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Measurement of Transverse Single Spin Asymmetries in π^0 Production from $p^\uparrow + p$ and $p^\uparrow + A$ Collisions at STAR

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In 2015 the first collisions between polarized protons and nuclei occurred at the Relativistic Heavy Ion Collider (RHIC), at a center-of-mass energy of $\sqrt{s_{NN}} = 200$ GeV. Comparisons between spin asymmetries and cross-sections in $p+p$ production to those in $p+A$ production provide insight into nuclear structure, namely nuclear modification factors, nuclear dependence of spin asymmetries, and comparison to models with saturation effects. The transverse single-spin asymmetry, A_N, has been measured in π^0 production in the STAR Forward Meson Spectrometer (FMS), an electromagnetic calorimeter covering a forward psuedorapidity range of $2.6 < \eta < 4$. Within this kinematic range, STAR has previously reported the persistence of large π^0 asymmetries with unexpected dependences on p_T and event topology in $p+p$ collisions. This talk will compare these dependences to those in $p+A$ production.

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1. Introduction

One of the principal observables which helps to gain insight on the spin and orbital angular momenta of partons within polarized protons is the transverse single-spin asymmetry, denoted A_N. Letting $d\sigma^{\uparrow(\downarrow)}$ denote the differential cross-section for leftward scattering of a spin up (down) polarized proton on an unpolarized target, A_N is defined as the following ratio:

$$A_N := \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}. \tag{1.1}$$

This asymmetry shows up as a $\cos\phi$ modulation of the cross-section, where ϕ is the azimuth of the observed particle. Since 1976, large values of A_N have been seen in forward pion production, with only modest dependence on the center-of-mass energy, $\sqrt{s}$ [1]. For forward π^0s, A_N increases with respect to $x_F := 2p_z/\sqrt{s}$, where p_z is the longitudinal momentum of the π^0, and A_N is mostly flat or rising with respect to π^0 transverse momentum, p_T. [2][3][4].

In 2015, the world's first polarized $p^\uparrow + A$ synchrotron collisions took place at the Relativistic Heavy Ion Collider (RHIC), at $\sqrt{s} = 200$ GeV. Significant data samples of polarized protons colliding against gold ($A = 197$) and aluminum ($A = 27$) nuclei were obtained. With these new data, there are a few observables and possible implications available. The first natural question from a spin physics point of view is how A_N in $p^\uparrow + A$ compares to that in $p^\uparrow + p$ collisions. One implication of this comparison is its use as a possible probe of gluon saturation: the color glass condensate model predicts that A_N in $p^\uparrow + A$ decreases as A increases [5]. The nuclear modification factor, R_{pA}, and its kinematic-dependences can also be assessed. Dependences of A_N on event topology can also be compared between $p^\uparrow + A$ and $p^\uparrow + p$ collisions, possibly leading to insight on fragmentation universality. Finally, dependences of A_N as well as R_{pA} on collision centrality is another avenue for exploring possible effects a nuclear medium has on these observables.

2. Forward Calorimetry at STAR

The primary detector used in this analysis is the Forward Meson Spectrometer (FMS), a Pb-glass electromagnetic calorimeter covering a pseudorapidity range of $2.6 < \eta < 4$. It is composed of 1,264 Pb-glass cells, each coupled to photomultiplier tubes, arranged in a square array as shown in Figure 1. The primary observable is the $\pi^0 \to \gamma\gamma$ decay channel, where the transverse distance between the two photons along with their energies provide access to the di-photon invariant mass, $M_{\gamma\gamma}$, and subsequently to π^0 reconstruction.

Another detector, which is used in quantifying systematic uncertainties in this analysis, is the pair of Beam Beam Counters (BBCs). Each BBC is an annular arrangement of hexagonally-tiled scintillator panels, as shown in the left side of Figure 2. The portion of the BBC used in this analysis covers a pseudorapidity range of $3.3 < |\eta| < 5$, where $\eta > 0$ denotes forward production (*i.e.*, toward the FMS) and $\eta < 0$ denotes backward production (*i.e.*, opposite the FMS). In $p+A$ collisions, the proton beam faces the FMS and the nuclear beam remnants scatter toward $\eta < 0$.

