Transverse single asymmetries in $\pi^0$ production in $p + p$, $p+Al$ and $p+Au$ collisions at mid-rapidity using the PHENIX detector system

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Transverse Spin

Large asymmetries in the forward $\pi^0$:

$$A_N = \frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$

Persists to high collision energies

PRD90, 012006 (2014)
**p_T dependent distributions**

**Sivers Effect** (Phys.Rev.D41,83): Introduce transverse momentum of parton relative to proton.


Correlation between **Proton** spin ($S_p$) and parton transverse momentum $k_{T,p}$

$$\tilde{f}_{1T}^{q} (x, k_{T,p}^2) \cdot D_q^h (z)$$

Correlation between **Proton** spin ($S_p$) and quark spin ($S_q$) + spin dep. frag. function

$$\delta q(x) \cdot H_1^\perp (z_2, \vec{k}_\perp^2)$$

Graphics from L. Nogach (2006 RHIC AGS Users Meeting)
Higher twist correlation functions

- QCD, collinear partons
- Multiple parton scattering

Higher twist interaction contributions expected to drop like \(1/p_T\)

What is expected \(A_N\) dependence on \(p_T\)?

\(p_T\) large, \(A_N \sim 1/p_T\)

PRD90, 012006 (2014)
Asymmetry in mid-rapidity

The asymmetry of $\pi^0$ and $\eta$ in midrapidity:
- Both agree very well
- Consistent with zero within errors

How does it change from p+p to p+A collisions?

Already some surprises, see
Neutron $A_N$ M. Kim’s talk (Tuesday)
$J/\psi$ $A_N$ C. Xu’s talk (Tuesday)
π⁰ reconstruction with PHENIX

Transverse asymmetry:

\[
A_N = \frac{1}{P} \frac{\sqrt{N_L^\uparrow N_R^\downarrow} - \sqrt{N_L^\downarrow N_R^\uparrow}}{\sqrt{N_L^\uparrow N_R^\downarrow} + \sqrt{N_L^\downarrow N_R^\uparrow}}
\]

Signal/Background:
- Estimated by mix-event technique
- Assuming the background \(A_N\) under the \(π^0\) mass has no mass dependency

Extracting the signal asymmetry:

\[
A_N^S = \frac{N_{S+B}}{N_\pi} A_{N^{S+B}} - \frac{N_B}{N_\pi} A_N^B
\]

- \(N_{S+B} = \text{number of counts in } π^0 \text{ mass window}\)
- \(N_\pi = \text{number of } π^0 \text{ counts}\)
- \(N_B = \text{number of background counts in } π^0 \text{ window}\)
**$A_N$ in $p+p$**

$p+p \rightarrow \pi^0 + X$ @ 200 GeV, $|\eta|<0.35$

- Factor of 3 increase precision in the statistical uncertainty with the previous result, precision at low $p_T < 3 \times 10^{-4}$
- Higher $p_T$ reach
- $A_N$ is consistent with zero within uncertainties
- Mid-rapidity $\pi^0$ $A_N$ has been used to constrain the Sivers gluon function:
$A_N$ in p+Au and p+Al in midrapidity

$A_N$ in p+A collisions @ 200 GeV in midrapidity:

• Asymmetry is consistent with zero within the uncertainties

• The precision in low-$p_T$ is $< 10^{-3}$
$A_N$ versus $A$

$p+A \rightarrow \pi^0 + X, \lvert \eta \rvert < 0.35$

Integrated $A_N$ for $p_T > 4$ GeV/c

- In pQCD region in mid-rapidity
- Combined result for $p+p$, $p+Al$ and $p+Au$
- The asymmetry is consistent with zero ($< 3 \times 10^{-3}$)
- Potential to constrain theoretical models using pA collisions

PHENIX preliminary
Forward and Mid-rapidity $\pi^0$

The $\pi^0$ asymmetries are comparable from p+p to p+Au (Al) collisions

*slide from Christopher Dilks (STAR)*
Summary

- The $\pi^0 A_N$ in *mid-rapidity* in p+p, p+Au and p+Al collisions at $\sqrt{s} = 200$ GeV was measured by PHENIX:
  - All asymmetries are *consistent with zero*
  - Higher $p_T$ reach as previously measured p+p result
  - Factor of 3 higher precision in p+p, low-$p_T < 4 \times 10^{-4}$
  - precision at low-$p_T$ in p+A < $10^{-3}$

- $\pi^0$ transverse asymmetry from p+p to p+A are *comparable* in mid- (PHENIX) or forward-rapidity (STAR)

- The $\pi^0$ production in p+p vs p+A ($R_{pA}$) will answer outstanding question considering *nuclear effects*

- *Theoretical input* for the mid-rapidity $\pi^0$ asymmetries is needed
Backup
Gluon Sivers function

Gluon Sivers at COMPASS

- **Deuteron is zero within the uncertainties:**
  The central value is negative with similarly large error

- **Proton is negative to 3σ precision**
  Also comparable with the deuteron result within uncertainties
$\pi^0 A_N$ in p+A collisions

Kang, Yuan: PRD84, 034019
Kovchegov, Sievert: PRD86, 034028