreement with luminosity one.
L90 represents the longitudinal depth where the energy deposit reaches 90% of total energy deposit.

Gamma events can be distinguished from neutron ones using that EM shower develops more rapidly than hadronic one.
$A_N$ calculation

\[
A_N = \frac{1}{P \epsilon} \frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}}
\]

- $P \ (\sim 0.55 \pm 0.05)$ can be calculated by polarization monitor.
- $R \ (\sim 0.970 \pm 0.02)$ is estimated by luminosity ratio of charged particles near IP.
- $\epsilon \ (\sim 0.95 \pm 0.05)$ can be studied by comparing actual and diluted $A_N$ in simulation.
Background $A_N$ subtraction

Background $A_N$s are all consistent with zero.

Difference between the $A_N$ with and without the $\pi^0$ tail was considered as a systematic uncertainty. Should be overestimated due to the $\pi^0$ tail.
Using other STAR detectors, event type dependence for the $A_N$ can be studied.

A follow-up experiment will be proposed to practically compare the each contribution from partonic and diffractive process.