In order to reconstruct π^0s, photons within 35 mrad isolation cones were collected. Within each event, only the highest energy photon pair in the highest energy isolation cone cluster was considered. This event selection yielded a $M_{\gamma\gamma}$ distribution with a lower background than less-restrictive event selections. To select π^0s from di-photon events, a mass cut of $|M_{\gamma\gamma} - 135| <$

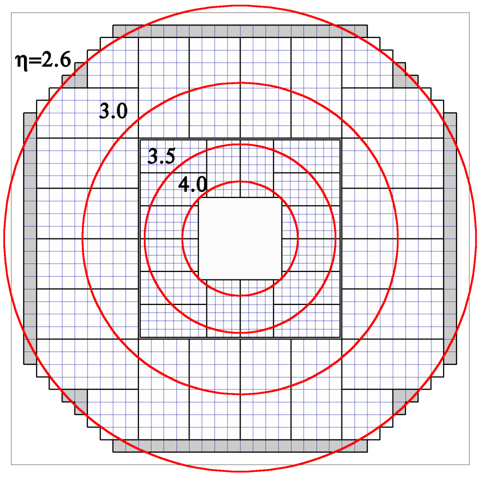

Figure 1: Schematic of the FMS Pb-glass cells. Red circles indicate rings of constant η, bold black double-lines indicate the boundary between large outer cells and small inner cells, and grey-colored cells are not in the trigger. The beam-pipe passes through the white square in the center.

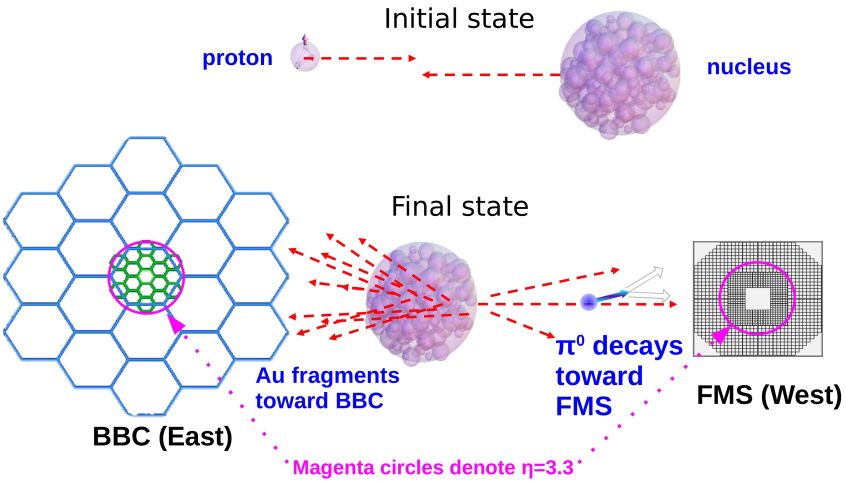

Figure 2: Schematic of the $p+A$ experimental setup, with the FMS and BBC shown in the final-state setup. The proton beam faces the FMS and the nuclear beam faces the opposite $\eta < 0$ BBC. Only the scintillators inside the pink $\eta = 3.3$ ring are considered in this analysis; this η-ring is also drawn on the FMS schematic for comparison.

120 MeV$/c^2$ was used, along with an energy-sharing cut of $|E_1 - E_2|/(E_1+E_2) < 0.7$, where $E_{1,2}$ denote the energy of the photons. Finally, after demanding the π^0 p_T to be above trigger threshold, these π^0s were then organized into E and p_T bins for subsequent asymmetry analysis.

The selected π^0s, within their E and p_T bins, are then binned in $\cos\phi$ bins. Letting $N^{\uparrow(\downarrow)}$ denote the π^0 yield from the scattering of spin-up(down) protons, the distribution of the raw transverse single-spin asymmetry is fit to the following linear equation with parameters $p_{0,1}$:

$$\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}} = p_0 + p_1 \cos\phi, \tag{2.1}$$

The measured A_N is then the amplitude of the azimuthal modulation of this quantity, divided by the beam polarization P, that is, $A_N = p_1/P$, whereas p_0 scales with the relative luminosity between spin up and spin down protons.

In $p+A$ collisions (and to a lesser extend in $p+p$ collisions), the extracted A_N depends on the away-side BBC multiplicity, *i.e.*, on the charged particle distribution from the nuclear remnants. In this analysis, this dependence is characterized as the dominant systematic uncertainty on A_N within each kinematic bin; further characterization of this dependence and its possible relation to centrality will be studied in future analyses.

3. Results and Discussion

The transverse single-spin asymmetries for forward π^0s produced in $p+p$ and in $p+Au$ collisions are shown as a function of p_T in six different $x_F \approx E_{\pi^0}/(100\ \text{GeV})$ bins in Figure 3, where the x_F approximation is valid for forward production kinematics; filled-in points are for π^0s from $p+p$ and open points are those from $p+Au$. Statistical uncertainties are represented by vertical error bars and the dominant systematic uncertainty from the charged particle multiplicity in the gold-going BBC is represented by the vertical size of the grey band centered at $A_N = -0.005$. The asymmetry from $p+p$ is similar to that from $p+Au$, within statistical and systematic uncertainties. These data represent a luminosity of approximately 35 pb^{-1} from $p+p$ and 205 nb^{-1} from $p+Au$. Forward proton beam average polarizations were $55.6\pm2\%$ and $60.4\pm2\%$ for $p+p$ and for $p+Au$, respectively.

Another study that was performed with data from the 2015 RHIC run is the dependence of π^0 A_N on event topology. Recent data from the FMS in previous RHIC runs have shown that isolated π^0s have a higher A_N than those which are surrounded by other forms of electromagnetic energy [3][4]. This dependence was studied again in the 2015 $p+p$ data and was compared to the $p+Au$ sample. For a given π^0 in a 35 mrad isolation cone, the next highest energy photon cluster with $E > 3$ GeV outside the isolation cone was considered; its (η,ϕ)-position relative to that of the π^0 was denoted $(\Delta\eta,\Delta\phi)$. The π^0 events were then separated into two isolation classes: those with electromagnetic energy deposited $\Delta\phi < 100$ mrad from the π^0 and its more-isolated complement, $\Delta\phi > 100$ mrad. Figure 4 shows the A_N for the two event classes, where more-isolated π^0s are plotted as filled-in squares and less-isolated as open circles. The same trend persists in $p+Au$: more isolated π^0s have a higher A_N.

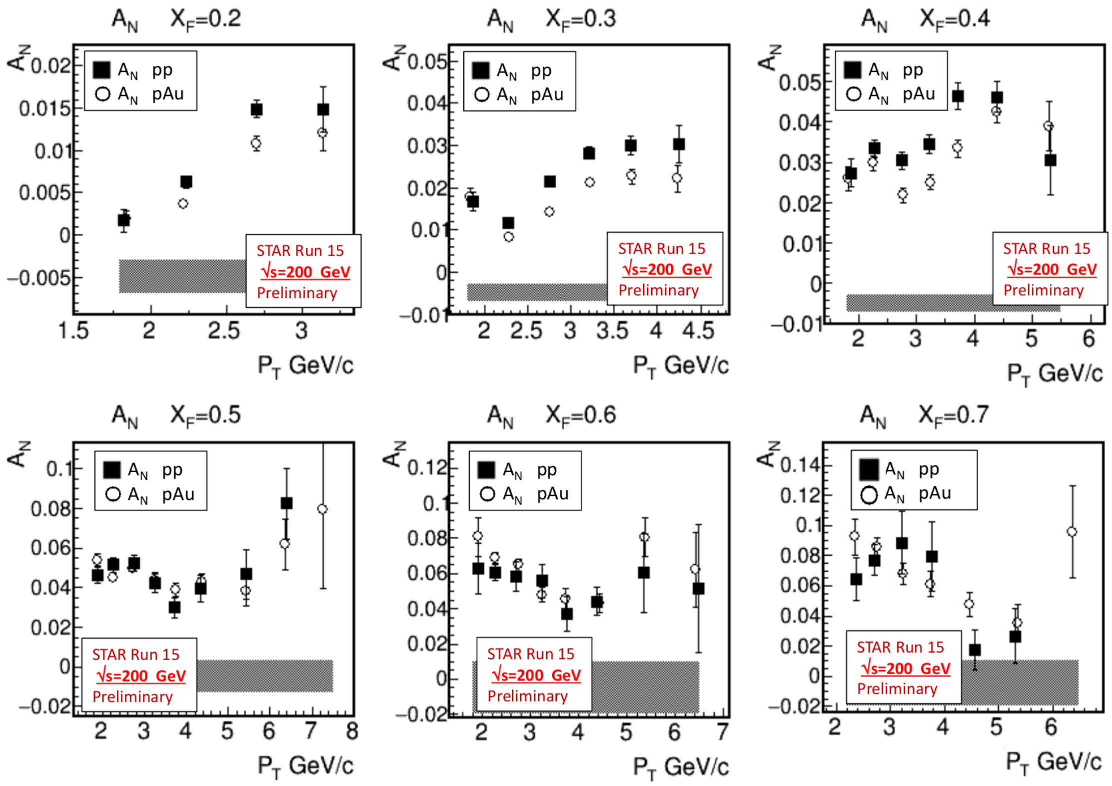

Figure 3: Transverse single-spin asymmetry A_N vs. p_T for π^0s from $p+p$ (filled points) compared to $p+Au$ (open points) for six x_F bins of widths 0.1 centered about the value indicated in the plot titles. Vertical error bars are statistical uncertainties and the vertical size of the grey band centered around $A_N = -0.005$ is the size of the systematic uncertainty from the BBC multiplicity. (Note: vertical scales are different in each plot)

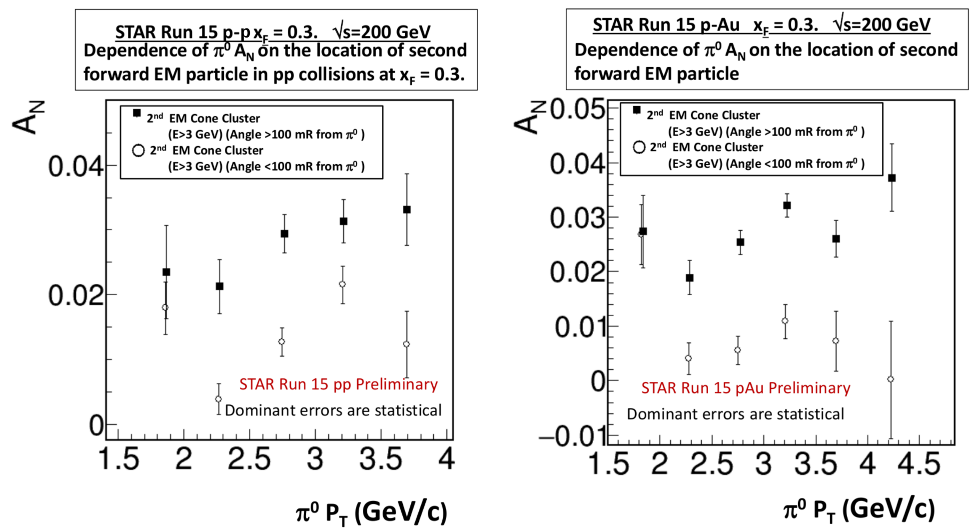

Figure 4: A_N for isolated (filled squares) and non-isolated (open circles) π^0s from $p+p$ (left) and $p+Au$ (right). (Note: vertical scales are different in each plot)

4. Conclusion

This analysis was of A_N from π^0s from the world's first synchrotron collisions of polarized protons against nuclei at $\sqrt{s} = 200$ GeV. The value of A_N in $p+p \rightarrow \pi^0 + X$ was shown to be within statistical and systematic uncertainties of that in $p+Au \rightarrow \pi^0 + X$ for all kinematic bins analyzed. The value of A_N in both cases appears to be flat or to be rising with respect to p_T and also rises with x_F. Its dependence on event topology is also similar for both cases: isolated π^0s are associated with higher values of A_N. Plans for future analyses include characterizing more carefully the dependence of A_N on nuclear breakup multiplicity and its possible relation to collision centrality, as well as studies of nuclear modification factors within these kinematics.

References

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